# DEFORMATION AND METAMORPHISM IN THE CONTACT

# AUREOLE OF THE SOUTH MOUNTAIN BATHOLITH, BEDFORD AREA

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# ABSTRACT

This study documents structures related to Halifax Pluton emplacement, in the Bedford area. Intrusion of the Devonian South Mountain Batholith caused both metamorphism and deformation of the Cambrian-Ordovician Meguma Group. Most previous structural interpretations for the area have attributed local structural features to regional deformation events. Field and petrographic analysis indicates that a strain and thermal aureole exists in a zone surrounding the Halifax Pluton. Mapping revealed several structures hitherto locally unrecognized, including a schistose lineated fabric ($LS_2$) and other minor contact-parallel features. Microscopic analysis of these rocks defined an aureole at least 1.5 km wide, divided into an outer biotite zone, a medial cordierite zone, and an inner K-feldspar zone. A cross-section along the axial trace of the Bedford Syncline indicates a variation in style of deformation and strain with proximity to the granite contact. An increase in dip of bedding towards the contact is interpreted as a result of flattening perpendicular to the granite boundary, probably with a high ratio of pure shear to simple shear. The same cross-section also offered insight on the depth to detachment of both the transverse anticline and the larger Magazine Hill Basin. Metamorphic minerals define the deformation structures (e.g. $LS_2$), which suggests deformation and metamorphism were both imposed by the rising, and possibly ballooning granite pluton. Therefore this study proposes that metamorphism and significant deformation of the Goldenville Formation in the study area are related spatially and temporally to the emplacement of the Halifax Pluton.

Keywords: Halifax Pluton, Goldenville Formation, Contact Metamorphism, Deformation, Emplacement, Aureole, Foliation

## ACKNOWLEDGEMENTS

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# CHAPTER 1 INTRODUCTION

## 1.1 Introduction

The South Mountain Batholith (SMB) forms one of the largest intrusive granitoid complexes in the Appalachian Orogen (Abbott, 1989). Emplacement of the South Mountain Batholith resulted in metamorphism and deformation of the pre-existing country rocks of paleo-Nova Scotia, the Meguma Group. This thesis concerns the Halifax Pluton member of the South Mountain Batholith, and its effect on the Meguma Group during emplacement.

The emplacement of the Halifax Pluton formed a metamorphic contact aureole adjacent to the pluton. In the Bedford area, this aureole contains a number of features never previously described, including metamorphic foliation, stretching lineation, and boudins. This study documents these features from structural, metamorphic, mesoscopic, and microscopic standpoints. A synthesis of these data allows new interpretations on the deformation, displacement, and metamorphism at the pluton boundary.

## 1.2 Pluton Emplacement

Pluton emplacement involves a body of magma upwelling through the crust and associated wall rock deformation and metamorphism. Mechanisms of magma rise have been the subject of vigorous debate since the 1940's. In recent years, the focus has changed to the connection between plutonism and regional deformation. Terms like "passive" (no forceful injection) and "active" (forceful injection) emplacement have been adopted without much thought about the mechanics behind such nomenclature (Paterson and Fowler, 1993).

The structural effects of pluton emplacement can change character with depth, even within a single pluton. Near surface, epithermal plutons are characterized by brittle deformation of wall rocks, moderate depth, mesothermal plutons are associated with transitional (brittle to ductile) deformation, whereas deep hypothermal interfaces show ductile deformation (Woodcock and Underhill, 1987; Paterson et al., 1992).

Stoping, cauldron subsidence, ballooning, diapirism, and doming are all possible mechanisms of pluton emplacement, and all have distinctive deformation patterns (Paterson et al., 1991b) (Fig. 1.1). Rise of magma is driven by density contrasts between the melt and surrounding rocks. The melt is more buoyant than the surrounding rocks, and this contrast drives the magma up (Paterson and Vernon, 1995). Rising ceases when the magma achieves a position of dynamic equilibrium in the crust. The crustal level where equilibrium is acquired is a complex function of the density, competency, and
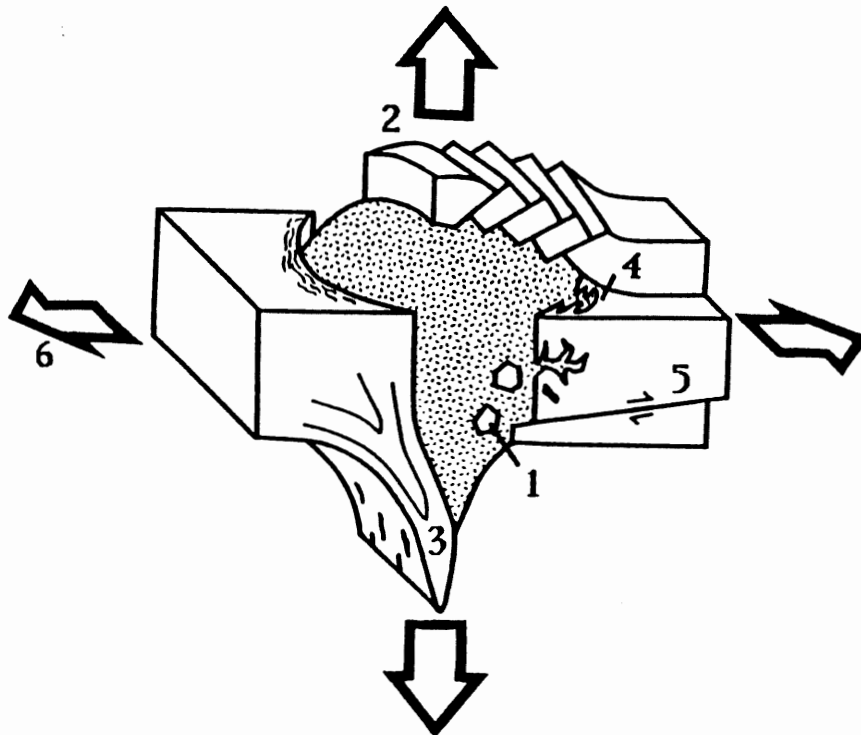
Figure 1.1 Pluton emplacement mechanisms. 1. Stoping. 2. Roof doming, with associated block faults. 3. Return flow and ductile wall rock alteration. 4. Anatexis and assimilation. 5. Lateral wall rock displacement. (From Paterson et al., 1991).

rheology of both the magma and the surrounding country rock. Therefore emplacement is controlled

by a combination of these factors (Paterson and Fowler, 1993).

## 1.3 Emplacement Effects

Wall rocks and magma interact as a coupled, open, and linked system, with chemical and

physical, e.g. material, exchange across the granite-wall rock boundaries. The emplacement of granite

is affected by the wall rocks, and vice versa (Paterson et al., 1991a). In ideal conditions, a chronology

of events related to pluton emplacement can be deduced from features recorded in metamorphic

aureoles.

The contact temperatures country rocks are subjected to during pluton emplacement can be

intense enough to cause melting. This melting results in a metamorphic contact aureole, which while

not regionally important, can be locally extensive (Paterson et al., 1993). Contact aureoles are

important because they may preserve a recordable gradient of the interaction of magma with

surrounding rocks. Metamorphosed wall rocks, if properly interpreted, offer an unrivalled record of

conditions during emplacement (Paterson et al., 1991b).

Perhaps the most pertinent information that aureoles can convey concerns the timing of pluton

emplacement. Relative timing of regional events (folding, faulting, or cleavage development), with

respect to pluton emplacement, can be deduced from textural relationships in contact aureoles (Fig.

1.2). A pluton emplaced after regional deformation would overprint regional fabrics within the

aureole. On the other hand, a pluton emplaced before regional deformation may affect subsequent
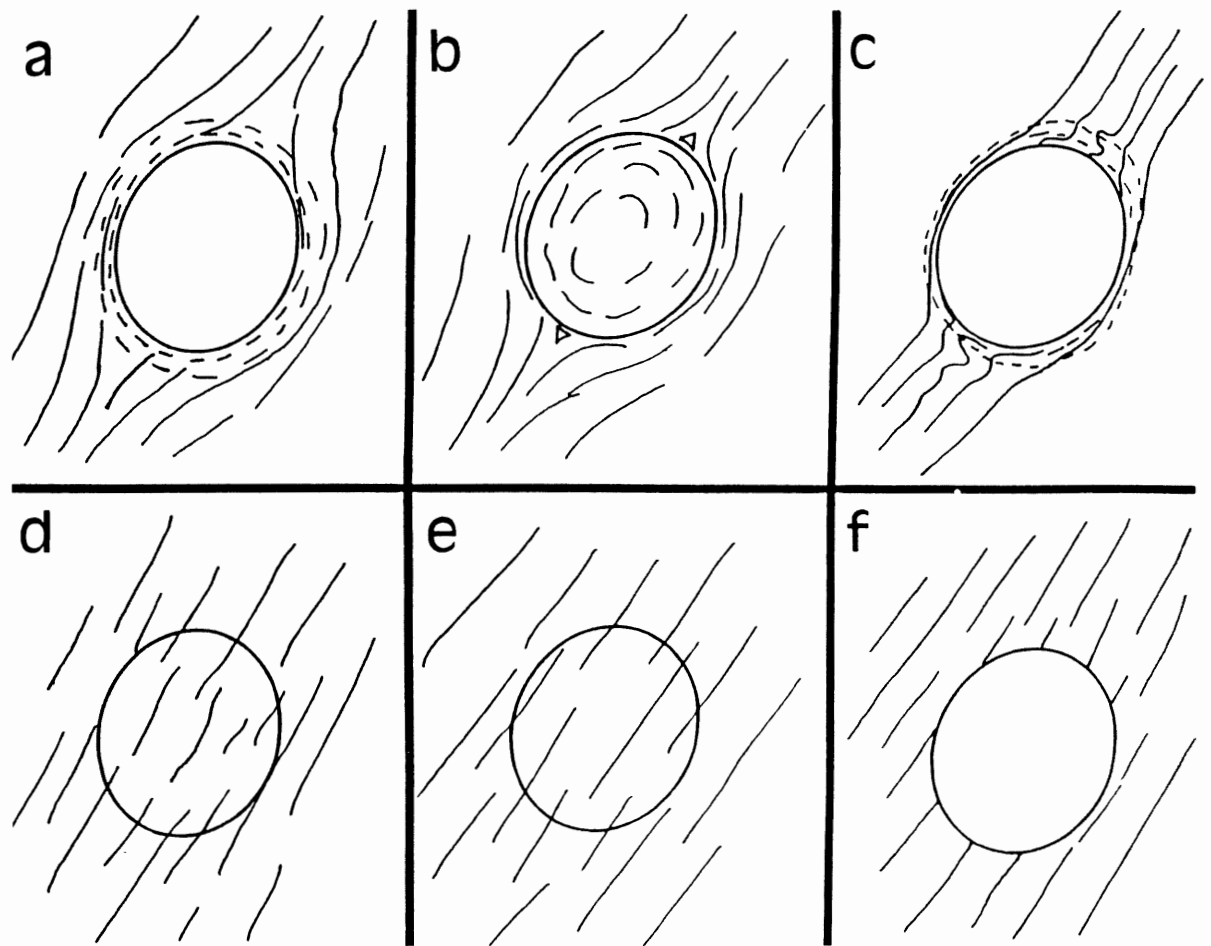
Figure 1.2  Hypothetical foliation patterns around pre- (a,d), syn- (b,e), and post-tectonic (c,f)
plutons.  (From Paterson et al., 1991).

deformation by deflecting it, or obviously be affected by it.   Therefore, suitable aureoles may indicate relative age determinations like pre-, syn-, or post-tectonic emplacement (Bateman, 1985; Guglielemo, 1994; Paterson et al., 1991b,1993).

The interpretative value of metamorphic contact aureoles is well understood.  Contact aureoles offer more than just interesting "natural laboratories" for unravelling metamorphic reactions.  The kinematics and mechanisms behind the development of structures, such as folds and foliations, may also be inferred.  Well documented contact aureoles are renowned for their emplacement-related metamorphic foliations, faults, folds, lineations, and high-grade metamorphism of adjacent rocks (Bateman, 1985; Woodcock and Underhill, 1987; Fyson, 1980; Paterson et al., 1991a).  Contact aureoles offer an indication of gradation in metamorphism over a relatively small area.  Relationships between structures such as fabrics, folds, and faults can be studied in these small, well constrained areas.

Deformational fabrics in aureoles offer unique insights into emplacement-related strain paths and histories.  Pluton emplacement is a "destructive" event, resulting in high-grade metamorphism and possibly complete annealing of pre-existing fabrics in country rocks.

Halifax Pluton emplacement appears to have been directly responsible for contact-parallel foliation, steeply plunging lineations, the transverse Kearney Lake Anticline, and possibly the Magazine Hill Basin of Burns (1995).

## 1.4 Scope and Purpose

This study documents and describes deformation of the Cambrian-Ordovician Meguma Group at the northeast margin of the Devonian South Mountain Batholith, Halifax Pluton. Both structural and metamorphic aspects of pluton-related deformation are addressed. Particular attention is paid to contact metamorphism and related foliation development within the pluton-adjacent rocks. Mesoscopic and microscopic analysis of mineralogy and mineral assemblages of the metamorphosed Goldenville Formation are presented.

The study area lies west of the Bedford Basin, north of Halifax, Nova Scotia. Most field work was done in the Kearney Lake area, just west of exit 2, off Highway 102 (Fig. 1.3). This area was chosen because it allowed a follow-up to Burns (1995) study.

Numerous workers have described the geology of the general area (Faribault, 1908; Horne et al., 1992; Clarke and Chaterjee, 1988). Yet the contact zone has several distinct structures previously undocumented. A series of recent road-cuts has allowed investigation of the contact zone. The transverse anticline located close and parallel to the Halifax Pluton contact was noted in previous studies (Faribault, 1908; Clarke and Tate, 1993), as was the more distant Magazine Hill Basin described by Burns (1995). Burns proposed a possible emplacement related derivation of the transverse folds and the Magazine Hill Basin.

This thesis examines effects of the emplacement of the Halifax Pluton from a number of data sources. These data sources include field mapping aided by Global Positioning equipment (Trimble Pathfinder+ with differential corrections, allowing < 5 meter accuracy), use of thin sections prepared

NOVA SCOTIA

Area of Map

N

215°

SCALE

Kilometers

## LEGEND

### STRUCTURAL FEATURES

#### Planar
(Strike and dip presented on each symbol)

- Bedding $(S_0)$

- Bedding $(S_0)$
  Compiled from Faribault (1908)
  and Burns (1995)

- Cleavage $(S_1)$

- Metamorphic Foliation $(S_2)$

#### Linear

- Trace of Axial Surface of Anticline

- Trace of Axial Surface of Syncline

- Mineral Lineation $(L_1)$
  Compiled from Burns (1995)

- Mineral Lineation $(L_2)$

- Intersection Lineation
  $(S_0$ and $S_1)$

### ROCK UNITS

#### DEVONIAN

Dg — SOUTH MOUNTAIN BATHOLITH
  granodiorite
  leucomonzogranite
  monzogranite

#### CAMBRIAN-ORDOVICIAN
Meguma Group

COH — Halifax Formation
  finely laminated black slates and siltstones

COG — Goldenville Formation
  greenish-gray metagraywackes and minor interbedded slates

HVY 7 — Major Roads

— SMB-Meguma Contact

--- — Halifax-Goldenville Contact

— Cross-Section Line

— Study Area

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Map labels: COH, COG, Dg, BEDFORD, Anderson Lake, Sandy Lake, 213, BEDFORD BASIN, Kearney Lake, Long Lake, Ash Lake, Birch Cove Lakes, Black Duck Ponds, Levett L, Northwest Arm, Long Lake, THE NARROWS, DARTMOUTH, Lake Banook, HALIFAX, HVY 102, HVY 2, HVY 7, HVY 3, HVY 103

Coordinates: 64°45', 64°40', 64°35', 44°45', 44°40'

Figure 1.3  Location map of study area.  Accompanying legend for use with all maps to follow, unless otherwise indicated.

from oriented samples collected within the aureole, and newly acquired measurements of bedding ($S_0$),

slaty cleavage ($S_1$), metamorphic foliation ($S_2$), and stretching lineations ($L_2$).  A compilation of these

newly acquired data, plus previous measurements (Appendix A), allows a structural and metamorphic

synthesis of the effects of pluton emplacement.

## 1.5  Organization

Chapter 2 deals with the regional geological setting, as well as local geological evolution.

Chapter 3 describes the macroscopic structures and features within the contact hornfels of the

Goldenville Formation, including the regional distribution, geometry, nature, and morphology of

metamorphic fabrics.  Chapter 4 describes the metamorphic nature of the contact aureole from a

microscopic standpoint, with thin section descriptions.  Chapter 5 presents new structural

interpretations from collected data and computer aided calculations, and concludes this thesis.

# CHAPTER 2 REGIONAL AND LOCAL GEOLOGY

## 2.1 Introduction

Atlantic Canada, and the Canadian Appalachians, contain several distinct terranes, including the Avalon, Gander, and Humber Terranes. Within Nova Scotia, the Avalon and Meguma Terranes are separated by the extensive strike-slip, Cobequid-Chedabucto Fault System (Fig. 2.1). The Meguma Terrane is dominated by two rock types: Cambrian-Ordovician Meguma Group metasedimentary rocks and Devonian granitoid bodies. This thesis is concerned with both the granitoid bodies (the South Mountain Batholith) and the Meguma Group.

The Meguma Terrane was metamorphosed and deformed during the Mid-Late Devonian Acadian Orogeny and metamorphosed again during subsequent plutonism. Timing and relationship of orogeny and plutonism is unclear, however evidence indicates that deformation continued in an episodic fashion after pluton emplacement (Horne and Culshaw, 1993). The orogeny may have played a pivotal role in controlling emplacement of the granite. These controlling factors will be addressed in following chapters.
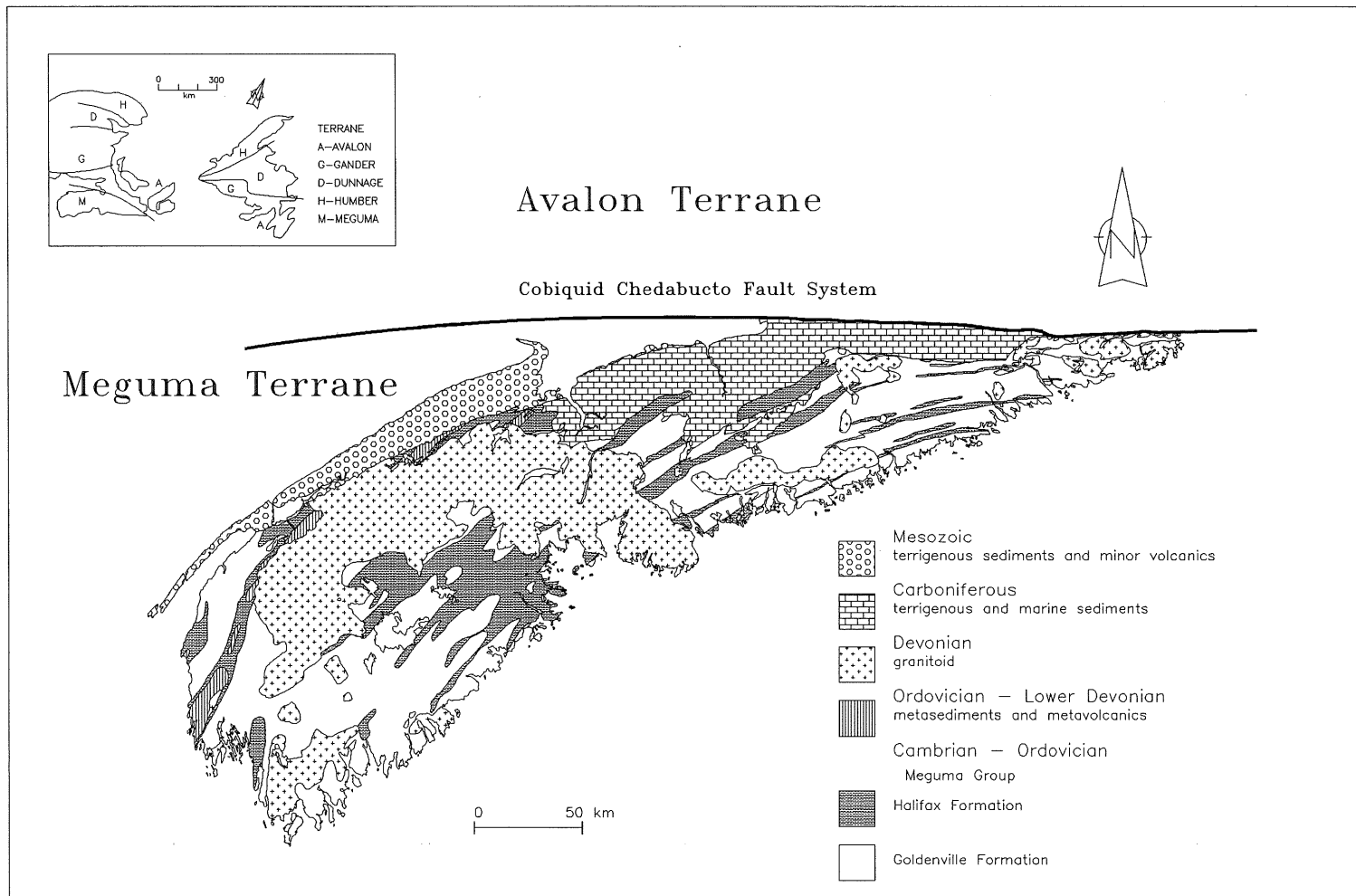
Figure 2.1  Regional geological map of Nova Scotia (Modified from Keppie, 1987)

## 2.2 Meguma Group

The Meguma Group contains the oldest rocks within the Meguma Terrane: Cambrian-Ordovician metapelites and metapsammites of the Halifax and Goldenville Formations, respectively. Together they form the largest single mass of sedimentary rock in the Atlantic Provinces. The older Goldenville Formation is a psammitic flysch-like deposit with an approximate stratagraphic thickness of six kilometers. The younger Halifax Formation is a pelitic shaly-flysch with a similar six kilometer thickness (Schenk, 1981). Together with the overlying Silurian-Devonian sedimentary and volcanic rocks, Schenk (1991) has estimated a total stratagraphic thickness of 20 km.

The Meguma Group is overlain by metaquartzite and other lithologies of the White Rock Formation, the shaly to silty Kentville Formation, the volcaniclastic New Canaan Formation, and the shaly to silty Torbrook Formation. These formations have depositional ages estimated from Ordovician-Silurian to Devonian (Emsian) (Schenk, 1981). The South Mountain Batholith intruded the Meguma Terrane between the Emsian and the Tournaisian, at approximately 370-395 Ma (MacDonald et al., 1992; Clarke et al., 1993). The Horton Group (Late Devonian to Tournaisian age) is a variable clastic terrestrial sediment, which non-conformably overlies the South Mountain Batholith.

Meguma Group deposition in a deep-sea to near-shelf gradational fan complex is one of the more widely accepted depositional theories (Schenk, 1981). In this setting, the Halifax Formation most likely represents a deep-water, anoxic depositional environment, whereas the

Goldenville Formation represents a more sandy, closer-to-shore environment.  Schenk (1991) has

further argued for deposition on the continental margin of Gondwana.


## 2.3  Acadian Deformation of the Meguma Group

The Meguma Group and overlying Silurian-Devonian White Rock, New Canaan,

Kentville, and Torbrook Formations were deformed and metamorphosed during the Acadian

Orogeny (Williams, 1979; Keppie and Dallmeyer, 1987; Horne et al., 1992).  This deformation

resulted in the development of straight limbed, open to tight, northeast-southwest trending

regional folds, with associated axial planar cleavage  (Faribault, 1908; Henderson et al., 1986;

Horne and Culshaw, 1993).  Evidence suggests that this deformation occurred ca. 390 Ma, prior

to the intrusion of the peraluminous granitoid bodies at ca. 375 Ma (Clarke et al., 1993).

Theories abound as to the cause and timing of deformation of the Meguma Group (Lajtai

and Stringer, 1981; Keppie, 1982;  Kontak et al., 1989).  If the Meguma is indeed an Acadian

accreted terrane, as widely accepted, deformation may have been directly associated with docking

during the Acadian orogeny.  Later deformation, which undoubtedly occurred (Horne and

Culshaw, 1993), would entail reactivated regional folds and enhanced folding and cleavage

development (pers. comm., N Culshaw, 1995).

## 2.4 Batholith Emplacement

About half the area of the southern peninsula of Nova Scotia is underlain by the South Mountain Batholith (Fig. 2.1), at over 7300 km$^2$ the largest exposed peraluminous granitoid body of the Appalachian Orogen (MacDonald et al., 1992). It is about 180 km long and 50 km wide. Abbott (1989), using geophysical information, interpreted the average thickness of the South Mountain Batholith as 5 km, with a maximum thickness of 25 km near the New Ross area.

MacDonald et al. (1992) subdivided the South Mountain Batholith into thirteen plutonic members, associated with two stages of emplacement. Early plutons (Stage 1), comprise granodiorite and monzogranite. Later plutons (Stage 2), comprise mostly monzogranite, leucomonzogranite, and leucogranite. The Halifax pluton, the focus of this study, is a stage 2 pluton.

The South Mountain Batholith intruded the Meguma Group later than the regional deformation event (Horne et al., 1992; Clarke et al., 1993), however, a connection between the two events is reasonable. Two possible causes of plutonism are: increased crustal thickness, and subduction-related lithosphere removal. After accretion, the increased crustal thickness may have caused melting at depth, with subsequent magma upwelling. This model, however, may not be feasible, due to the limited thickness of the Meguma (some 20 km), compared with crustal depth. With such constraints, the increase in crustal thickness would not be enough to cause melting at depth (pers. comm., N. Culshaw, 1995). Clarke and Tate (1993) postulated that the subducting North African plate caused lithospheric plate removal under paleo-Nova Scotia. This removal

allowed upwelling of the hot asthenosphere, allowing crustal melting. The ensuing crustal melt

combined with mantle melt, forming the South Mountain Batholith and small ultramafic to mafic

intrusions.

Studies on the Liscomb Complex by Clarke et al. (1993) have shown that the granite

source may be sub-Meguma basement rock. Crustal melting and crustal assimilation seem to be

involved with granite generation at depth.

Horne et al. (1992) have produced some evidence of structural controls on South

Mountain Batholith emplacement. This evidence includes the two main pluton boundary

orientations, northeast and northwest. Pre-existing faults probably influenced stage 2 pluton

emplacement. Further, the regional similarity of joint trends in second stage plutons possibly

indicates some degree of syntectonic emplacement. There may have been a continued sense of

stress applied to the region during and after this second stage of emplacement.


## 2.5 Post-Granite Deformation

Post-South Mountain Batholith deformation is evident throughout the Meguma Terrane.

Reactivation of existing faults and folds, complete with intensification of cleavage, is the result of

this later deformation (Horne and Culshaw, 1993). Later deformation could explain the "wrap

around" cleavage seen along the southeast margin of the South Mountain Batholith. Deformation

may have occurred at such low temperatures (lower greenschist facies) that the granite was only

slightly (non-visibly) altered.

Horne and Culshaw (1993) argue convincingly for post-granite deformation. Their evidence includes flexural slip shear fractures within the Halifax Formation that truncate cordierite porphyroblasts associated with the thermal aureole of the Halifax pluton in Halifax. Some deformation certainly took place post-South Mountain Batholith emplacement, but how long after is unclear.

## 2.6 Summary

Regional folds and axial planar cleavage were produced in the Meguma Terrane during the Devonian Acadian Orogeny. Relatively shortly thereafter, plutonism occurred, forming the South Mountain Batholith. Deformation continued after, and possibly during South Mountain Batholith emplacement, controlling its emplacement. Evidence of direct deformational effects of pluton emplacement are seen only in the immediate vicinity of the pluton, and no extensive regional structures resulting from granite emplacement have been documented. Structures resulting from deformation are described in the next two chapters.

# CHAPTER 3  FIELD RELATIONS

## 3.1  Introduction

This chapter describes the mesoscopic and macroscopic features at the northeast end of Halifax Pluton, within and close to the Halifax Pluton metamorphic aureole. There are several major and minor structures within the aureole; none however are evident in the granite. The major structures are: the northeast-southwest (trend 230°) regional folds (Waverley Anticline and Bedford Syncline), the transverse (contact-parallel) Kearney Lake Anticline (trend 120°), and the Magazine Hill Basin described by Burns (1995) (Fig. 3.1 and 3.2). Minor structures include: axial planar cleavage of the regional folds ($S_1$), metamorphic foliation ($S_2$), mineral lineations ($L_2$) (together forming a composite fabric, $LS_2$). The major fold-structures illustrated in Figure 3.1 are defined by bedding ($S_0$) trends measured by the author, and those compiled from Faribault (1908) and Burns (1995).

## 3.2  Thermal and Strain Aureoles

### 3.2.1  Metamorphic Thermal Aureole

A metamorphic contact aureole is defined as a zone surrounding an igneous intrusion, characterized by contact metamorphism (Yardley, 1989). The metamorphic thermal aureole of the Halifax Pluton contains contact metamorphic features which grade away from the pluton into
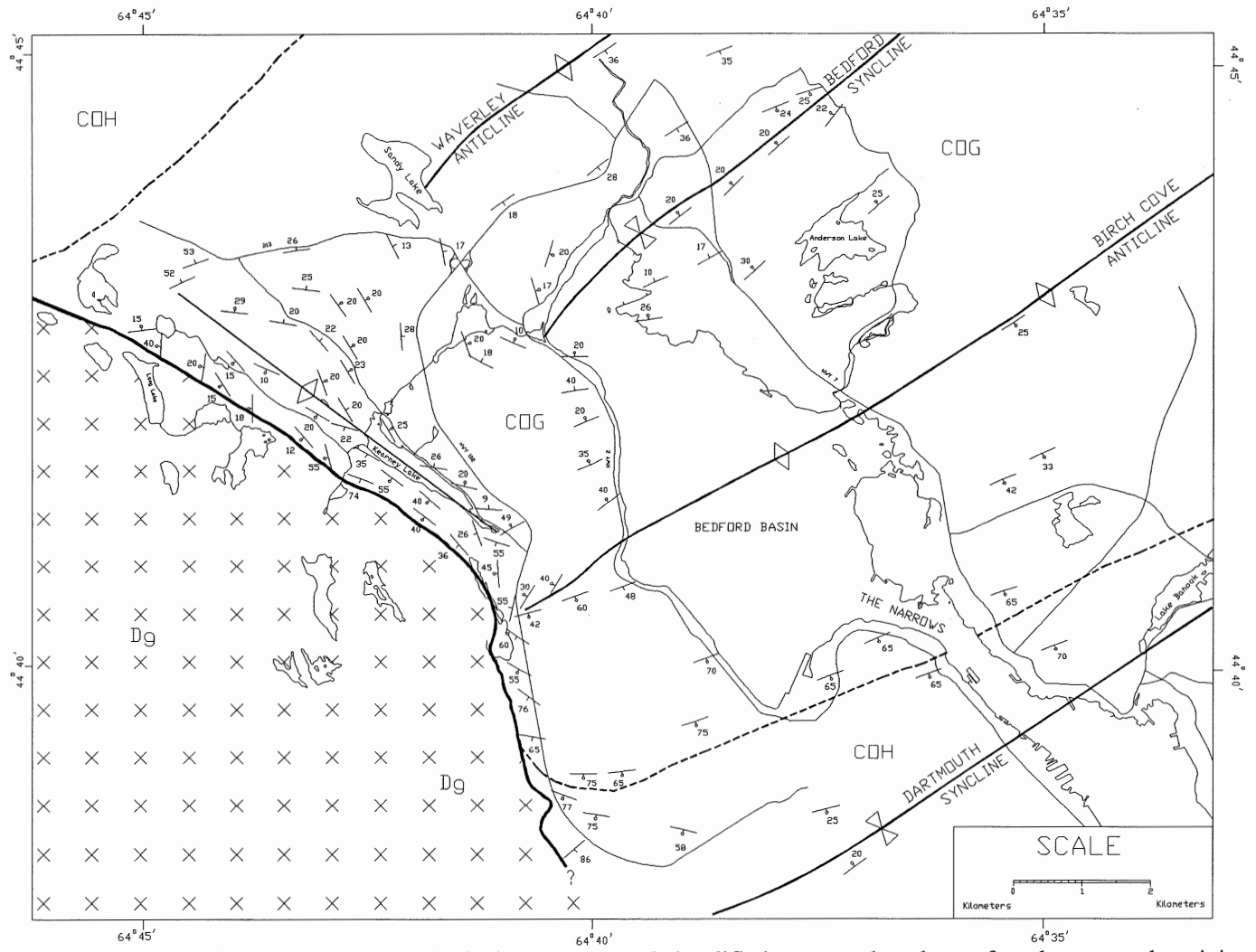
Figure 3.1  Major geological structures and simplified structural geology of study area and vacinity.
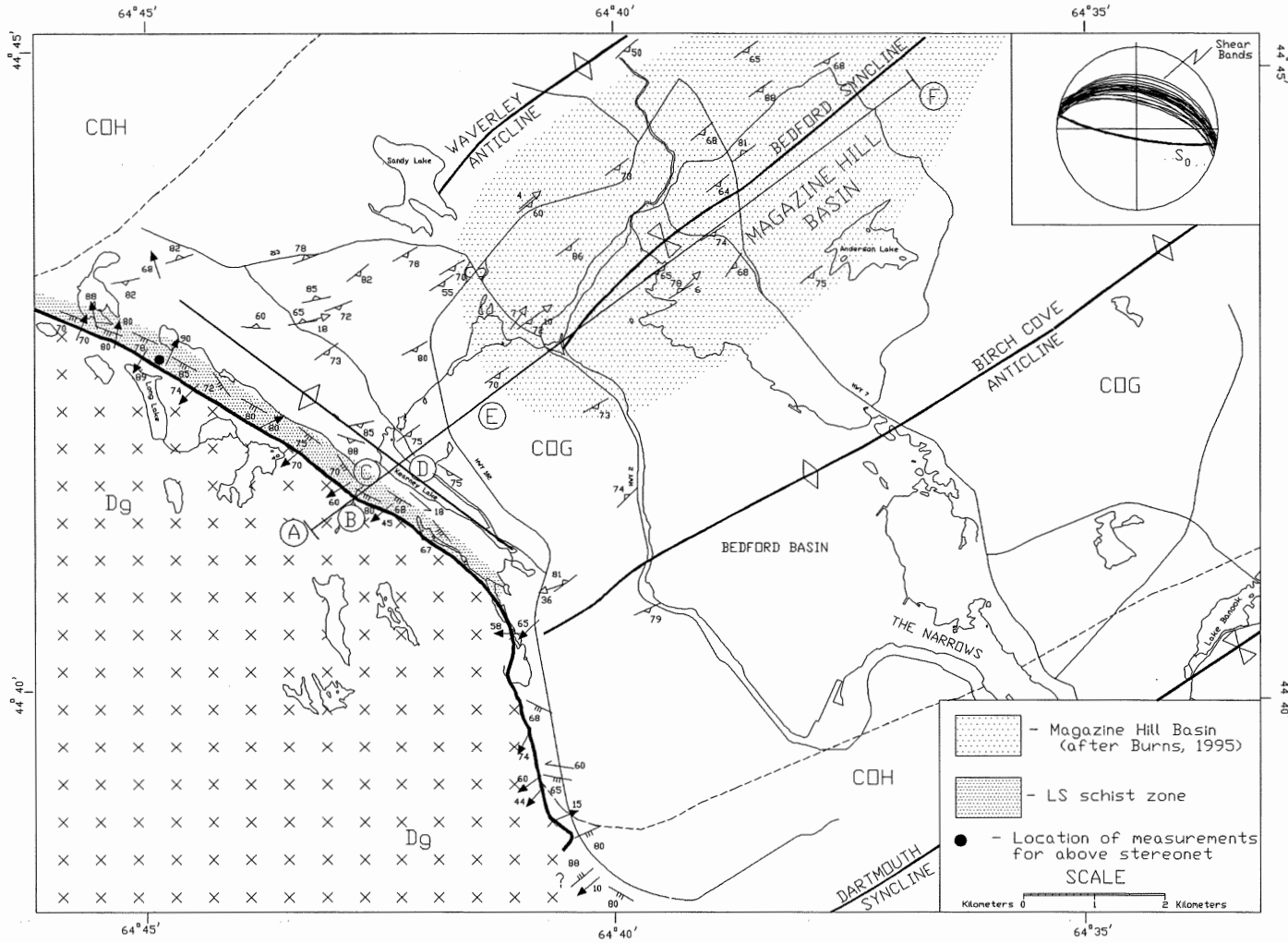
Figure 3.2  Geology of the Kearney Lake area.  Interpreted Magazine Hill Basin of  Burns (1995) is shaded.  $LS_2$ schist zone is stippled.  A-F line represents cross-section on Figure 5.1.  Inset stereonet: shear band-like planr features (thin great circles) and $S_0$ (thick great circle).

regional metamorphic features. The change is reflected in textural and mineralogical distinctions, e.g. appearance of cordierite and associated grain coarsening. The thermal aureole extends about 1.5 km from the granite contact. Chapter 4 will cover this topic.

### 3.2.2  Strain Aureole

The strain aureole of the Halifax Pluton is defined here as the zone containing fabrics directly related to pluton emplacement. The schist with planar-linear fabric ($LS_2$), the transverse Kearney Lake Anticline, and the Magazine Hill Basin, are all interpreted as emplacement related structures, because of their anomalous nature compared to regional structures of the Meguma Group (Fig. 2.1). Interestingly, the strain aureole extends farther than the thermal aureole, approximately six kilometers.

The transect on Figure 3.2 illustrates the strain aureole, the variation of rock types within it, and the aforementioned major structures. The point labelled (A) lies within the unfoliated, massive monzogranite. The contact between the granite and hornfels is indicated by point (B). The rocks here contain a well developed, penetrative, planar-linear schistose fabric, $LS_2$. $LS_2$ decreases in intensity with distance from the granite, and is less penetratively developed between C and D. At approximately point D, $LS_2$ is no longer mesoscopically discernible, and axial planar cleavage ($S_1$, defined by phyllosilicates) appears in slates. This trend continues farther out, with $S_1$ intensifying. Point E represents the beginning of the Magazine Hill Basin of Burns (1995).

### 3.3 Major Structures at the Northeast End of Halifax Pluton

Figures 3.1 and 3.2 illustrate the major structures in this study: the Waverley Anticline, the Bedford Syncline, the Magazine Hill Basin of Burns (1995), and the transverse Kearney Lake Anticline. Field mapping from this study has relocated granite contact placement slightly from the provincial map.

Bedding which defines these major structures, measured in the Goldenville Formation is difficult to recognize, particularly in the rather massive, recrystallized hornfels of the contact aureole. If present, rare metamorphosed shaly interbeds however, provide reliable measurements.

The transverse Kearney Lake Anticline trends parallel to the granite boundary (approximately 120°), and normal to the regional folds. This fold has an approximate length of >4.3 km and width of 1.6 km. It is an upright fold, with an approximate interlimb angle of 130°. The regional Bedford Syncline in comparison trends 270°, is periclinal, upright, has an approximate interlimb angle of 150°, a cylindrical axial trace for tens of kilometers, and is about 3.5 kilometers wide (Faribault, 1908).

Previous studies in the area (Faribault, 1908; MacDonald et al., 1992; Burns, 1995), indicated the presence of a transverse rim syncline associated with the Kearney Lake Anticline. The author has inspected the area, and was unable to recognize bedding in outcrops in the critical area of the reported syncline. Faribault's measurements have however been confirmed with astounding accuracy at almost every location. The syncline may be present, but it will require

further careful field work to confirm or disprove its existence. Hence, with all due respect, this study proposes then that the rim syncline is not reliably defined.

## 3.4 Predominant Minor Structures

Predominant minor structures in the strain aureole are; the metamorphic schistosity ($S_2$ component of the $LS_2$ fabric) and the steeply plunging mineral lineation ($L_2$). $L_2$ lies in the $S_2$ plane, and together with $S_2$ defines the $LS_2$ schist (Fig. 3.3a). $LS_2$ contains no asymmetric fabric elements, e.g. rotated feldspars, or C-S fabrics. The variably developed $S_2$ parallels the trend of the granite boundary, striking approximately 120°. The width of the $LS_2$ schist band ranges up to 250 m, and is developed over the entire length of the contact in the study area, some 10 km (Fig. 3.2). Most common orientations of $S_0$ and $S_2$ are 100°/80° and 120°/85°, respectively (Appendix B). In a very narrow zone within this schist band, close to the contact, $S_0$ and $S_2$ are sub-parallel to parallel. Beyond approximately 250 m from the contact, schistosity is indistinct.

A shift in strike accompanies the decrease in $LS_2$ intensity. Within the $LS_2$ zone, foliation is essentially parallel to the contact. Roughly 300 m from the contact, the strike of $S_2$ (230°) resembles that of regional fold limbs (Fig. 3.2). Intermediate trends are measured between 300 and 700 m from the contact. No evidence of over-printing between $S_1$ and $S_2$ was observed.

Hand samples of $LS_2$ display compositional banding defined by alternating leucocratic (quartz-feldspar-cordierite) and melanocratic (biotite) aggregates at a mm scale (Fig. 3.4). These leucocratic aggregates are penetrative, and have a flattened, blade-like shape. Individual grains
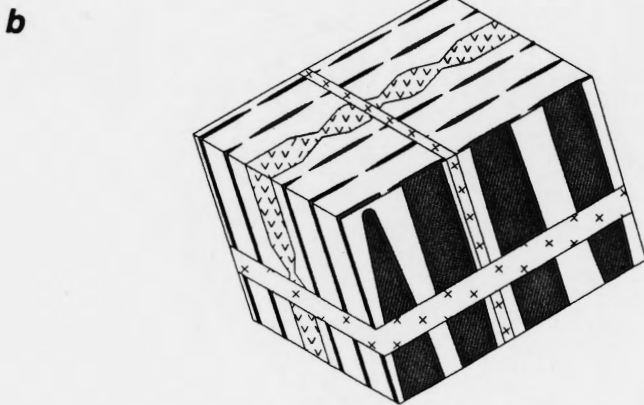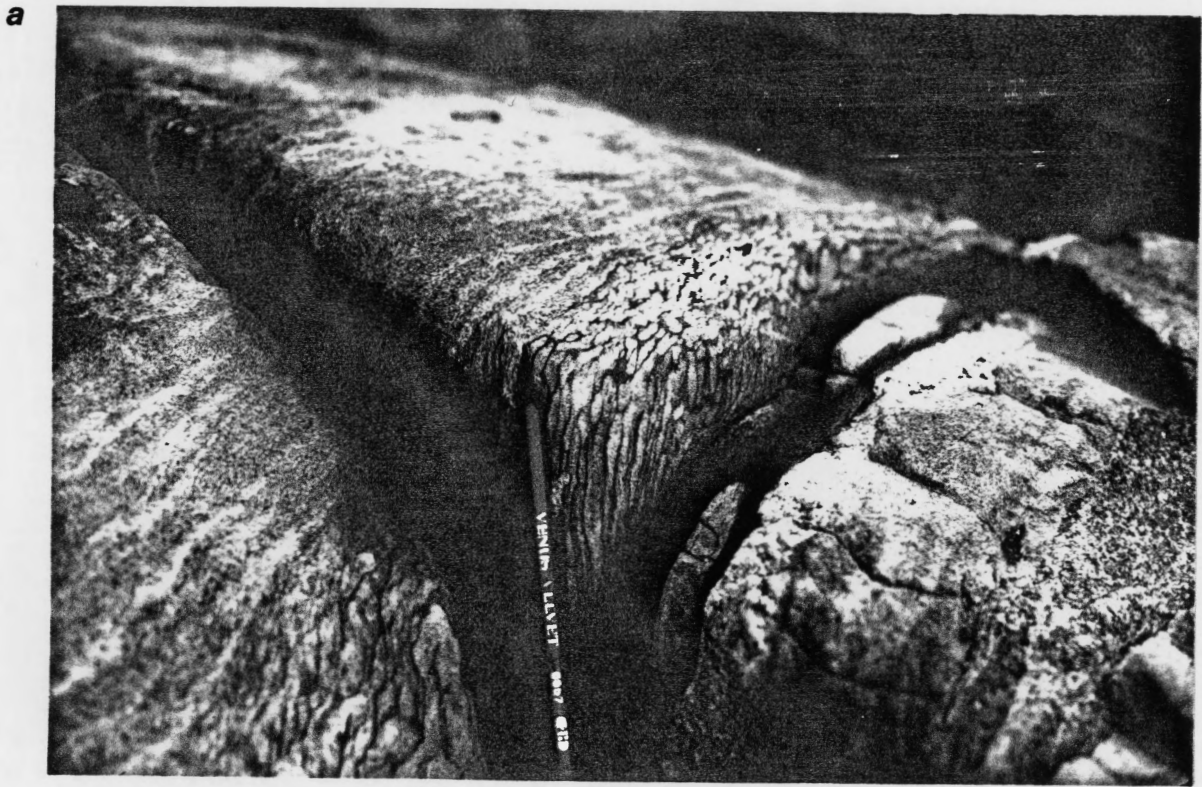
Figure 3.3a)  Photograph of LS$_2$ fabric from site 95-76.  Steeply dipping lineation (L$_2$) parallel to pencil, metamorphic foliation (S$_2$), an S$_2$ parallel band containing L$_2$, and boudins (stretched along S$_2$ and down L$_2$).  Pencil is 14 cm. b)  Idealized block diagram illustrating LS$_2$ fabric.
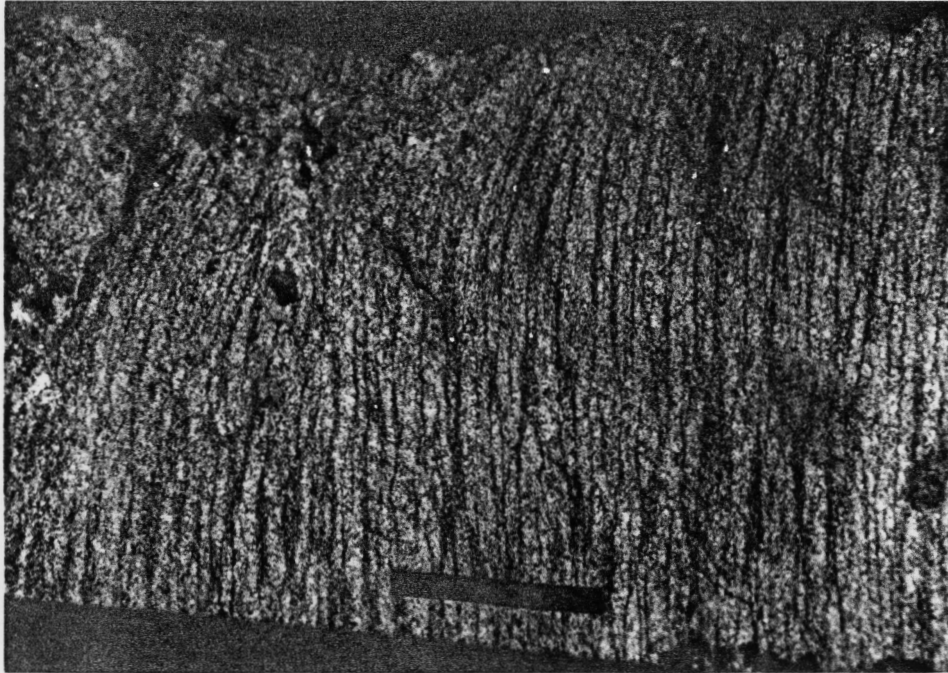
Figure 3.4 Weathered surface showing schistose $S_2$ (sample 95-15). Although foliation appears curved, weathered surface is curved, giving false impression of plane foliation. Red bar is 1 cm.

defining the aggregates are small, ~1 mm on average. Complete recrystallization is evident in these rocks, with weak grain elongation or alignment. Chapter 4 will investigate this aspect of these $LS_2$ fabrics.

Away from the contact the well developed $LS_2$ gives way to a non-penetrative fabric. These subtle fabrics are best recognized on weathered surfaces. In thin section, this fabric is not well defined because the scale of aggregates that define the fabric are greater than a low power field of view, 3-5 mm.

## 3.5 Other Minor Structures

Within the $LS_2$ schist zone, other minor structures occur, including boudins and quartz and feldspar (granite ?) filled extensional, shear-band-like structures.

### 3.5.1 Boudins

Decimetric boudins are developed from cross-cutting and concordant pegmatites and calc-silicate layers. The blade-like geometry of the boudins is illustrated in Figures 3.3a/b and 3.5. They display elongation within the $S_2$ plane, both parallel to the strike of $S_2$ and the plunge of $L_2$. A flattened, blade-like shape is thus evident (K value between 1 and 0). This shape fabric indicates a similar strain geometry to $LS_2$, albeit a larger scale.

Figure 3.5  Calc-silicate boudins, on a horizontal surface.  Necks of calc-silicate join separate boudins, and slightly darker reaction rims surround the boudins.  Diameter of lens cap 5 cm.

Calc-silicate layers that form many of the boudins, are common in some stratagraphic horizons of the Goldenville Formation. The shape of these boudins is comparable to the shape fabric that occurs in the $LS_2$ schist, and is consistent with the finite strain of these rocks. Close to the contact (100-150 m), foliation wraps around the calc-silicate nodules in an augen-like manner, suggesting ductile flow of the country rock. Reaction rims of slightly darker minerals, averaging <5 mm widths, form concentric zones on these nodules, making them stand out on weathered surfaces (Fig. 3.5).

### 3.5.2 Pegmatite

Two orientations of pegmatite exist in the $LS_2$ schist zone: concordant to $LS_2$ (boudinaged) approximate trend 115°, and cross-cutting (filling fractures perpendicular to the lineation) approximate trend 190° (Fig. 3.3b and 3.6). The presence of such kinematically early and late pegmatite indicates that granite was available throughout the period of deformation. This evidence indicates syn-plutonic deformation of the country rocks.

### 3.5.3 Extensional Planar features

Quartz and feldspar (?) filled planar features are common immediate to the contact. They displace $L_2$, and they cut and separate the schistosity at approximately 280° (Appendix B). These dip away from the granite and occupy a very narrow zone, 25-35 m, from the contact (Fig. 3.2).

Figure 3.6  Cross-cutting pegmatite on horizontal surface, cutting and separating $S_2$ and calc-silicate boudins.  Diameter of lens cap 5 cm.

## 3.6 Eastern Pluton Edge

This study focused on the northeast end of the Halifax Pluton, and its contact aureole. Some mapping and sampling was done farther south, around the corner of the pluton, near Burnside Industrial Park (Fig. 3.3). $S_2$ and $L_2$ are present in this area, though much less well developed. $S_2$ orientations vary considerably from those at the northeast margin, with averages close to regional trends, 240°. Also, the granite-country rock contact is more irregular in detail, than at the northeast margin.

These distinctions from the northeast end of the pluton may be a indicative of specific emplacement-related processes. For example, if the pluton was expanding normal to regional compression, the northeast end would show signs of forceful injection, e.g. contact-parallel $LS_2$. In the same scenario, sides parallel to regional compression would not display the same well developed features (Guglielmo, 1992). The study area is not extensive enough to answer these questions, however, documentation of these observations may prove important for further studies.

## 3.7 Summary

Major and minor structures occur within the strain aureole of the Halifax Pluton. Structures close to the contact (e.g. $LS_2$ and the Kearney Lake Anticline), trend parallel to the contact, unlike any other regional structures. The anomalous nature of these structures, the presence of syn-kinematic pegmatites, and the obvious relationship between metamorphic

recrystallization and $LS_2$ schistosity, leads to the interpretation that granite emplacement directly caused their development.

The shape of the finite strain ellipsoid, deduced from various features (Fig. 3.3a and b), reflects the integrated total strain accompanying the deformation. The strain shape, regardless of scale ($LS_2$, boudins, or $S_2$), is a triaxial, flattened, blade-like ellipsoid, with its long axis near vertical and a component of extension parallel to the strike of the granite contact. Further, the lack of asymmetric fabric elements associated with $LS_2$, suggests irrotational, pure flattening strain. A more quantitative view of this evidence is the topic of chapter 5.

# CHAPTER 4  MICROSCOPIC STRUCTURES AND METAMORPHISM

## 4.1  Introduction

This chapter describes the microscopic structures and features within the metamorphic contact aureole of the Halifax Pluton. Petrographic descriptions are based on thin sections collected and prepared by the author (Appendix C). Sample sites, indicated on Figure 4.1, represent traverses across the aureole, from regional structures to the pluton. Data compiled from these traverses illustrate the variation in mineralogy and textures, embodied as changes in metamorphic grade within the Goldenville Formation adjacent to the Halifax Pluton.

A thermal contact aureole, extending approximately >1.5 kilometers from the pluton-Goldenville Formation contact is here defined on the basis of microscopic features. As is common in contact aureoles, contact metamorphic features grade directly into regional metamorphic features (Pattison and Tracy, 1991), hence an accurate outer limit of the aureole was not defined in this study area. The mesoscopic features used to define the width of the aureole (Chapt. 3), are augmented by microscopic evidence in the present chapter.

The thermal aureole of the Halifax Pluton exhibits several attributes typical of contact metamorphic aureoles. Kerrick (1991) defined contact aureoles in terms of processes that the country rocks were subjected to during granite intrusion: coarsening, neocrystallization, metasomatism, anatexis, and deformation. This aureole contains evidence of these
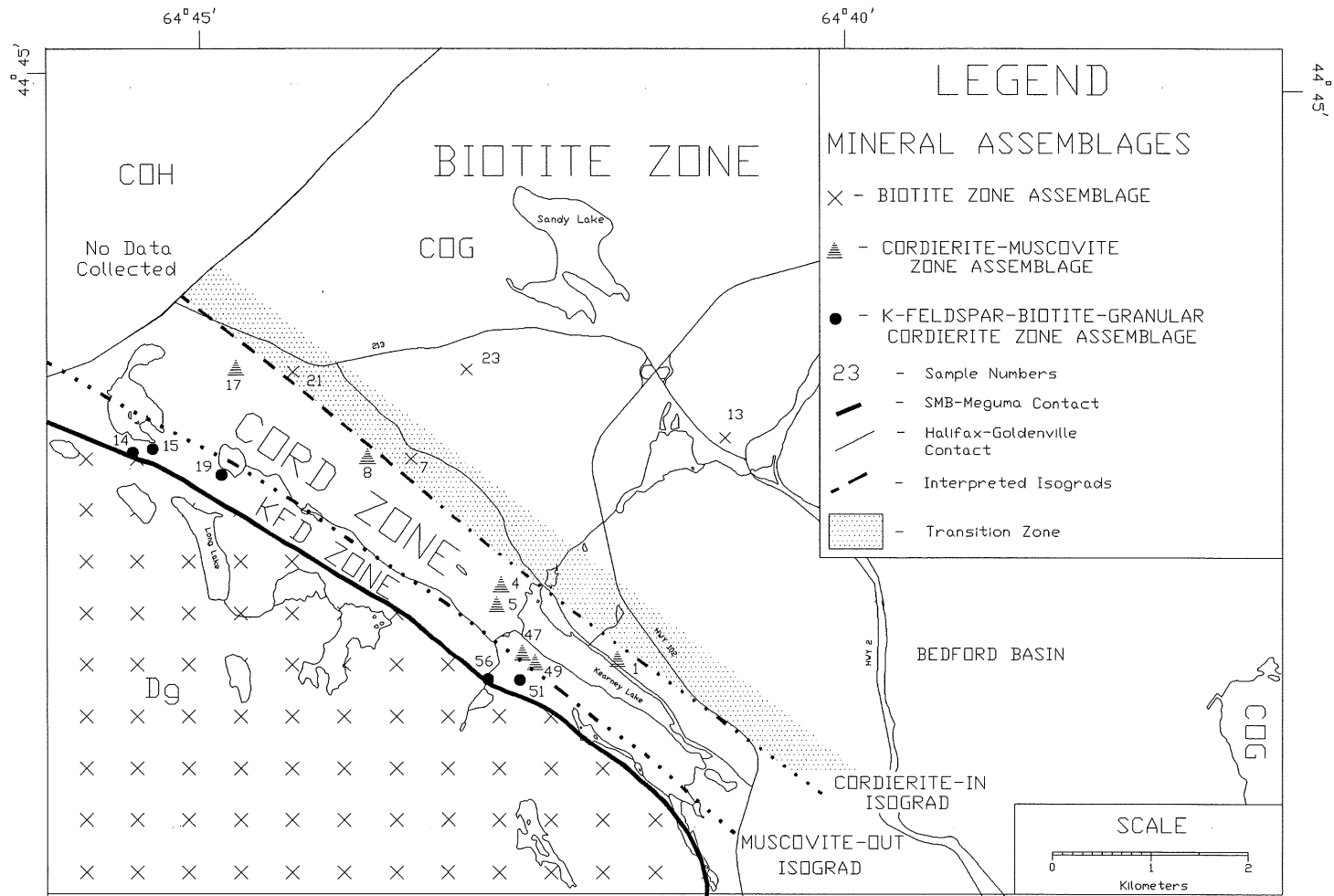
Figure 4.1  Sample sites (numbered) and metamorphic zones as defined by mineral assemblages and textures.  Zones separated by inferred isograds.

processes, locally in combination. Bergantz (1991) defined a metamorphic aureole by changes in

texture, composition, and mineralogy. Both definitions are consistent with the contact aureole of

the Halifax Pluton.

Based on aforementioned changes in mineralogy and texture, it is possible to infer

metamorphic isograds (Fig. 4.1). Evidence for a common reaction in metamorphic aureoles of

pelitic rocks (Pattison and Tracy, 1991) is seen from petrographic analysis. Further, an

interpretation of the pressure and temperature conditions during formation are inferred from the

same information. Microscopic analysis indicates that metamorphism and deformation in the

Kearney Lake area is directly related to pluton emplacement.

## 4.2 Metamorphic Aureole Zonation

Three distinct zones are defined based on mineral assemblages and textures from samples

at the northeast end of the Halifax Pluton (Fig. 4.1). The outer zone (biotite zone), is only a small

part of the study area, but extends beyond the limit of mapping (Fig. 4.1). The middle zone

(cordierite zone), a little less than 750 m wide, extends over the entire length of the northeast end

of the Halifax Pluton. The inner zone (K-feldspar zone), is directly adjacent to the contact,

approximately 250 m wide, and has a lateral extent similar to the cordierite zone.

### 4.2.1 Biotite Zone

The biotite zone is interpreted to begin about 1.5 km from the pluton contact (with

increasing grade toward the pluton), and represents the transition from regional to contact

metamorphism. Small (<1 mm) biotite porphyroblasts, a fine grained unaltered matrix, a lack of

cordierite, and the dominance of phyllosilicate-defined regional $S_1$ cleavage characterize this zone.

The peak mineral assemblage is biotite, chlorite, quartz, and muscovite. The biotite zone extends

beyond the limit of sampling, however the boundary with higher grade rocks is defined where

cordierite enters the assemblage, at the cordierite-in isograd. A transition zone (Fig. 4.1) is

interpreted between the biotite and cordierite zones, here the assemblages and textures represent a

combination of both zones.

Sample 13 is typical of this biotite zone (Fig. 4.2). The sample consists of numerous, <1

mm sized, randomly oriented biotite porphyroblasts in a very fine-grained matrix of quartz and

muscovite. Muscovite is subtlely aligned approximately parallel to the regional axial planar

cleavage ($S_1$), 240°. The sample contains fresh biotite and no indications of deformation effects.

The biotite zone represents both the outer limits of contact metamorphism, and the

transition to regional metamorphism. The exact transition surface from biotite zone to regional

grade is not defined accurately. Muecke and Keppie (1979) have defined the regional

metamorphic grade of the area to be of chlorite/biotite grade.

*4.2.2 Cordierite Zone*

The presence of cordierite, an increase in muscovite abundance, and grain size

coarsening, define the cordierite zone. Chloritized cordierite porphyroblasts ("eyes") are

omnipresent, and attain relatively large sizes, >3 mm, giving the slates in this zone a spotted look

(samples 1, 8, and 17 are excellent examples). Minor sphene is seen in most samples from this
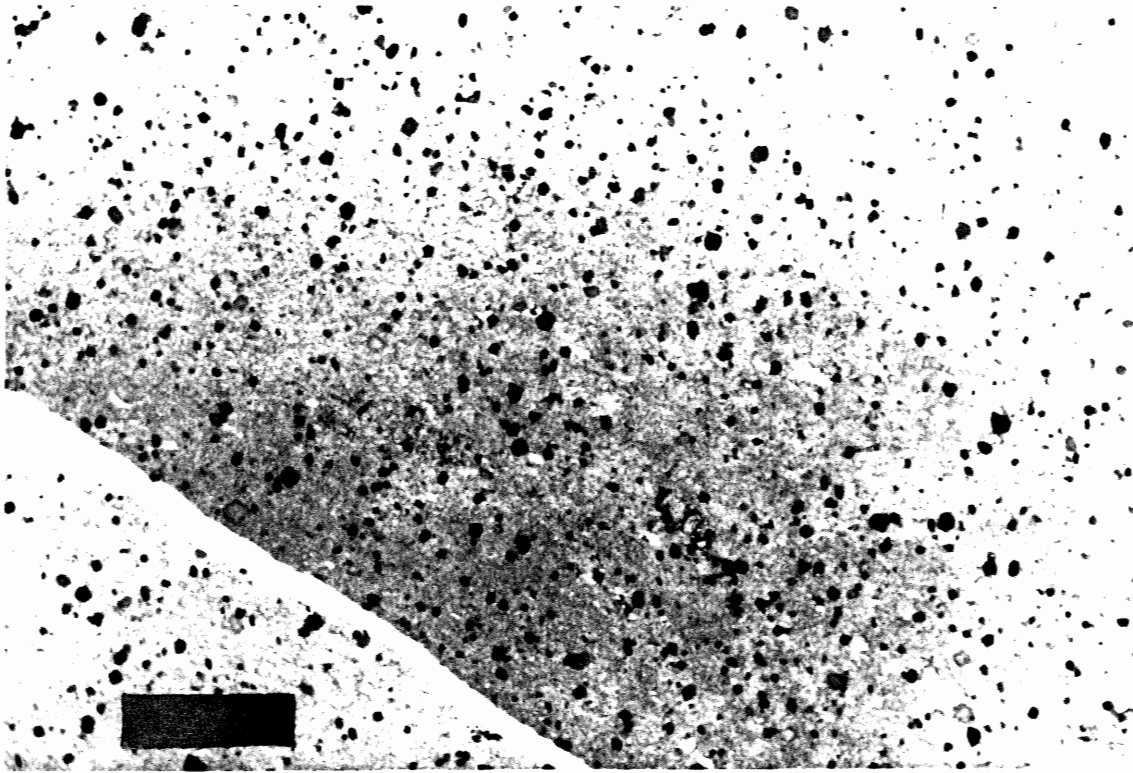
Figure 4.2  Sample 95-13, typical texture and mineral assemblage of Biotite zone.  Dark ovals are  biotite, fabric trends parallel to crack in slide.  Horizontal section, north right, bar is 2 mm.

zone, forming very tiny, <1 mm well rounded grains. The peak mineral assemblage is cordierite,

biotite, muscovite, quartz, and plagioclase. Most porphyroblasts of cordierite are completely

chloritized (retrograde), and only its characteristic ovoid crystal habit allows identification.

Cordierite and biotite porphyroblasts are randomly oriented, and inclusion trails are not observed

(Fig. 4.3). The outer zone boundary is the cordierite-in isograd, and the inner boundary is the

muscovite-out isograd. (Fig. 4.1).

The muscovite-defined foliation intensifies with decreasing distance from the contact in

this zone. Porphyroblast-rich samples show a foliation-intensification at porphyroblast edges, and

between adjacent porphyroblasts (Fig. 4.4). Muscovite in these areas is coarser grained and better

developed than elsewhere within the matrix. This well developed muscovite alignment trends

approximately parallel to the pluton boundary. Samples further from the contact have foliation

trends oblique to the contact and intermediate between $S_1$ and $S_2$ (Fig. 3.3).

Grain size in the cordierite zone is larger on average than in the biotite zone. Textures

indicate some recrystallization; strained quartz, augen structures, and grain coarsening (e.g.

samples 4, 5, 17, and 8). Some lithological differences lead to textural and mineralogical variation

of the host rock. For example, sample 21 consists of calc-silicate nodules which contain

amphibole and epidote (not seen in any other sections). Similar observations have been

interpreted as metasomatic effects (Purves, 1974).

There are noticeable differences in rock mineralogy and texture within the cordierite zone.

Variation, related to lithological layering is expected, however, and therefore isograd placement
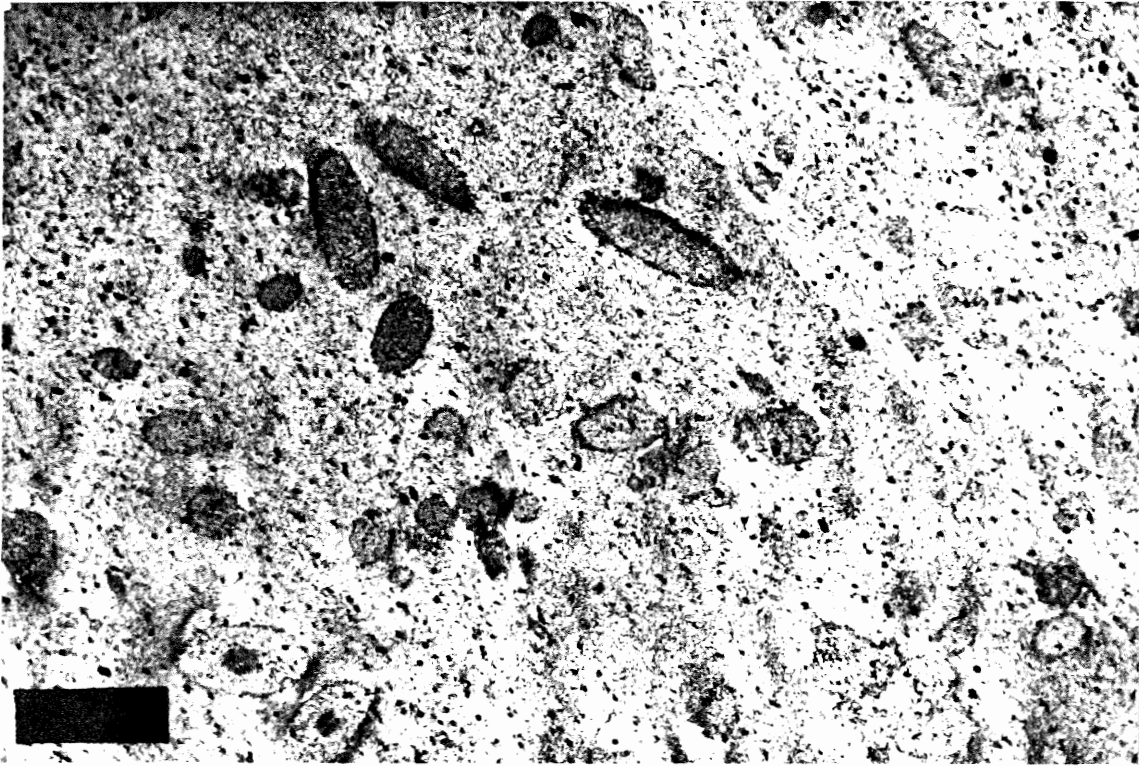
Figure 4.3 Sample 95-17, representative of Cordierite zone. Randomly oriented, large cordierite porphyroblasts (dark ovals) in fine grained matrix. Fabric running diagonally (lower left corner), north up. Horizontal section, bar is 4mm.
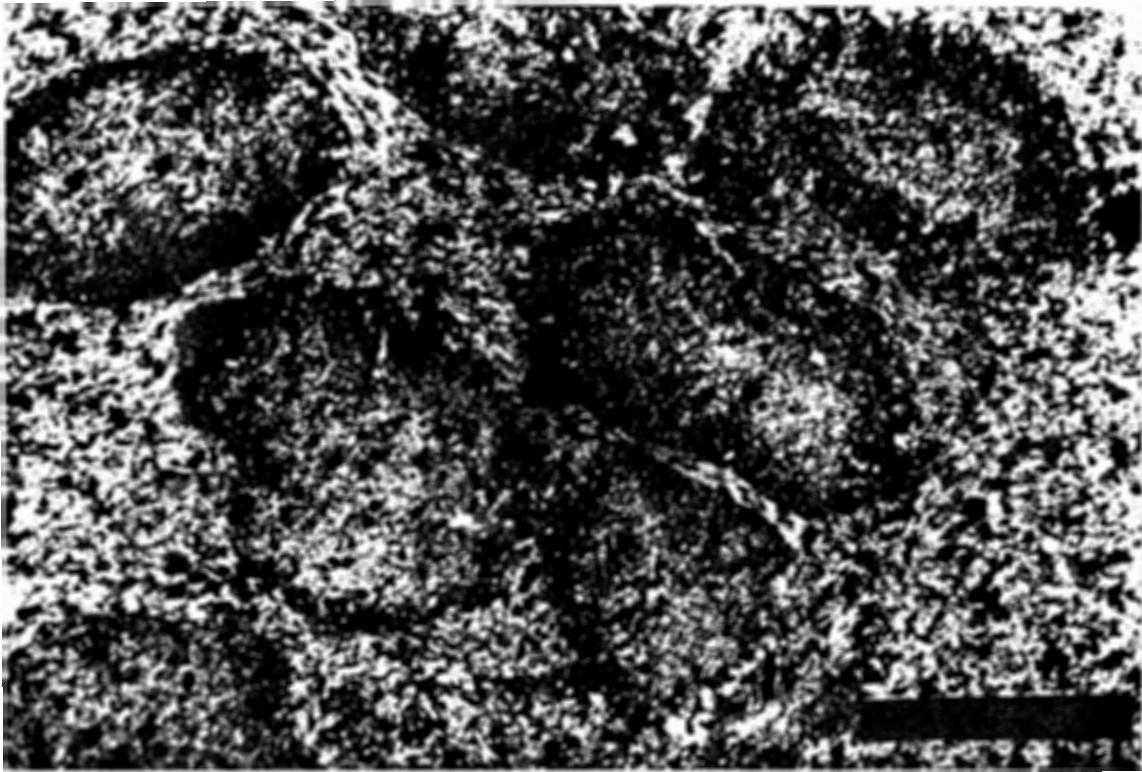
Figure 4.4 Sample 95-8a, illustrating muscovite-defined-cleavage intensification on edges and in between adjacent cordierite porphyroblasts. Oval grains are altered (chloritized) cordierites, light areas in between aligned muscovites, north up. Horizontal section, bar is 1 mm.

was based on a combination of textures and mineral assemblages. Samples closer to the contact show increasing evidence of recrystallization and an intensification of contact parallel cleavage.

### 4.2.3 K-feldspar Zone

The K-feldspar zone contains the highest grade rocks of the aureole, recrystallized massive $LS_2$ tectonites. The contact-parallel $LS_2$ fabric is characteristic of this zone, where complete recrystallization is evident from the fabric, unstrained quartz, and an increased grain size (Fig. 4.5).

Intergranular cordierite, K-feldspar, and a lack of muscovite characterize this zone. Muscovite is rare and where present, grains are irregularly shaped, embayed, and ragged. The feldspars are large, and some samples show myrmekite textures. Sphene is present as tiny crystals in some samples. The peak mineral assemblage is K-feldspar, biotite, quartz, plagioclase and cordierite. This zone is approximately 250 meters wide, bounded by the Halifax Pluton and the interpreted muscovite-out isograd, respectively.

Foliations ($S_2$) are visible in some of the sections (14 and 15 contain the best developed examples). This foliation, while "wavy", is oriented approximately parallel to the contact. Interestingly, $S_2$ does not appear as well defined in thin section as in outcrop or hand sample scale. $S_2$ is defined by quartz+K-feldspar-rich zones separated by biotite-rich bands. The biotite-rich bands have weak grain alignment in samples far from the contact (e.g. samples 14 and 15).

Lineations ($L_2$) in this zone (samples 19, and 19a in particular) are defined by biotite-rich aggregates, with some grain alignment. $L_2$ shows better grain (biotite) alignment than any of the
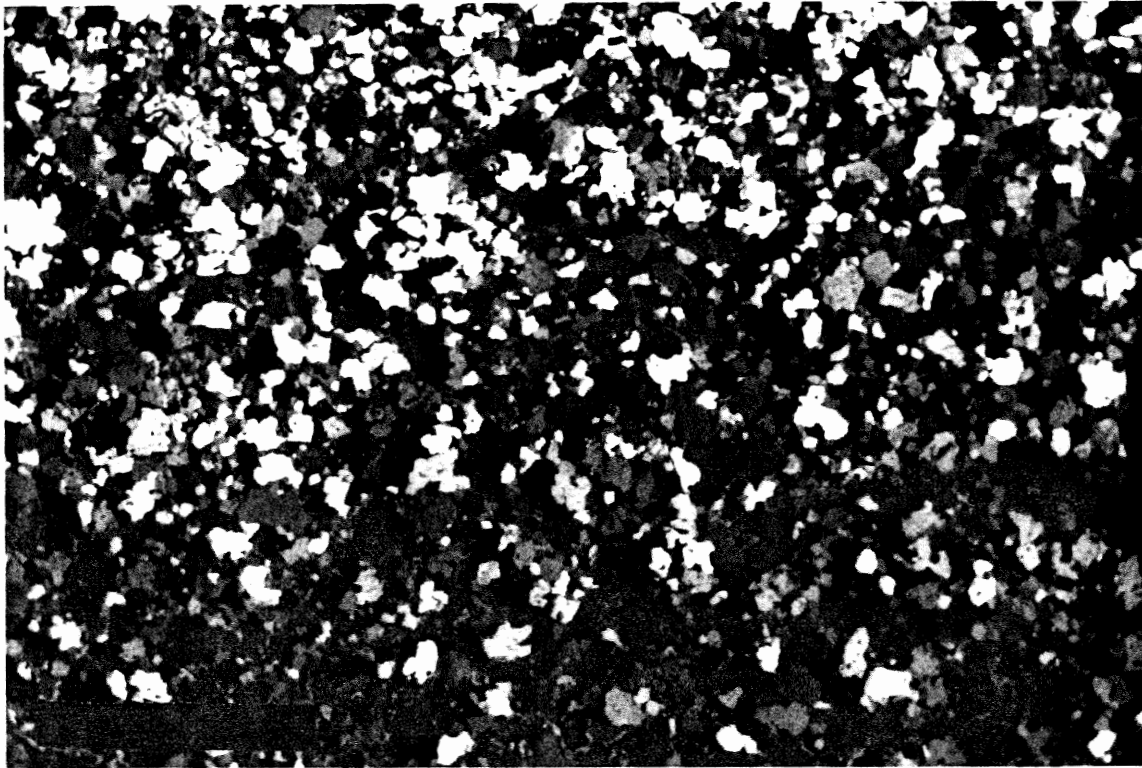
Figure 4.5  Sample 95-14, significant grain coarsening and $S_2$ (subtle at thin section scale) running top left-bottom right, north up.  Horizontal section, bar is 2 mm.

other fabrics. Cordierite is altered and strung out between these biotite bands (Fig. 4.6a and b). The biotite-rich bands anastomose and pinch and swell along their length, but indicate no consistent asymmetry (Fig. 4.6a).

Sample 56 illustrates the characteristic mineralogy and textures from the K-feldspar zone particularly well. Biotite, feldspar, and quartz make up the bulk of this sample. The "wavy" foliations described earlier are well developed in this section, however ring-like structures dominate some parts of the sample (Fig. 4.7a). The origin of the "rings" is not clear. The biotite exhibits a deep rich brown color with numerous pleochroic haloes (Fig. 4.7b). Quartz shows no signs of strain, and there is a total lack of muscovite. The feldspars are mostly K-feldspar, orthoclase or possibly sanidine specifically (as defined from 2V angle determination), indicating rapid cooling and therefore shallow level, low pressure environment of formation (pers. comm. Dr. R. Jamieson, 1996). Conspicuous grain boundary zonation, myrmekite alteration (Fig. 4.8), and the proximity of the sample to the contact (Fig. 4.1), indicate a high diffusion rate.

## 4.3 Similar Contact Aureoles

Metamorphic contact aureoles are common in Meguma-like sedimentary rocks. The Comrie aureole of Scotland (Tilley, 1924; Paterson et al., 1991; Pattison and Tracy, 1991; Paterson and Vernon, 1995), the aureole of the Duluth Complex (Labotka et al., 1981), and the Oslo hornfelses (Goldschmidt, 1911), are perhaps the most analogous, well studied metamorphic contact aureoles. Pattison and Tracy (1991) describe mineralogical, textural, and compositional
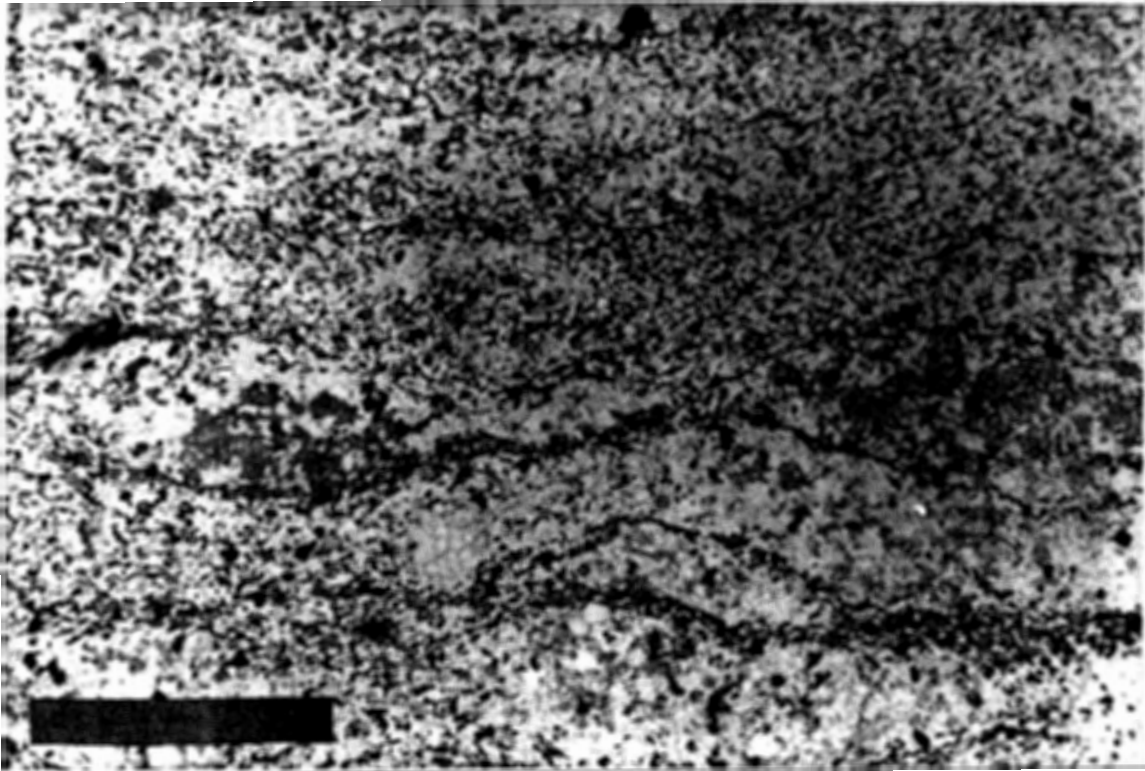
Figure 4.6a) Sample 95-19, intergranular cordierite (dark gray masses) strung out between wavy $L_2$, notice biotite grain alignment in $L_2$ bands, north right. Horizontal section, bar is 4 mm.
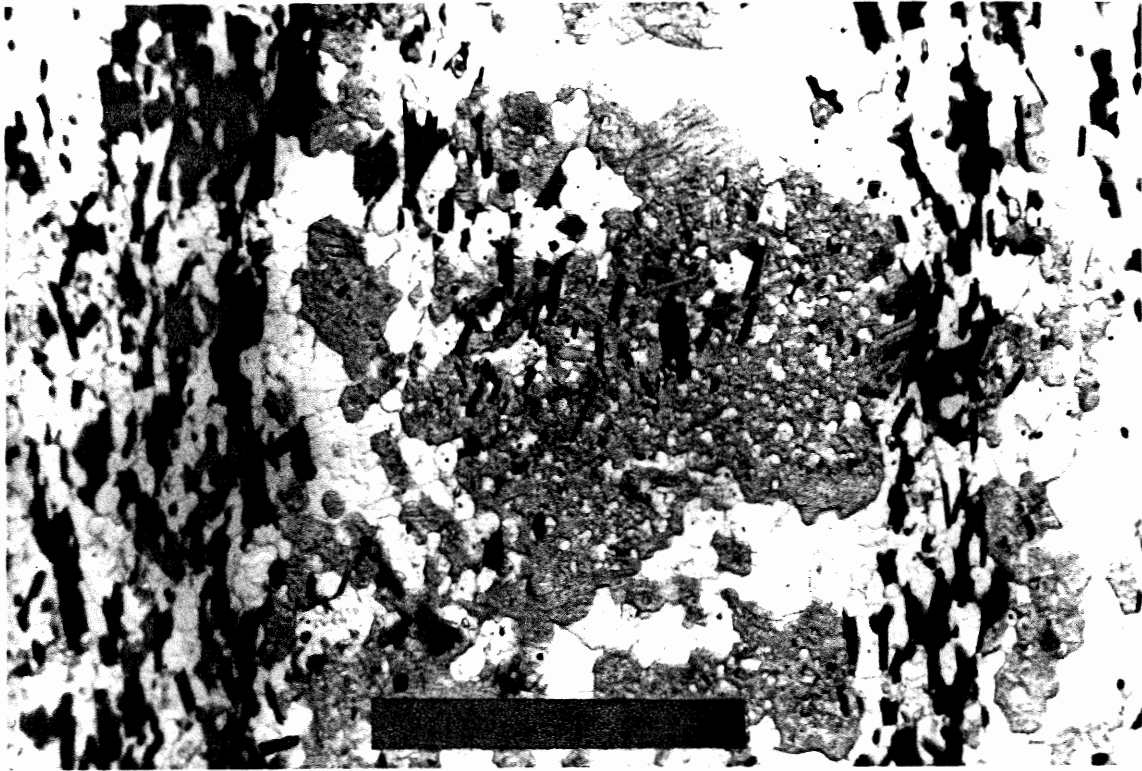
Figure 4.6b) Sample 95-19a, vertical section showing biotite grain alignment (black) and intergranular cordierite (light gray). Bar is 1 mm.
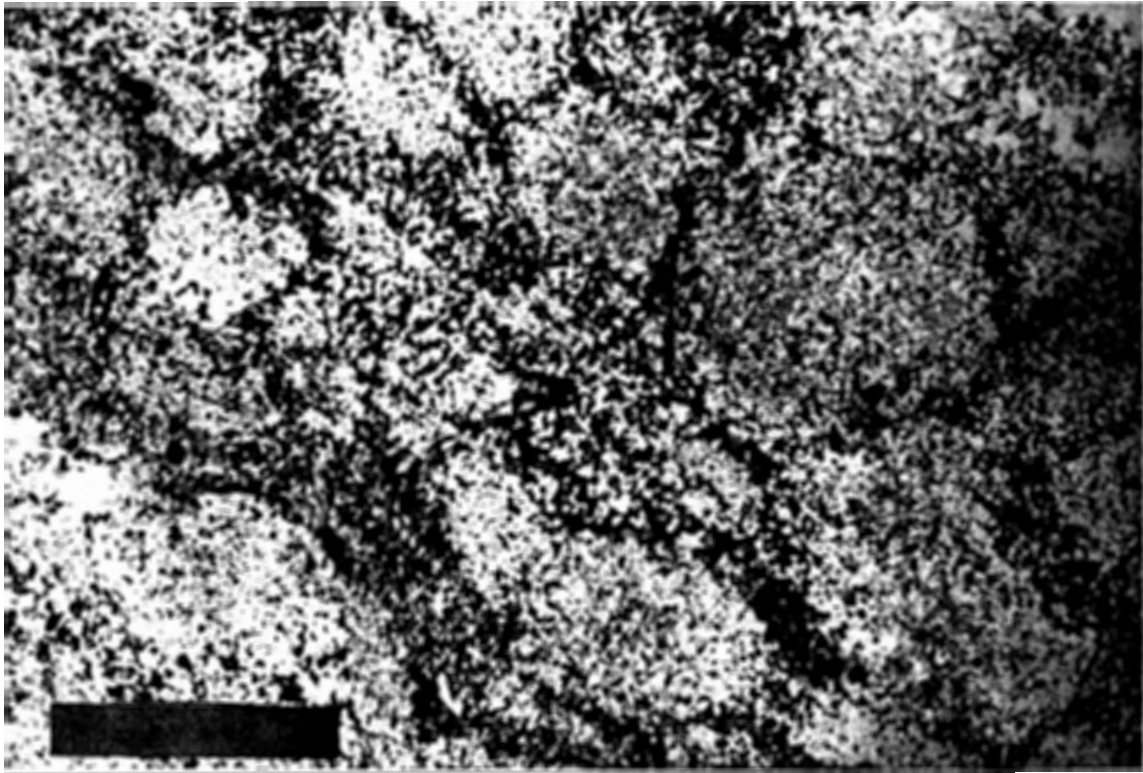
Figure 4.7a) Sample 95-56, biotite (black) defined ring-like structures. K-feldspar, quartz, and plagioclase within rings. Fabric running top left-bottom right. Horizontal section, bar is 4 mm.
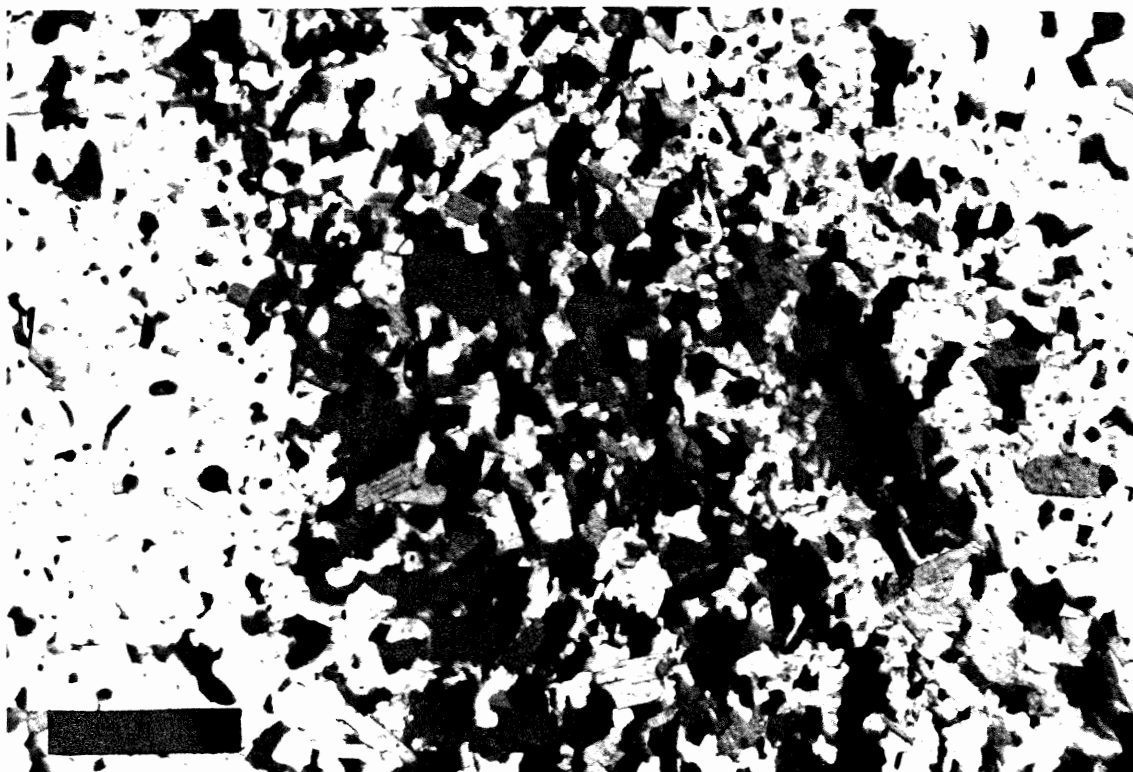
Figure 4.7b) Sample 95-56, randomly oriented biotite grains (dark and elongate) defining the ring-like structures. Horizontal section, bar is 1 mm.

Figure 4.8 Sample 95-56, mymekite alteration of plagioclase (dark gray) by K-feldspar (light gray). Horizontal section, bar is 0.25 mm.

changes within the Comrie aureole comparable to those of Halifax Pluton aureole. Diagnostic

features include the presence of cordierite, absence of andalusite, and muscovite-quartz

breakdown with associated K-feldspar. The Comrie aureole therefore serves as an excellent

model. Pattison and Tracy (1991) interpret the Comrie sequence to represent a low pressure, low

temperature environment, and present a sequence of model reactions for the Comrie aureole.

Two of the more pertinent reactions for the Halifax Pluton are:


Cordierite-in isograd  (Halifax Pluton aureole)

$$Ms+Chl+Qtz=Crd+Bt+H_2O \qquad\qquad (4.1)$$
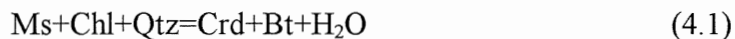
Muscovite-out isograd  (Halifax Pluton aureole)

$$Ms+Bt+Qtz=Crd+Kfs+H_2O \qquad\qquad (4.2)$$
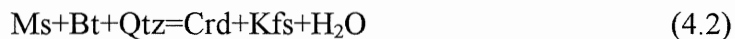

Comparable reactions appear to operate at both the Comrie aureole and the Halifax Pluton

aureole. These two reactions (4.1 and 4.2) seem consistent with the interpreted isograds,

indicating the growth of cordierite and the progressive elimination of muscovite, respectively. It

appears the Halifax Pluton aureole experienced contact metamorphic conditions similar to the

Comrie aureole.

Field descriptions of Pattison and Tracy (1991) indicate a variation in mineralogy and

texture with distance from the contact that closely resembles variation in the Halifax Pluton

aureole. These descriptions include a decrease in fissility of hornfels and anatexis at the granite boundary. Similar conditions (e.g. temperature, pressure, and depth of formation) presumably existed during formation of each contact aureole.

### 4.4 Timing of Contact Metamorphism and Deformation

Within the $LS_2$ schist zone, metamorphism and deformation appear synchronous. Evidence for this is seen in sample 95-19 (Fig. 4.6a and b). Figure 4.6a illustrates the biotite bands anastomosing around cordierite porphyroblasts. Figure 4.6b shows inclusions of biotite grains within the intergranular cordierite, aligned with the biotite bands. Both observations indicate that $L_2$ formed when cordierite was growing, suggesting a synchronous relationship between metamorphism and deformation. In addition, high temperature metamorphic minerals K-feldspar, plagioclase, and recrystallized quartz define the $LS_2$ fabric, the deformation responsible for the fabric, must have occurred with metamorphism.

Further from the contact, metamorphism appears to have been initiated prior to deformation. Porphyroblasts of cordierite grew unaffected by any foliation. However, they deflect a contact-parallel foliation. A thermal pulse preceding the magma plume may be responsible for this initial growth. Post-cordierite strain presumably formed the contact-parallel structures, e.g. $LS_2$, boudins, the Kearney Lake Anticline, and the muscovite defined foliation of the cordierite zone.

## 4.5 Conclusions

Petrographic analyses allow the metamorphic contact aureole of the Halifax Pluton to be interpreted in terms of a set of metamorphic zones. Figure 4.9 summarizes all mineral assemblages, and Appendix C tabulates all petrographic observations.

Metamorphism adjacent to the northeast end of the Halifax Pluton is related to pluton emplacement. With this conclusion plus compositional, mineralogical, and textural evidence; pressure and temperature conditions of formation were concluded (Fig. 4.10). Figure 4.10 is a phase diagram indicating under what conditions, inferred reactions may occur. The phase diagram constrains the pressure and temperatures to approximately 2.5 kb and 550-700 °C, respectively. The work done on the similar Comrie aureole corresponded, with interpretations for temperatures of 500-600 °C, at pressures of approximately 3 kb (Pattison and Tracy, 1991).

The interpreted isograds, while roughly positioned, indicate specific changes in mineralogy and textures directly related to contact metamorphism. Both field and microscopic evidence lead to the conclusion that at least a 1.5 kilometer wide zone of the Meguma Group was subjected to contact metamorphism, as a result of Halifax Pluton emplacement.
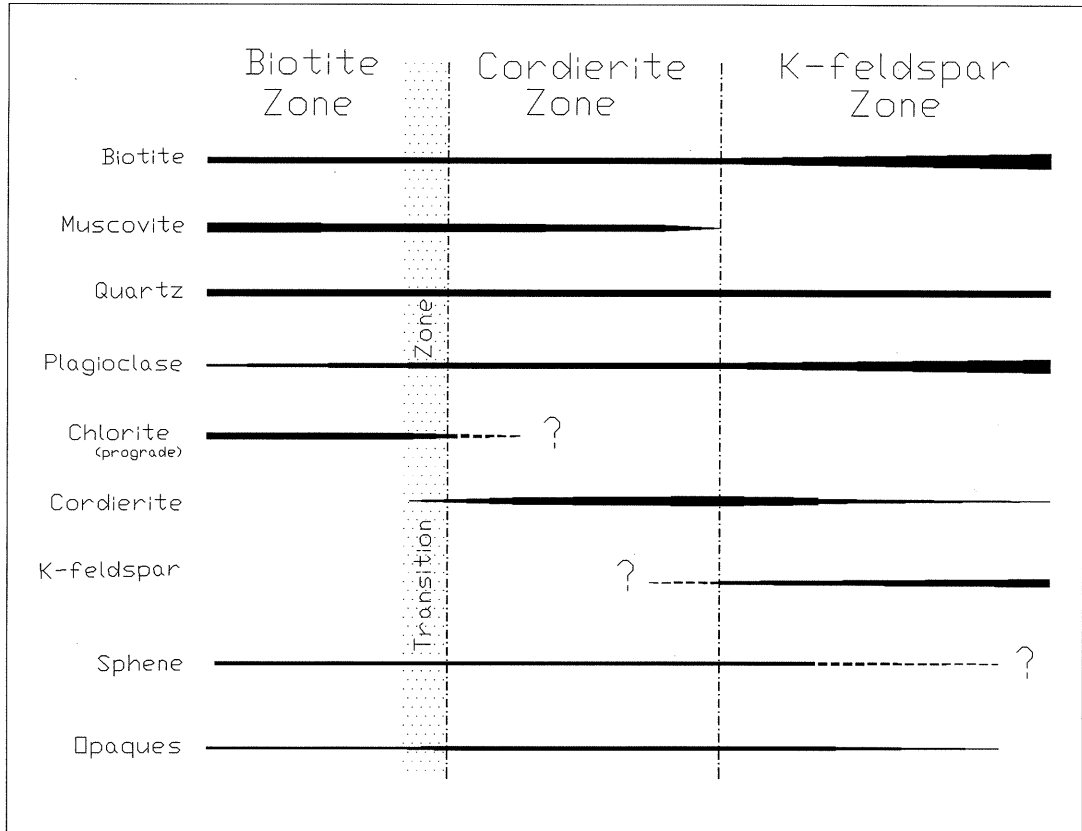
Figure 4.9 Summary of mineral assemblages. Isograds separate distinct zones. Stippled area represents transition zone.
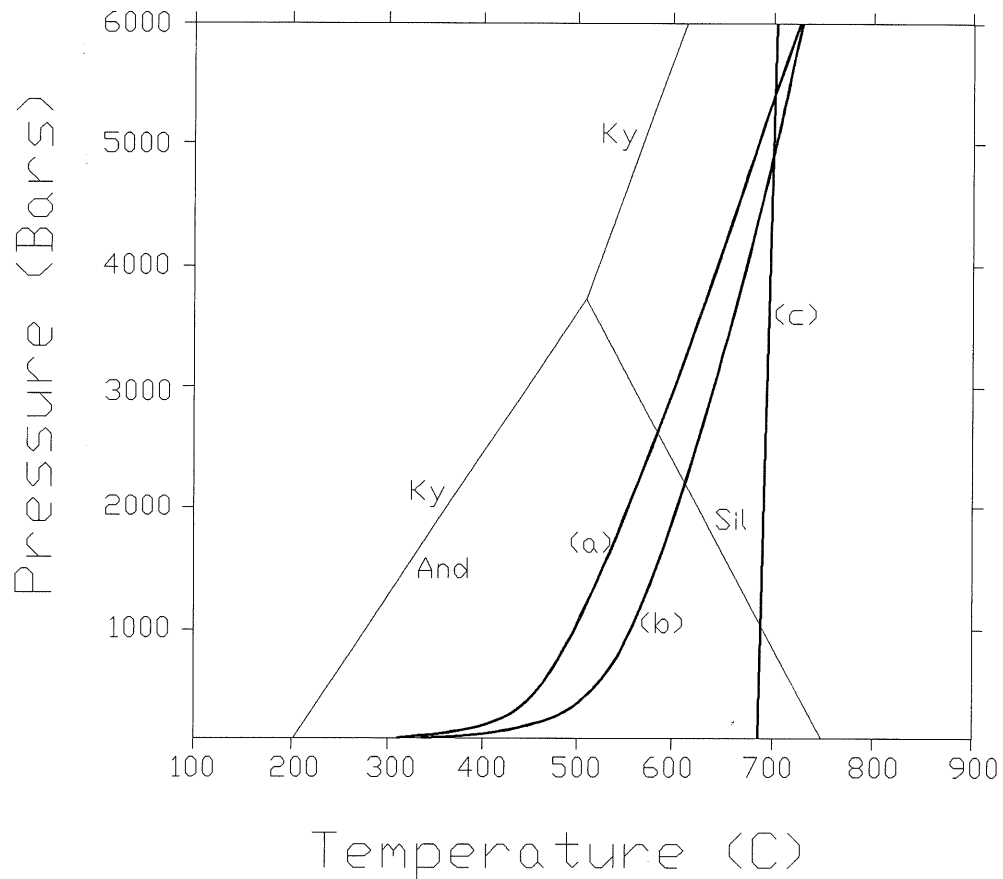
Figure 4.10 Phase diagram of metamorphic minerals present in K-feldspar zone. Andalusite (And), Sillimanite (Sil), and Kyanite (Ky) field for reference. Line (a) indicates reaction (Mus+Bt+Qtz $\Rightarrow$ $H_2O$+Kfs+Crd), line (b) (Mus+Qtz $\Rightarrow$ Kfs+$Al_2SiO_5$+ $H_2O$), and line (c) (Kfs $\Rightarrow$ Sanadine). Typical compositions for metamorphic minerals were used in calculations: 80% Mg-Crd and 50% Phlogopite. Phase diagram determined with PTXSS software after Brown et al., 1979.

# CHAPTER 5  DISCUSSION AND CONCLUSIONS

## 5.1 Introduction

Evidence for the mechanism of emplacement surrounding the South Mountain Batholith is rare.  Until recently the batholith was considered to have been emplaced by exclusively passive mechanisms.  This study and the work of Burns (1995) have led to recognition of emplacement-related structures that suggest a more active mode of emplacement along the northeast flank of the Halifax Pluton.  Field mapping for this study documented a metamorphic contact aureole containing several deformation structures previously unknown in this area.  Detailed macroscopic and microscopic work has determined that deformation and metamorphism in the contact aureole were essentially synchronous.  No overprinting relationship between contact and regional metamorphism was recognized in this study.  This new evidence sheds light regarding the mode of emplacement for the Halifax Pluton.

The previous chapters have documented data which defined a metamorphic contact aureole and zone of emplacement-related strain.  Interpretations have been left to the present chapter, where constraints on pluton-associated strain on the country rocks will be discussed.

## 5.2 Cross-section

A cross-section along the NE-SW hinge of the Magazine Hill Basin was presented by Burns (1995). The present study has augmented the cross-section with the addition of $S_0$ and $S_2$ data close to the contact (Fig 5.1). $S_0$ and $S_2$ measurements lying close to the cross-section line were projected back along strike to the line, where apparent dips were calculated and subsequently drawn on the vertical plane. The moderately dipping beds of the Magazine Hill Basin, and the much more steeply dipping beds of the transverse anticline are evident. Beds dip gently far from the contact, but steepen considerably closer to the contact. A detailed section of the $LS_2$ schist zone illustrates that $LS_2$ generally dips more steeply than bedding $(S_0)$(Fig. 5.1 inset). The cross-section clearly shows a decrease in strain with distance from the contact and therefore reinforces Burn's (1995) conclusion that these features are related to pluton emplacement.

Additionally, the cross-section allows an interpretation of the profile geometry of the transverse anticline. The cross-section (Fig. 5.1) indicates that parallel disharmonic folding is not possible, rather similar folds with limb thinning are more likely adjacent to the Halifax Pluton. Therefore, the transverse fold is probably one of a harmonic stack that may propagate downwards as far as layered rock extends adjacent to the pluton. Significant strain (shortening perpendicular to the contact) would be accommodated in the zone close to the contact according to this model of deformation. Such folding would be expected in rocks adjoining the contact, where the heated rocks may act in a ductile manner. With increasing distance from the pluton-country rock

MUS-OUT
ISOGRAD

CORD-IN
ISOGRAD

TRANSVERSE
ANTICLINE

MAGAZINE HILL BASIN

0        1        2
km

SOUTH
MOUNTAIN
BATHOLITH

A

B

MUS-OUT

CROSS SECTION

- granodiorite

- thermal
  aureole

- schistose zone

- apparent dip of
  $(S_0)$ plane in aureole

- apparent dip of
  $(S_2)$ plane

- apparent dip of
  $(S_0)$ plane

- anticline

- syncline

0        meters        500
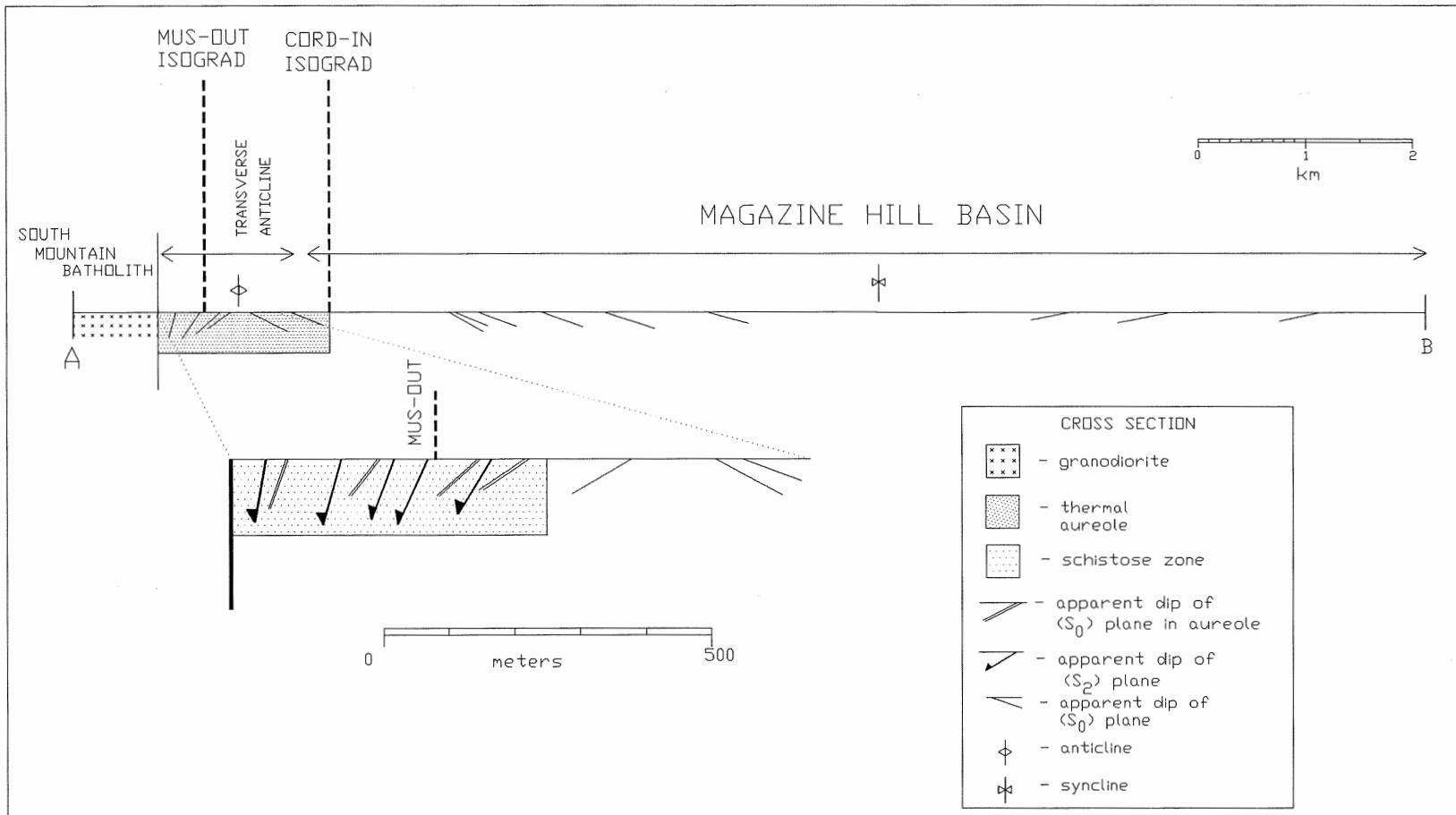
Figure 5.1  Cross-section from A-F line from Figure 3.2 (drawn parallel to hinge of Bedford Syncline and Magazine Hill Basin).  Inset highlights $S_0$ and $S_2$ dips within $LS_2$ schist zone.

contact, temperatures diminish dramatically, and ductile deformation is no longer feasible

(Paterson et al., 1991b). There the Magazine Hill Basin is a parallel fold and therefore probably

detaches at a relatively shallow depth.

Paterson and Vernon (1995) argue that strains inflicted on country rocks by an expanding

pluton must be very high near the contact, but decrease in intensity with distance from the

contact, due to the increased volume of rock being deformed. Paterson and Vernon (1995) also

conclude that structural (strain) aureoles are much less extensive than thermal aureoles. The

Magazine Hill Basin, if it is interpreted as emplacement-related, makes the strain aureole of the

Halifax Pluton significantly wider than its thermal aureole. Therefore, the Magazine Hill Basin

may warrant further investigation.


## 5.3 Strain Path at the Granite Contact

In order to estimate the strain path of the marginal schist ($LS_2$) in the Goldenville

Formation, model 2-D strain paths were calculated using MathCAD, and compared with field

data. The relevant field observations are as follows: $L_2$ plunges steeply and represents the

maximum finite elongation direction., $S_0$ and foliation within the $LS_2$ schist zone ($S_2$) dip towards

the granite contact; $S_2$ generally dips more steeply than $S_0$; the granite contact is vertical (Fig.

5.2a); a small wavelength re-fold lies just beyond the schist zone; and a large wavelength basin

separates the re-fold from any rocks unaffected by pluton intrusion.
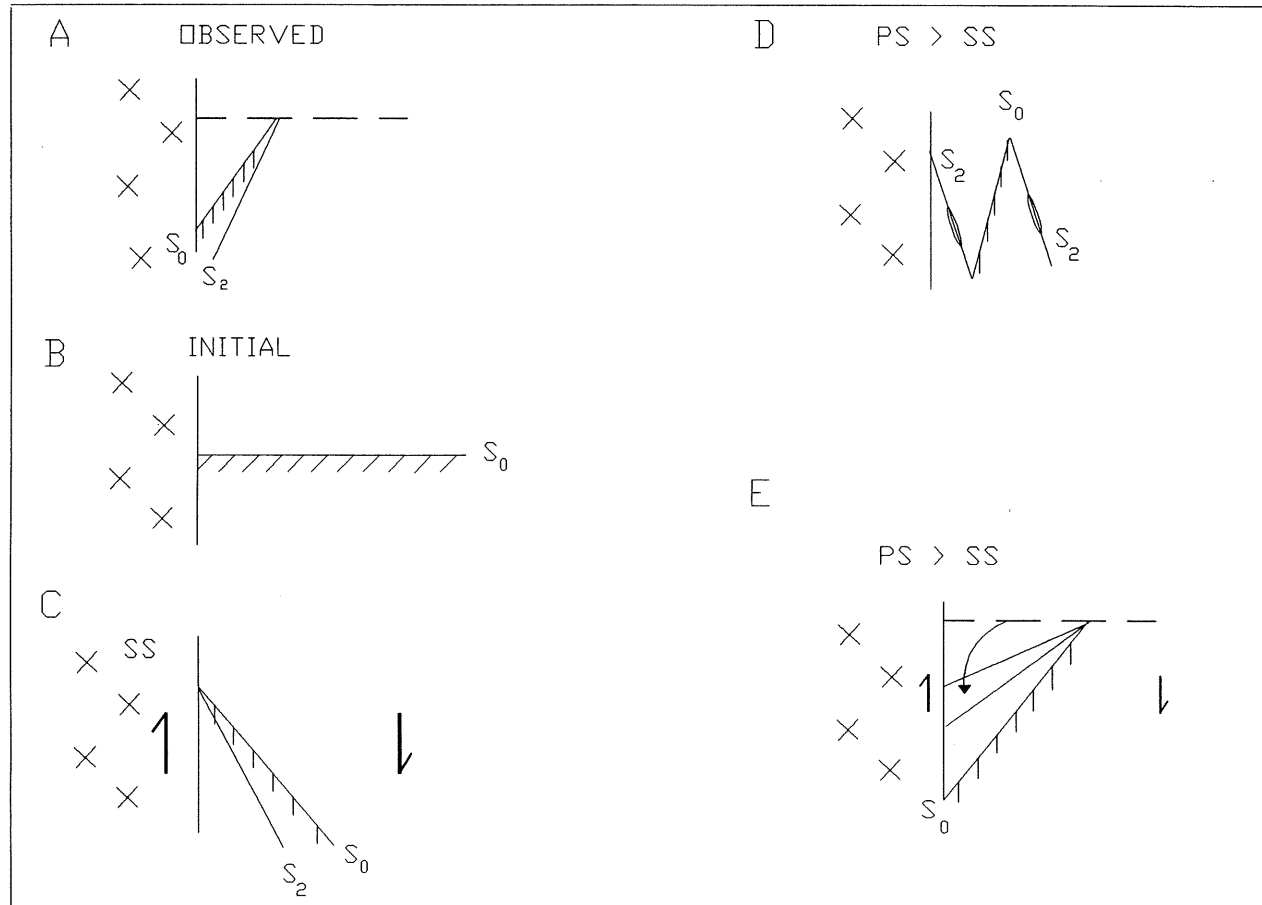
Figure 5.2a) Observed geometry of $S_0$, $S_2$, and vertical granite contact. b) Schematic representation of assumed initial geometry. c) Orientations of $S_0$ and $S_2$ produced from calculations of exclusively simple shear. d) Orientations of $S_0$ and $S_2$ produced from a high pure shear-simple shear combination. e) Intermediate steps and final orientation of granite dipping $S_0$ produced from calculations using a large pure shear to simple shear ratio.

Simplifying assumptions were required in order to reproduce, as closely as possible, the observations. These assumptions are: the initial trace (prior to any intrusion-related deformation) of $S_0$ on the section plane is horizontal or possibly slightly inclined to the southwest, $S_2$ represents the trace of the XY plane of the strain ellipsoid (as shown by minor structures associated with $LS_2$) (pers. comm. N. Culshaw, 1996), and simple shear exerted by granite intrusion on the Goldenville would have been granite-side-up (Fig. 5.2b). The assumptions are necessary, but do entail some degree of approximation. For instance, the orientation of the granite contact may not be perfectly vertical. Also the model pure and simple shear strain paths are two dimensional (confined to the section plane). This is a moderate oversimplification in view of the Y-parallel (3 dimensional) extension evident from field observations of the orthorhombic $LS_2$ fabric (Fig. 3.6a). Using the previous assumptions, model strain paths were calculated. Assuming that the granite boundary is vertical, and exclusively a simple shear plane, incorrect orientations of $S_0$ and $S_2$ were produced (Fig. 5.2c). A combination of simple shear and pure shear results in orientations close to the observed. $S_0$ and $S_2$ orientations did not exactly match the observed, rather they were dispersed to either side of the shear plane (Fig. 5.2d). What is important, however, is that only a high ratio of pure shear to simple shear produced $S_0$ that dipped toward the granite. Therefore, model results suggest that pure shear (i.e. expansion of the pluton perpendicular to its boundary) was more important than simple shear in pluton emplacement, and associated deformation of the Meguma Group in the ductile aureole.

The geometry of the transverse fold in the same section plane (Fig. 5.1) is further evidence for flattening perpendicular to the contact. The steep $S_0$ measurements adjacent to the contact, define an asymmetric fold. Post-emplacement, regional deformation does not seem a reasonable source for its configuration

.

## 5.4 Field and Microscopic Interpretations

Microscopic evidence supplements field observations and implies that metamorphism and deformation were synchronous. Mineral assemblages are consistent with well known contact metamorphic reactions, indicating that metamorphism was due to pluton emplacement. Trends of $S_1$ cleavage swing from regional to contact-parallel ($LS_2$). This may be interpreted to indicate that $S_1$ and $S_2$ are the same structure, with separate orientations caused by deformation of the country rock during pluton emplacement (Guglielmo, 1992). This interpretation would entail syntectonic, or perhaps late syntectonic plutonism (Guglielmo, 1992).

## 5.5 Halifax Pluton Emplacement

The above observations fit well with current models of rising plutons; a thermal pulse precedes the main bulk of the magma, hot magma is then emplaced in cold country rocks, metamorphism ensues. Subsequently, the tail of the pluton rises, pushing out the now crystallized pluton margins and initiating another stage of deformation (Paterson et al., 1991b). In these models, pluton expansion causes flattening of adjacent country rock, hence schistose foliations

form in both the granite and deformed country rock. Marginal foliations in the granite are not

evident in the Halifax Pluton; although a country rock strain aureole does exist, containing

foliations ($LS_2$).

$L_2$ structures may indicate some vertical movement between the pluton and the country

rocks, perhaps emplacement derived, or perhaps from post-emplacement regional deformation.

The latter seems unlikely due to the steeply plunging nature of $L_2$ on the foliation plane.

Evidently, $L_2$ is syn-plutonic and indicates a vertical material transfer was active during pluton

emplacement (Paterson et al., 1991b)..

Regional deformation can play an additional role in material transfer during pluton

emplacement. Paterson and Vernon (1995) argue that regional deformation accompanying

emplacement is of only minor importance. Their evidence comes in the form of a lack of far-field

(> 0.4 of pluton radius) displacements around the studied plutons (Ardara, Ireland; Cannibal

Creek, Australia; Papoose Flat, California). The anomalous Magazine Hill Basin may be an

example of such far-field displacement.


## 5.6 Conclusions

This study recognized and documented some regionally anomalous structures in the

vacinity of Kearney Lake, defined a contact aureole, and inferred relationships between

metamorphism and deformation. The main results of this investigation indicate contact

metamorphism and deformation were intimately related and the emplacement-derived nature of

these local structures as interpreted by Burns (1995) was reinforced. Further work outside the limited study area may answer some of the remaining questions. Specifically, further internal examination Halifax Pluton (in an attempt to define a fabric) and an investigation of southwest and northwest pluton boundaries (to find the $LS_2$ schist). As well, identification of any further regionally anomalous structures may shed more light on pluton-emplacement processes involved with the Halifax Pluton, and indeed the South Mountain Batholith.

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# Appendix A: Tabulated Field Data

| STATION # | EASTING | NORTHING | BEDDING | | CLEAVAGE ($S_1$) FOLIATION ($S_2$) | | | LINEATIONS ($L_2$) INTERSECTION ($L_2$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | STRIKE° | DIP° | STRIKE° | DIP° | | TREND° | PLUNGE° |
| PDG-001 | 444675 | 4949435 | 295 | 28 | 122 | 76 | $S_1$ | | |
| PDG-002 | 443925 | 4950003 | 310 | 25 | | | | | |
| PDG-003 | 442864 | 4949925 | 249 | 20 | | | | | |
| PDG-004 | 443755 | 4949742 | 330 | 20 | | | | | |
| PDG-005 | 443703 | 4949581 | 105 | 22 | 108 | 73 | $S_1$ | | |
| PDG-007 | 442846 | 4951132 | 280 | 20 | | | | | |
| PDG-008 | 442355 | 4951100 | 275 | 22 | | | | | |
| PDG-009 | 445632 | 4948210 | 160 | 26 | | | | | |
| PDG-010 | 445513 | 4948193 | 140 | 36 | | | | | |
| PDG-011 | 445235 | 4948752 | 155 | 18 | | | | | |
| PDG-013 | 445912 | 4951698 | 022 | 22 | 032 | 72 | $S_1$ | | |
| PDG-014 | 439968 | 4951139 | | | 110 | 70 | $S_2$ | 22 | 70 |
| PDG-015 | 440167 | 4951185 | 172 | 12 | 114 | 88 | $S_2$ | 348 | 88 |
| PDG-016 | 440459 | 4951685 | | | 80 | 82 | $S_1$ | | |
| PDG-017 | 440657 | 4952252 | 245 | 52 | 247 | 82 | $S_1$ | 335 | 68 |
| PDG-018 | 440414 | 4950913 | | | 110 | 80 | $S_2$ | 12 | 82 |
| PDG-019 | 440877 | 4950902 | | | 118 | 90 | $S_2$ | 210 | 89 |
| PDG-020 | 441140 | 4950686 | | | 120 | 85 | $S_2$ | 25 | 90 |
| PDG-021 | 441543 | 4951960 | 250 | 53 | | | | | |
| PDG-022 | 445213 | 4952385 | 350 | 17 | 055 | 55 | $S_1$ | | |
| PDG-023 | 443468 | 4952356 | 246 | 12 | 056 | 82 | $S_1$ | | |
| PDG-026 | 441516 | 4950397 | | | 145 | 72 | $S_2$ | 225 | 74 |
| PDG-028 | 441913 | 4950220 | | | 148 | 68 | $S_2$ | | |
| PDG-030 | 442269 | 4949906 | | | 100 | 90 | $S_2$ | | |
| PDG-031 | 442435 | 4949766 | | | 120 | 80 | $S_2$ | 63 | 80 |
| PDG-034 | 442896 | 4949457 | | | 110 | 80 | $S_2$ | 225 | 83 |
| PDG-035 | 443056 | 4949479 | | | 133 | 72 | $S_2$ | 230 | 70 |
| PDG-037 | 443565 | 4948964 | | | 145 | 70 | $S_2$ | | |
| PDG-038 | 443585 | 4949147 | 135 | 42 | | | | | |
| PDG-039 | 443598 | 4949161 | 135 | 42 | | | | | |
| PDG-040 | 443081 | 4949612 | | | 130 | 75 | $S_2$ | | |
| PDG-043 | 444635 | 4948511 | 143 | 38 | | | | | |
| PDG-044 | 444495 | 4948712 | | | 140 | 70 | $S_2$ | | |
| PDG-045 | 443814 | 4949173 | 120 | 35 | | | | | |
| PDG-047 | 443877 | 4948974 | | | 119 | 60 | $S_2$ | | |
| PDG-048 | 443878 | 4948921 | | | 120 | 70 | $S_2$ | | |
| PDG-050 | 443854 | 4948838 | | | 123 | 68 | $S_2$ | 230 | 45 |
| | | | | | | | | 130 18 $L_3$ | |
| PDG-051 | 443929 | 4948831 | | | 110 | 58 | $S_2$ | 238 | 60 |
| PDG-052 | 443832 | 4948772 | | | 118 | 80 | $S_2$ | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PDG-053 | 443817 | 4948750 | 340 54 | | | | | |
| | | | 112 74 | | | | | |
| PDG-056 | 443578 | 4948835 | | | 118 70 | S$_2$ | | |
| PDG-057 | 446293 | 4944711 | 100 65 | | 88 65 | S$_2$ | 220 44 | |
| | | | | | 238 75 | S$_2$ | 278 60 | |
| PDG-059 | 446370 | 4945322 | | | 160 85 | S$_2$ | 207 74 | |
| PDG-060 | 446332 | 4945481 | 126 76 | | | | | |
| PDG-061 | 446079 | 4945550 | 105 65 | | 117 68 | S$_2$ | | |
| PDG-062 | 445798 | 4946256 | | | 325 80 | S$_2$ | | |
| PDG-063 | 445723 | 4946435 | 125 60 | | | | 225 60 | |
| PDG-064 | 446124 | 4946313 | 192 55 | | | | 270 58 | |
| PDG-065 | 446068 | 4946825 | 130 63 | | | | 227 65 | |
| PDG-066 | 446123 | 4945942 | 50 86 | | 230 88 | S$_2$ | 230 10 | |
| PDG-068 | 446910 | 4943547 | | | 65 80 | S$_2$ | 67 15 | |
| PDG-069 | 446665 | 4944021 | | | 120 80 | S$_2$ | | |
| PDG-070 | 447246 | 4943266 | | | 275 80 | S$_2$ | | |
| PDG-071 | 446722 | 4944037 | | | 70 90 | S$_2$ | | |
| PDG-072 | 446585 | 4944383 | | | 174 81 | S$_2$ | | |
| PDG-075 | 440757 | 4950791 | | | 122 76 | S$_2$ | | |
| PDG-077 | 440589 | 4940932 | 100 77 | | 120 86 | S$_2$ | | |
| PDG-078 | 440412 | 4950573 | | | 110 80 | S$_2$ | | |

* UTM coordinates determined from GPS (Trimble Pathfinder+). Data points differentially corrected with a Bangor Maine, U.S.A. base station. Positions accurate to <5 meters.

# APPENDIX B:
# LS$_2$ Schist Zone Measurements

LS$_2$ foliation measurements (strike and dip in degrees)

     124°/89°
     119°/85°
     120°/86°
     122°/88°
     121°/89°
     120°/80°

S$_0$ measurements (strike and dip in degrees)

     108°/78°
     100°/77°
     099°/80°
     102°/80°

Shear Band-like planar feature measurements (strike and dip in degrees)

| | |
|---|---|
| 287°/51° | 280°/52° |
| 290°/55° | 282°/48° |
| 287°/62° | 283°/45° |
| 276°/50° | 279°/50° |
| 281°/63° | 283°/42° |
| 285°/65° | 285°/48° |
| 282°/53° | 278°/54° |
| 284°/54° | 282°/52° |
| 280°/35° | 278°/47° |
| 284°/50° | 280°/53° |
| 281°/38° | 283°/59° |
| 281°/38° | 283°/59° |
| 281°/48° | 288°/52° |

# APPENDIX C: TABLE OF PETROGRAPHIC DESCRIPTIONS

| SAMPLE # | MINERAL ASSEMBLAGE | TEXTURE | PORPHYR-OBLASTS | ALTERATION | COMMENTS (Distance from contact) |
|---|---|---|---|---|---|
| 95-13 | Quartz, Muscovite, Biotite, Chlorite, and Sphene | Very fine Grained Cleavage  -Mus. defined | Small (<1mm), randomly oriented Biotite | Unaltered | Weakly defined foliation wrap around P'blasts. Shadow zones. Rounded Biotites. (3350 meters) |
| 95-23 | Quartz, Biotite, opaques, Muscovite, chlorite | Fine Grained Cleavage  -Mus. Defined Bedding compositional | Biotite | Some Biotite is chlorotized | Bedding~240° Cleavage~068° Irregular Biotite Quartz vein (2510 meters) |
| 95-21 | Quartz, Amphibole, Chlorite, Sphene, Biotite | Medium Grained. Large Quartz Grains. Bedding  -compositional | Acicular amphibole | | Bedding~245° Amphibole alignment? Well preserved clastic texture. Calc-silicate 1550 meters |
| 95-7 | Cordierite, Biotite, Quartz, Muscovite, Sphene | Fine Grained. Cleavage  -Mus. Defined | Cordierite. Biotite Magnetite Many P'blasts | Chloritization of Cordierite | Opaques equant and omnipresent. Quartz vein. Cleavage~255° (1400 meters) |
| 95-17 | Quartz, Biotite, Muscovite, Opaques, Cordierite, some Plagioclase. | Medium Grained. Strong Cleavage  -Mus. defined Bedding  -compositional  -grain sizes differences | Large Cordierite.  Red-brown Biotite. | Chloritization of micas, and minor cordierites.  Biotite totally replaced by chlorite. | Enhanced Fabric development at P'blast sides. Major Augen wrap around structures. Bedding=Cleavage~245°   -Intermediate trend Grain coarsening. Change in Biotite color. (1260 meters) |
| 95-8 95-8a | Quartz, Muscovite, Biotite, Chlorite, Cordierite, opaques (magnetite) | Fine grained. Cleavage  -Mus/Bt defined | Cordierites Large (~3-4 mm) | Chloritization of Cordierites  - rimmed alteration Biotites altered to chlorite | Fabric enhanced near and between P'blasts. Augen wrap around structures. Cleavage~215° Highly altered-retrograde (1170 meters) |
| 95-1 | Quartz, Muscovite, Biotite, Cordierite, opaques, Chlorite | Fine Grained Cleavage  -Mus defined | Cordierites (~3mm) Biotites (>1mm) | Chloritization of Cordierites and Biotites. Retrograde chlorite. | Fabric enhanced at P'blast edges. Cleavage~285° Alteration evident (800 meters) |

| | | | | | |
|---|---|---|---|---|---|
| 95-4 | Quartz, Feldspar, Muscovite, Biotite, Chlorite, Sphene, Hematite. | Medium Grained, clastic texture. Bedding -Compositional Cleavage -Mus/Bt defined | None | Not highly  Chlorite replaceing Bt | Chlorite well developed Bedding~125° Recrystallized No Cordierites-- lithological? Weak foliation. (860 meters) |
| 95-5 | Quartz, Feldspar, Muscovite, Biotite, Cordierite, Chlorite, Sphene, Garnet | Medium Grained. Compositional, pelitic and clastic layers. Bedding? Cleavage -Mus defined | Biotite  Cordierite concen. in pelitic layers | Chloritization of Biotite and Cordierite. | Intense fabric around P'blasts. -P'blasts appear rotated -Cleavage anastomoses Cleavage~125°--parallel to bedding. Compositional layering. Intense retrogression (630 meters) |
| 95-47 | Plagioclase, Biotite, Quartz, Amphibole, Sphene, Muscovite, opaques, Hematite | Medium Grained. feldspar/quartz coarsening. | Muscovite.  Oxides. | Muscovite highly altered. Feldspar altered to Clinozoisite and chlorite | Clastic texture  Recrystallized  (420 meters) |
| 95-49 | Plagioclase, Biotite, Cordierite, Muscovite, opaques | Medium grained. | Corierite | Muscovite beginning to alter on edges | Recrystallized.  foliation~100°  (350 meters) |
| 95-19 | Quartz, Feldspar, Plagioclase, Biotite, Cordierite | Medium Grained. Lineation -Bt alignment in zones | Cordierite granular and strung out and aligned in $L_2$ | Cordierites reacting out. | $L_2$ Biotite defined lineation pinch and swell structure. Minor Mus.-replacement  (261 meters) |
| 95-15 | Quartz, Plagioclase, Biotite, Cordierite, Muscovite, Sphene, opaques | Medium Grained. Gneissic- recrystallized quartz rich Foliation -Bt/Mus Defined | Cordierite but pretty grungey | Cordierite  Plagioclase -Sericite | Cordierite and Biotite well developed. Foliation~120° Cordierite granular Partly preseved clastic texture (110 meters) |
| 95-51 | Quartz, Biotite, Muscovite, Feldspar, Plagioclase | Medium to fine grained. Gneissic- recrystallized | None | Muscovite altered, and reacting out | Foliation defined by linear biotite zones, and grain sizes. (150 meters) |
| 95-14 | Quartz, Feldspar, Plagioclase, Muscovite, Biotite -both retrograde | Coarse Grained. Recrystallized Foliation -Banding of Bt/Qtz | None | Symplectite feldspar alteration. Muscovite retrograde Chlorite retrograde | Foliation segragated into bands, wavy development ~120° Quartz-rich lithology  (60 meters) |

| 95-56 | Quartz, Feldspar, Plagioclase, Biotite, Zircon | Fine to Medium Grained. recrystallized/ annealed. | None | Myrmekite Feldspar alteration | Ring like Structures Granoblastic texture Lack of Muscovite. Grain Boundary zonation. (5 meters) |
|-------|-------------------------------------------------|---------------------------------------------------|------|-------------------------------|------------------------------------------------------------------------------------------------|
| 95-58 | Quartz, Biotite, Muscovite, Feldspar, Plagioclase, Zircon | Fine Grained. Massive and recrystallized | Rare | Chloritized Biotite rims, and some completely replced. | Weakly defined foliation -perhaps 2 or 3 directions Rare, but present Muscovite.  Around corner of pluton near Burnside Industrial Park.  Does not enter into metamorphic zonation |