GEOLOGICAL SETTING AND GENESIS OF THE EASTERN AVALON HIGH ALUMINA BELT

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Geological Setting and Genesis of the Eastern Avalon High Alumina Belt

by

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CONTENTS

Page

CHAPTER 1 1
INTRODUCTION 1
1.1 Introduction 1
1.2 Project Background and Aim of Present Study 3
1.3 Methods 3
1.4 Location, Access and Geographic Databases 4
1.5 Physiography and Glaciation 4
1.6 Previous Work 6
1.7 Regional Tectonic Setting of the Avalon Peninsula 7
1.8 Description of the Pyrophyllite Occurrences 10
1.8.1 Oval Pit Mine 10
1.8.2 Mine Hill 11
1.8.3 Trout Pond Prospect 11
1.8.4 Dog Pond–Jakes Gully Prospects 12

CHAPTER 2
REGIONAL GEOLOGY OF THE AVALON PENINSULA 13
2.1 Introduction 13
2.2 Avalonian Orogeny, Geochronology and Tectonism within the Avalon Zone 13
2.3 The Geology of the Avalon Peninsula 15
2.3.1 Introduction 15
2.3.2 The Harbour Main Group Subdivision and Chemical Affinity 18
2.3.3 Relationship of Conception and Harbour Main Groups 20
2.3.4 Holyrood Intrusive Suite and its Relationship to the Harbour Main/Conception Groups 21
2.3.5 Precambrian Sedimentary Rocks 22
2.3.6 Cambrian and Later Evolution 24
2.4 Geochronology 25

CHAPTER 3
BEDROCK GEOLOGY OF THE STUDY AREA 27
3.1 Introduction 27
3.2 General Stratigraphy and Relationships in the Field Area 27
3.3 The Foxtrap Diorite 28
3.3.1 Description 28
3.3.2 Age Relations of the Foxtrap Diorite 31
3.4 The Johnnies Pond Formation (Unit 2) 32
3.4.1 Definition of the Johnnies Pond Formation 32

3.4.2 Contact and Age Relationships 33
3.4.3 Description of Rock Types 35
3.4.3.1 Rhyolitic Crystal Tuffs – Field Description and Relationships 36
3.4.3.2 Petrography 37
3.4.3.3 Lithic Tuffs 38
3.4.4 Coarse Breccias 39
3.4.5 Conglomerate 39
3.5 Holyrood Intrusive Suite (Unit 3) 40
3.5.1 Introduction and Nomenclature 40
3.5.2 Age of Intrusion 41
3.5.3 Description of Phases 42
3.6 Harbour Main Group 46
3.6.1 Introduction 46
3.6.2 Contact Relations 47
3.6.3 Volcanic Facies Association 49
3.6.3.1 Mafic Flows 49
3.6.3.2 Agglomerates 50
3.6.3.3 Ash and Lapilli Tuffs 51
3.6.3.4 Felsic Rocks 51
3.6.4 Sedimentary Facies 52
3.6.4.1 Coarse Debris-style Deposits 52
3.6.4.2 Greywacke Facies 54
3.6.5 Correlation 55
3.7 Black Mountain Formation Conception Group 56
3.7.1 Introduction 56
3.7.2 Contact Relationships 58
3.7.3 Facies Relationships and Lithologies 59
3.8 Conclusions 61

CHAPTER 4
STRUCTURAL GEOLOGY AND GEOLOGICAL HISTORY 63
4.1 Introduction 63
4.2 Main Structural Elements in the Study Area 64
4.3 D_1–Foxtrap Diorite 65
4.4 D_2–Pre-AHAB Deformation of the Johnnies Pond Formation 65
4.5 D_3–Regional Structural Significance of the Avalon High Alumina Belt 68
4.6 D_4–Post-AHAB Uplift and Basin Development 69
4.7 D_5–Topsail Fault and Related Structures 73
4.7.1 Topsail Fault 73
4.7.2 Structures Related to the Topsail Fault 74
4.7.3 Timing of Deformation along the Topsail Fault Zone 83

4.8 Veins and Metamorphic History 83
4.9 Post-Cambrian Deformation 86
4.10 Summary of Structural and Depositional History 86

CHAPTER 5
DETAILED DESCRIPTION OF ALTERATION AND STRUCTURES WITHIN THE AVALON HIGH-ALUMINA BELT 89
5.1 Introduction 89
5.2 Alteration Types 89
5.2.1 Overview 89
5.2.2 Alkali Feldspar Metasomatism and Adularia 90
5.2.3 Silicification 91
5.2.4 Sericitic Alteration 93
5.2.5 Pyrophyllite 98
5.2.6 Diasporization 109
5.2.7 Hematization 110
5.3 Structural Control on Secondary Mineral Development 111
5.3.1 Introduction 111
5.3.2 Alteration Zonation and Structural Style 113
5.3.3 Role of Fractal Fracture 114

CHAPTER 6
THERMOCHEMISTRY AND SOLUBILITY RELATIONSHIPS BETWEEN PHASES IN THE ALTERATION SYSTEM 118
6.1 Introduction 118
6.2 Review of Stability Data and Relations 118
6.2.1 Alteration Minerals in the AHAB 118
6.2.2 A Review of Stability Relations between Phases 120
6.3 Mineral Dissolution Rates and Solubility 124
6.4 Description of the Genesis of the Alteration 129

CHAPTER 7
GEOCHEMISTRY OF THE AHAB 131
7.1 Introduction 131
7.2 Trends in Major Component Composition 132
7.2.1 Overview of Alumina–Silica–Potassium Compositions 132
7.2.2 Bivariate Analysis of Major Element Data 139
7.2.2.1 Silica–Alumina Variation 139
7.2.2.2 Al_2O_3–TiO_2 Variation 142
7.2.3 Ternary Diagrams of Major Element Data 144
7.3 Trace Element Chemistry 146
7.3.1 Introduction 146
7.3.2 Classification Diagrams 148

7.3.3 Pearce Element Ratios 152
7.4 Discussion 154

CHAPTER 8
ECONOMIC GEOLOGY 155
8.1 Introduction 155
8.2 Overview of Epithermal Alteration Systems 156
8.2.1 Introduction 156
8.2.2 Acid-Sulfate 157
8.2.3 Adularia–Sericite Systems 160
8.3 Avalonian Deposits 162
8.4 Base Metals and Gold Systematics of the AHAB 162
8.5 Conclusion 166

CHAPTER 9
CONCLUSIONS 167
9.1 Metallotectonics 167
9.2 Alteration 168
9.3 Regional Geology 169
9.4 Acknowledgments 169

REFERENCES 171

FIGURES

Figure 1.1	Regional geology of the eastern Avalon Peninsula and location of the study area. Geology modified from King (1988)	5
Figure 1.2	Geology of the Avalon Zone in Newfoundland (after Colman-Sadd et al., 1992)	9
Figure 2.1	Geology of the Avalon Peninsula (from King, 1990)	16
Figure 3.1	Geological map of the Avalon High Alumina Belt	29
Figure 3.2	Tuffisite veining in the Holyrood Intrusive Suite, Manuels River	44
Figure 4.1	Primary and secondary (AHAB-related) structures in the Johnnies Pond Formation	67
Figure 4.2	Bedding and cleavage relationships within the Harbour Main Group	75
Figure 4.3	Detailed geological map of the Mine Hill area	77
Figure 4.4	Thrust fault in roadcut at Mine Hill. The hanging wall consists of AHAB pyrophyllite zone and the footwall contains relatively unaltered Harbour Main Group basalts	79
Figure 4.5	Orientation of veins within the Johnnies Pond Formation and the Harbour Main and Conception groups	85
Figure 4.6	Age relations and timing of structural events in the eastern Avalon Peninsula	87
Figure 5.1	Hydrothermally brecciated and silicified rhyolite near Johnnies Pond	92
Figure 5.2	View of silicified zone at the southern end of Mine Hill showing relict flow banding and layering	94
Figure 5.3	Quartz–hematite breccia vein near Oval Pit Mine	95
Figure 5.4	Fracture hosted sericitic alteration in silicified rhyolites north of Trans Canada Highway	97

Figure 5.5	Pyrophyllite in sheared rhyolite, Mine Hill	99
Figure 5.6	Pod of pyrophyllite from Mine Hill with block of silicified rhyolite	101
Figure 5.7	Example of pyrophyllite pod from north of Oval Pit Mine. The pod is located in the interstices of large diamond-shaped fractured blocks of pyrophyllite. The pyrophyllite pod in the photo appears dark-grey to black due to lichen (pen knife is resting on pod). The white coloured rocks are massive silicified rhyolite.	102
Figure 5.8	Example of pyrophyllite pod near south part of Oval Pit Mine. Pyrophyllite pod is irregularly shaped and appears to be infilling between blocks of silicified rock	103
Figure 5.9	Hematite alteration zones proximal to pyrophyllite zones in the Oval Pit Mine	112
Figure 5.10	Overview of alteration zonation and structural development of AHAB	115
Figure 6.1	Phase relations in the system Al_2O_3-SiO_2-H_2O (from Hemley et al., 1980)	121
Figure 6.2	Feldspar–mica–aluminosilicate equilibria (from Sverjensky et al., 1991)	123
Figure 6.3	Feldspar dissolution rate after Hellman, 1994	126
Figure 6.4	Solubility of SiO_2 after Dove (1994)	128
Figure 7.1	Cumulative frequency diagram of SiO_2 within the AHAB	135
Figure 7.2	Cumulative frequency diagram for K_2O in the AHAB	137
Figure 7.3	Cumulative frequency diagram for Al_2O_3 in the AHAB	138
Figure 7.4	Al_2O_3 vrs SiO_2 for altered and unaltered rocks of the Avalon High Alumina Belt. Note the pronounced variation in slope of the pyrophyllitized rocks from the remaining samples and also the preponderanc of silicified and sericitized samples falling at the high alumina part of the main trend	140

Figure 7.5 TiO_2 vrs Al_2O_3 diagram for the AHAB revealing discrete patterns of covariation relative to type of alteration 143

Figure 7.6 Ternary diagram showing the relationship of Al_2O_3–SiO_2–K2O with respect to the major mineral phases 145

Figure 7.7 Ternary diagram showing K_2O–Na_2O–TiO_2. The relationship between the alkalias and the immobile component TiO_2 demonstrates the influence of original chemistry of the rhyolite in controlling the distribution of K and Na 147

Figure 7.8 AHAB rhyolitic rocks plotted on the Zr/TiO_2 vrs. Nb/Y discrimination diagram of Winchester and Floyd (1977) 149

Figure 7.9 AHAB rhyolitic rocks classified using the Rb vrs. Y+Nb diagram of Pearce et al. (1984) 151

Figure 7.10 Discrimnation diagram using immobile elements demonstraing the use of Pearce Element Ratios to classify rhyolitic rocks of the Johnnies Pond Formation 153

Figure 8.1 Morphology of high-sulfidation or acid-sulfate type deposits 159

Figure 8.2 Morphology of adularia–sericite deposits 161

Figure 8.3 Gold and silver occurrences in the AHAB 165

MAPS

Map 1. Geology of the Eastern Avalon High-Alumina Belt .... In pocket

TABLES

Table 1.1 Previous geological studies of the eastern Avalon Peninsula and the Avalon High Alumina Belt 7

Table 2.1 Summary of geochronology data for the eastern Avalon Peninsula 26

Table 3.1 Table of formations 30

Table 6.1 Partial listing of minerals in the system 119

Table 7.1 A comparison of SiO_2, Al_2O_3 and K_2O grouped by alteration type 133

Table 8.1 Overview of Avalonian volcanic-hosted hydrothermal alteration zones and deposits 163

ABSTRACT

The eastern Avalon High-alumina belt is an alteration system of Precambrian age, hosted by the Johnnies Pond formation. The Johnnies Pond formation is a newly recognized unit and is separated from the Harbour Main group which was previously thought to be the only major volcanic unit on the eastern Avalon Peninsula. Detailed mapping demonstrates the presence of a major regional unconformity between the Conception Group and the Johnnies Pond formation. The remaining volcanic rocks in the Harbour Main group conformably underlie the Conception Group. The Holyrood Granite is pre-Conception in age and clearly intrudes both the Johnnies Pond Formation and foliated hornblende diorite of the Foxtrap diorite, which is interpreted to be the oldest unit on the Avalon Peninsula on the basis of structural relationships.

The eastern Avalon High-alumina belt is marked by the development of silicification, sericitization and pyrophyllitization within the rhyolitic ash-flow tuffs of the Johnnies Pond Formation. The earliest alteration in the zone involved silicification, presumably proximal to pyrophyllitization at depth, subsequently overprinted by fracture hosted sericite and pyrophyllite. Early silicification is accompanied by pyritization which locally contains anomalous gold. The alteration system and the redistribution of rock components were likely controlled by dissolution mechanisms and kinetically inhibited precipitation of less soluble hydrous aluminosilicates producing amorphous reaction products which subsequently recrystallize to pyrophyllite.

CHAPTER 1

INTRODUCTION

1.1 Introduction

High-alumina altered rocks in eastern North America have been of economic interest since the first gold rush in North America occurred. During the 1700's gold deposits were discovered in the Carolinas associated with high-alumina zones of Precambrian age (Worthington and Kiff, 1970). These zones have had an intermittant mining history that extends into the present day. In the early 1980's the discovery of gold in high-alumina altered rocks at Hope Brook, sparked a modern gold rush in Newfoundland. Since that time much research has been done revealing the relationship of the historically known deposits of gold bearing zones at Hope Brook, and new occurrences which have been subsequently found throughout the Avalon Zone. The Avalon Zone is a lithotectonic zone, characterized by Precambrian volcanic, sedimentary and intrusive rocks that can be traced along the eastern coast of North America from Newfoundland to Georgia (Williams, 1979).

High-alumina alteration zones, intermittently mined at Manuels since the 1900's under a fee simple mining lease, have also provided raw material for the ceramic tile industry in North America. The present operation known as the Oval Pit Mine, has been in continuous production since the 1950's. The deposit at the Oval Pit Mine is part of a linear belt of pyrophyllite occurrences which extend over a distance of 14 km. The pyrophyllite occurrences are enveloped by an aureole of related sericitic alteration and silicification and the belt defines a major regional structure, termed the Avalon High-Alumina Belt (AHAB). Significant gold mineralization also occurs in silicified and sericitized rocks within the belt and as such the AHAB represents the northern terminus of a gold/high-alumina metallotect within Avalonian strata of the Appalachian Orogenic Belt. Outside of the Avalon Peninsula, the Avalon Zone has been deformed and metamorphosed. Consequently other high-alumina zones and their host rocks are overprinted by Silurian and younger orogenic events. The AHAB is not extensively deformed and provides a unique opportunity to understand the formation and geologic relations of high alumina alteration in the Avalon Zone. The AHAB also constrains the timing of magmatism and basin development on the Avalon Peninsula which is the type area of the Avalon Zone.

The most widely documented occurrences of pyrophyllite are those which are associated with acid-sulfate (or high-sulfidation) alteration systems. The AHAB, however, is not an acid-sulfate system which suggests that there can be a second environment of pyrophyllite formation. In the AHAB-type pyrophyllite deposits alteration, textural and structural development of the high-alumina zone are interrelated. It is therefore important to establish the regional geological setting and to isolate subsequent structural events from those which are contemporaneous with the alteration system.

1.2 Project Background and Aim of Present Study

This study originated as a Newfoundland Department of Mines and Energy (presently the Newfoundland Department of Natural Resources, NDNR) project to determine the gold potential of the alteration zone hosting the Oval Pit Mine (Hayes and O'Driscoll, 1990). It is part of a longer term effort by the NDNR to understand the metallogeny of the Avalon Zone in Newfoundland. The aim of this particular study is to model the genesis of the AHAB, including timing with respect to the regional geology, and thereby improve understanding of the geological history of the Avalon Peninsula and the economic geology of this class of deposit within the Newfoundland Avalon Zone.

1.3 Methods

To complete this project, field mapping and detailed sampling were carried out. Extensive field description of textures and structures related to the development of the alteration zone were made, and major, trace element and stable isotope geochemical studies, were carried out on a suite of samples representative of the AHAB and its host rocks. Mapping of the alteration system and host rocks, at a scale of 1:12,500 with more detailed follow-up mapping in the vicinity of the Oval Pit Mine, was undertaken from May to September 1989. Field visits were also made to areas on the Avalon and Burin peninsulas that have similarly altered rocks with gold or base metal mineralization. Major, trace and precious element (Au, Ag) data have been previously published (Hayes, 1994).

1.4 Location, Access and Geographic Databases

The field area is located in the eastern part of the Avalon Peninsula (Figure 1.1) and is readily accessible from St. John's via the Conception Bay or Trans-Canada Highways. Secondary roads provide access to the Oval Pit–Mine Hill (Country Path and Dawes Road) and Dog Pond Area (Pastureland Road). Access is enhanced by abundant trails, cutovers and power lines.

The area is completely covered by 1:50,000 and 1:12,500 topographic maps (NTS 1N/10, 1N/7). Map coverage for the northern part of the field area is also available at 1:25,000 and 1:5,000 scales. There is also complete 1:12,500 colour air photograph coverage from a 1978 survey.

1.5 Physiography and Glaciation

The physiography of the Conception Bay region is largely controlled by bedrock geology. The coast is bordered by a 2 km wide lowland, underlain by a belt of friable Cambrian sedimentary rocks, which rises inland to a dissected inland plateau of well exposed Precambrian strata and intrusive rocks. The plateau is drained by a series of streams and rivers running north into Conception Bay which are localized along late faults that dissect the plateau.

Figure 1.1. *Regional geology of the eastern Avalon Peninsula and location of the study area. Geology modified from King (1988).*

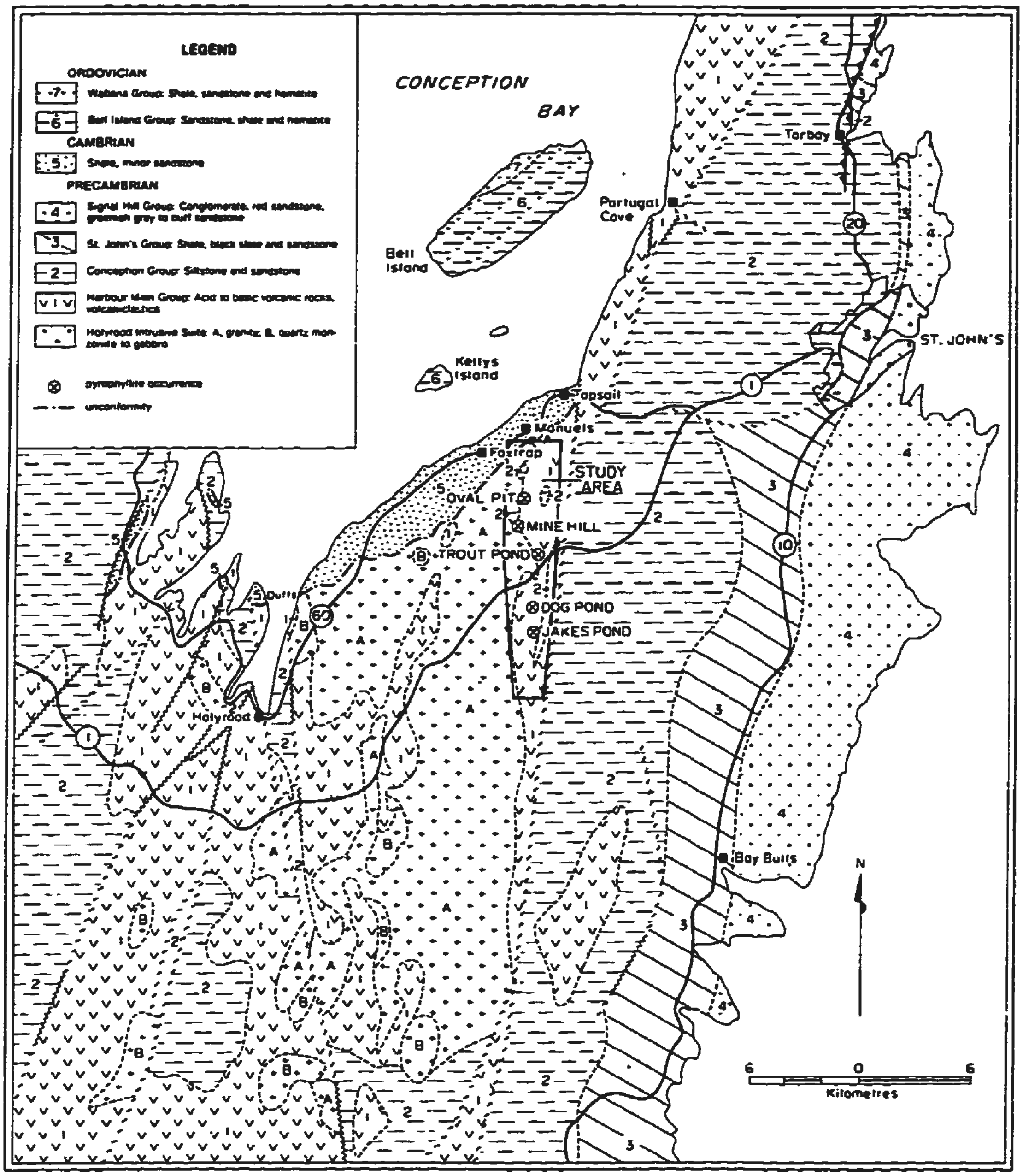


Figure 1. *Regional geology of the eastern Avalon Peninsula showing the location of the study area (after O'Driscoll* et al., *1988).*

Away from the fault valleys, much of the upland area is covered by glacial drift and peat bogs, however, bedrock exposure is excellent near the plateau margin. Thick overburden deposits appear to be confined to valleys and local topographic lows. Glacial erratics are rare on the plateau but are more abundant in valleys and on the lowland. Within the alteration zones the comparatively soft pyrophyllite lenses and the general outcrop area of pyrophyllite schists are fluted on a north-south axis indicating a dominantly northerly ice flow direction.

1.6 Previous Work

The geology of the high alumina alteration and its host rocks have been the subject of numerous investigations since the 1800's (see Table 1.1). The most comprehensive regional mapping to date was undertaken by the Geological Survey of Canada in the 1950's and 1960's (Rose, 1952, McCartney, 1967) to which major stratigraphic revisions have been made by Williams and King (1979), and King (1985, 1988, 1990, and personal communication 1993). The history of stratigraphic nomenclature outlined by King (1990) for the St.John's (1N/10) map area is equally applicable to the AHAB host and country rocks.

1.7 Regional Tectonic Setting of the Avalon Peninsula

The Avalon Peninsula lends its name to the more extensive Avalon tectono-stratigraphic zone or "Avalon Zone" (Williams, 1979) which is the most continuous litho-

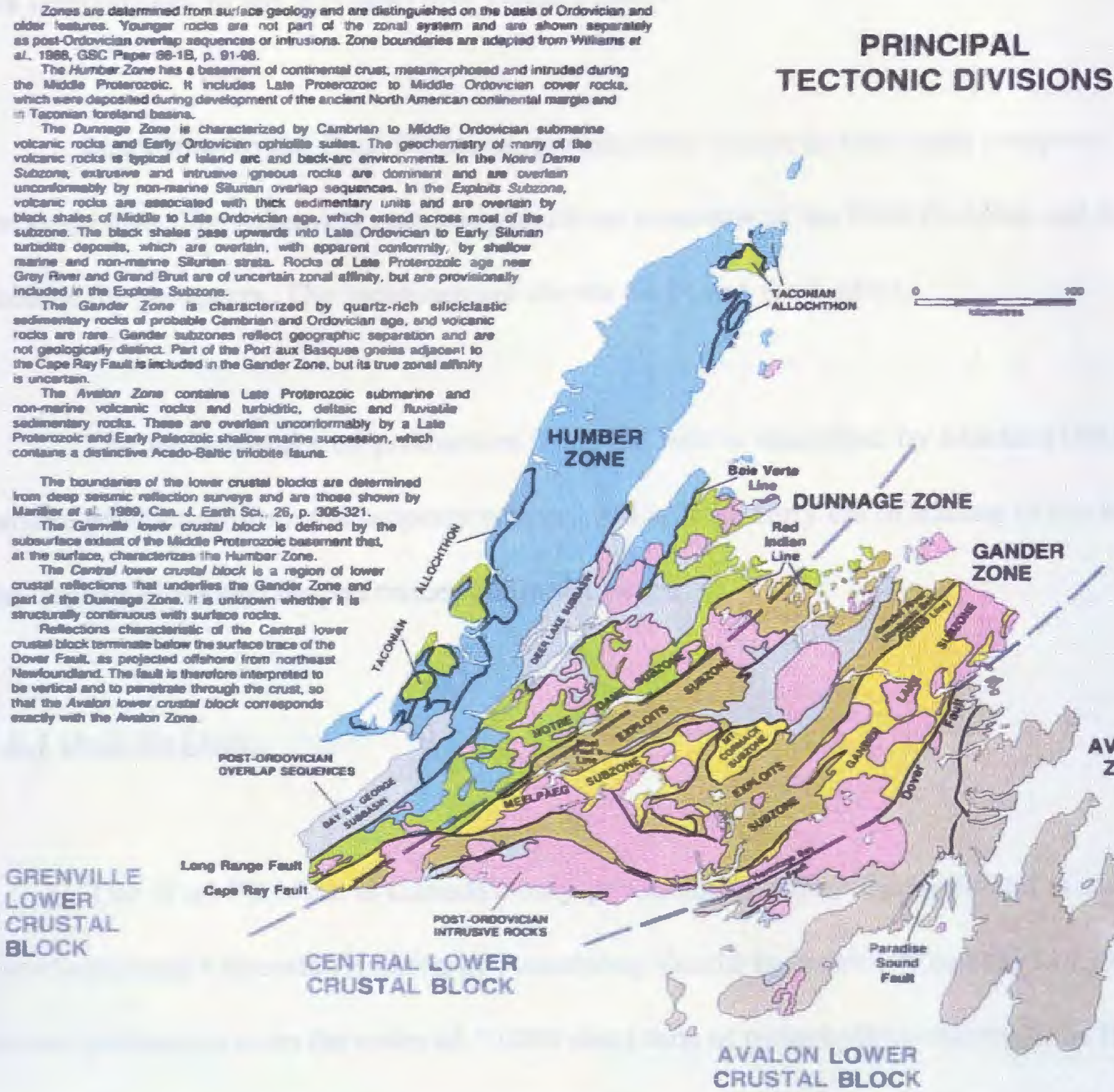
Table 1.1. *Previous geological studies of the eastern Avalon Peninsula and the Avalon High Alumina Belt*

Year	Investigator(s)	Major results/theme of study
1843	Jukes, J.B.	Regional geology, first stratigraphic column
1881	Murray, A. and Howley, J.P.	Geological map of Avalon Peninsula
1885	Howley, J.P.	Unpublished geological map of pyrophyllite schists in Foxtrap area
1889	Walcott, C.D.	Revison of stratigraphic nomenclature, Avalon Peninsula
1916	Buddington, A.F.	First geological description of altered rocks and regional geology. Noted proximity to Holyrood Granite and inferred the alteration was related to the granite
1936	Vhay, J.S.	Investigation of pyrophyllite occurrences and map of alteration zones
1952	Rose, E.R.	Geological report and mapping of Torbay mapsheet (1 inch=5 miles)
1958	Lee, B.W.	Mapping and tonnage estimation of the Mine Hill occurrence
1959	Gillespie, C.R.	Drilling report and tonnage estimate of Oval Pit Mine deposit
1963	Dawson, J.M.	Detailed geological investigation of the Topsails Foxtrap area
1967	McCartney, W.D.	Comprehensive geological report and map of the Avalon Peninsula
1970	Keats, H.F.	Geological, mineralogical and chemical investigation of the pyrophyllite deposits. Origin by fluids from the Holyrood Granite proposed.
1978	Papezik, V.S., Keats, H. and Vhatra, J.	Geological, mineralogical and chemical investigation of the pyrophyllite deposits. Origin by fluids from the Holyrood Granite proposed.
1978	Batten and Hume	Investigation of the pyrophyllite potential of the Trout Pond area.
1986	King, A.F.	Detailed mapping of the St. John's area including stratigraphic revision
1988	O'Driscoll, C.F., Collins, C.J. and Tuach, J.	Examination of the high-alteration. Proposed an epithermal style atleration system
1988	King, A.F.	Geological map of Avalon Peninsula with revised stratigraphic nomenclature
198?	Saunders,C., APEX	Gold exploration in the Dog Pond area.
1986	Lenters, M., ESSO	Geological/geochemical investigation following discovery of a gold anomaly in Topsail River. Mapping and sampling of bedrock exposures along AHAB.
1989	Hayes, J.P. and O'Driscoll, C.F.	1:12,500 map of alteration system
1994	Hayes, J.P.	Comprehensive multi-element geochemical database including Au and Ag data

tectonic zone of the Appalachian orogenic belt (Williams and Hatcher, 1983). This zone is characterized by a thick sequence of Late Precambrian volcanic and sedimentary rocks that flank the eastern edge of the North American craton. The Carolina Slate Belt of the south-eastern United States, which hosts high-alumina alteration systems similar to the AHAB (cf. Schmidt, 1985), is also part of the Avalon Zone.

Within the Newfoundland Appalachians, the Avalon Zone forms a broad belt, sub-parallel to the Gander tectonostratigraphic zone (Figure 1.2). The Avalon–Gander zone boundary is marked by the Dover Fault to the north and the Hermitage Bay Fault to the south (Blackwood and Kennedy, 1975; Blackwood and O'Driscoll, 1976). Both faults are cut by the Devonian Ackley Granite which provides a minimum age of juxtaposition. The low grade of metamorphism and strain of the Avalon Zone in comparison with older zones of the Newfoundland Appalachians were interpreted to indicate that the zone was outside the Appalachian orogenic cycle (Williams and Hatcher, 1983). Recent studies (O'Brien *et al.*, 1993; O'Brien *et al.*, 1985 in press and references therein) indicate the presence of Late Precambrian rocks at the western part of the Hermitage flexure. These rocks have been postulated to be the part of the Gondwana continent which faced the Iapetus Ocean (O'Brien *et al.*, 1993) and imply that at least part of the zone may have been involved with the Appalachian cycle. O'Brien *et al.* (1995) proposed that much of the Late Neoprotozoic sequences were dispersed in the late Proterozoic but were reamalgamated by Silurian orogenesis at the end of the Appalachian Orogeny.

Figure 1.2. *Geology of the Avalon Zone in Newfoundland (after Colman-Sadd* et al., *1992).*


PRINCIPAL
TECTONIC DIVISIONS
Zones are determined from surface geology and are distinguished on the basis of Ordovician and older features. Younger rocks are not part of the zonal system and are shown separately as post-Ordovician overlap sequences or intrusions. Zone boundaries are adapted from Williams et al., 1988, GSC Paper 88-1B, p. 91-98.
The Humber Zone has a basement of continental crust, metamorphosed and intruded during the Middle Proterozoic. It includes Late Proterozoic to Middle Ordovician cover rocks, which were deposited during development of the ancient North American continental margin and in Taconian foreland basins.
The Dunnage Zone is characterized by Cambrian to Middle Ordovician submarine volcanic rocks and Early Ordovician ophiolite suites. The geochemistry of many of the volcanic rocks is typical of island arc and back-arc environments. In the Notre Dame Subzone, extrusive and intrusive igneous rocks are dominant and are overlain unconformably by non-marine Silurian overlap sequences. In the Exploits Subzone, volcanic rocks are associated with thick sedimentary units and are overlain by black shales of Middle to Late Ordovician age, which extend across most of the subzone. The black shales pass upwards into Late Ordovician to Early Silurian turbidite deposits, which are overlain, with apparent conformity, by shallow marine and non-marine Silurian strata. Rocks of Late Proterozoic age near Grey River and Grand Bruit are of uncertain zonal affinity, but are provisionally included in the Exploits Subzone.
The Gander Zone is characterized by quartz-rich siliciclastic sedimentary rocks of probable Cambrian and Ordovician age, and volcanic rocks are rare. Gander subzones reflect geographic separation and are not geologically distinct. Part of the Port aux Basques gneiss adjacent to the Cape Ray Fault is included in the Gander Zone, but its true zonal affinity is uncertain.
The Avalon Zone contains Late Proterozoic submarine and non-marine volcanic rocks and turbiditic, deltaic and fluviatile sedimentary rocks. These are overlain unconformably by a Late Proterozoic and Early Paleozoic shallow marine succession, which contains a distinctive Acado-Baltic trilobite fauna.
The boundaries of the lower crustal blocks are determined from deep seismic reflection surveys and are those shown by Marillier et al., 1989, Can. J. Earth Sci., 26, p. 305-321.
The Grenville lower crustal block is defined by the subsurface extent of the Middle Proterozoic basement that, at the surface, characterizes the Humber Zone.
The Central lower crustal block is a region of lower crustal reflections that underlies the Gander Zone and part of the Dunnage Zone. It is unknown whether it is structurally continuous with surface rocks.
Reflections characteristic of the Central lower crustal block terminate below the surface trace of the Dover Fault, as projected offshore from northeast Newfoundland. The fault is therefore interpreted to be vertical and to penetrate through the crust, so that the Avalon lower crustal block corresponds exactly with the Avalon Zone.
TACONIAN ALLOCHTHON
0 100
kilometres
HUMBER ZONE
Baie Verte Line
DUNNAGE ZONE
Red Indian Line
GANDER ZONE
TACONIAN
ALLOCHTHON
DEER LAKE SUBBASIN
NOTRE DAME SUBZONE
EXPLOITS SUBZONE
MT. CORMACK SUBZONE
MEELPAEG SUBZONE
GANDER LAKE SUBZONE
Dover Fault
AVALON ZONE
POST-ORDOVICIAN OVERLAP SEQUENCES
BAY ST. GEORGE SUBBASIN
Long Range Fault
Cape Ray Fault
GRENVILLE LOWER CRUSTAL BLOCK
POST-ORDOVICIAN INTRUSIVE ROCKS
CENTRAL LOWER CRUSTAL BLOCK
Paradise Sound Fault
AVALON LOWER CRUSTAL BLOCK

1.8 Description of the Pyrophyllite Occurrences

In addition to the Oval Pit Mine, pyrophyllite occurs in four other prospects within the study area. The following sections provide an overview of the Oval Pit Mine and describe each of the prospects. The locations are shown on Map 1 (in folder).

The early history of production from the belt is described by Martin (1983). The earliest production from the property was in 1904 and the early era of mining of the belt saw the deposit close and reopen twice within six years.

1.8.1 Oval Pit Mine

The Oval Pit Mine is Canada's only producing pyrophyllite mine and is owned by Newfoundland Minerals Division of Armstrong World Industries (Canada) Ltd. Average annual production is on the order of 50,000 short tons of pyrophyllite-rich rock; in 1992 the value of production from the deposit was on the order of $750,000 US. Material from the Oval Pit is blended after crushing to a minimum grade of 18% Al_2O_3 and a maximum total alkali ($Na_2O + K_2O$) content of 0.65%, for use primarily in the production of ceramic tile.

1.8.2 Mine Hill

The Mine Hill Quarry was the site of the earliest production from the AHAB. It is located on the west side of Johnnies Pond and is accessible by a dirt road and cart trail from Country Path. Mine Hill itself is an elongate north trending ridge composed of variably altered felsic volcanic rocks. Old quarry workings on the east side of the hill provide excellent exposures of pyrophyllite lenses. This site was probably chosen as the steep sides of the hill provided easy access to small, but high-grade deposits which were amenable to mining by drill steel and block powder.

1.8.3 Trout Pond Prospect

The Trout Pond Prospect is located approximately 500 m north of the Trans-Canada Highway on the western side of a prominent north trending ridge which extends into the Oval Pit Mine area. The area was first investigated in the early 1900's through construction of two short drifts and numerous small test pits. All of the workings from this period are overgrown or filled with water and humus and none of the drifts were safely accessible during the present study. Renewed exploration on the site during the late 1970's included drilling and stripping, however, no significant pyrophyllite reserves were defined (Batten and Hume, 1978a, b).

1.8.4 Dog Pond–Jakes Gully Prospects

The Dog Pond and Jakes Gully prospects consist of a group of outcrops along an elongate ridge south of the Trans Canada Highway. The area is easily accessible by narrow roads and foot trails leading from the Pastureland Road. The prospects are separated by a marsh with no exposures, however, the regional alteration pattern indicates that these may be both part of the same zone (Map 1). This is supported by exploration work conducted on the two prospects and drilling in the intervening area indicates they are exposures of a continuous zone of pyrophyllitized volcanics (Batten and Hume, 1978a, b). The Dog Pond–Jakes Gully Prospect contain zones of high grade pyrophyllite mineralization with a reported tonnage of ~40,000 short tons of pyrophyllite (Keats, 1970).

CHAPTER 2

REGIONAL GEOLOGY OF THE AVALON PENINSULA

2.1 Introduction

The purpose of this chapter is to provide a regional framework for discussion of geological relationships in the study area. Some of the key problems of the geology of the Avalon Peninsula are discussed in this chapter as the field area contains several major units.

2.2 Avalonian Orogeny, Geochronology and Tectonism Within the Avalon Zone

Crustal deformation and granitoid intrusion within the Avalon Zone was the basis for the recognition and definition of the Avalonian Orogeny (Lilly, 1966) and this name has been subsequently applied to stratigraphic and tectonic events that span much of history of the zone (cf. O'Brien *et al.*, 1983; Cawood *et al.*, 1988). Since most of the Avalonian successions lack penetrative deformation, the evidence for orogenesis has historically come from unconformities, such as the basal Cambrian unconformity and the Lilly unconformity (Anderson *et al.*, 1975; King, 1990). The application of high-precision geochronological techniques has led to the recognition that periods of magmatism likely coincide with tectonic disturbances (O'Brien *et al.*, 1992b). Outside of the Avalon Peninsula detailed mapping and age dating has permitted recognition of significant Avalonian tectonic events that were previously unrecognized and indicate a complex history for much of the Avalon Zone (O'Brien *et al.*, 1996).

The earliest evidence of Avalonian orogenesis is the temporal gap between the Burin Group (763 +2.2/−1.8) and volcanic rocks of the Tickle Point Formation (681 ± 3 Ma) (O'Brien *et al.*, 1992b). The Burin Group has been correlated with the Bou Azzar ophiolite in Morocco (Krogh *et al.*, 1988) and the ophiolitic affinity of these rocks has been interpreted as indicating an extensional tectonic setting (cf. O'Brien *et al.*, 1983).

By far the most regionally extensive events are represented by volcanism in the Harbour Main, Love Cove and Connaigre Bay groups which occurred in the period 630–620 Ma (Krogh *et al.*, 1988; O'Brien *et al.*, 1992b). The 580–550 Ma period was also marked by volcanism and magmatism and examples of these rocks are found throughout the zone. On the Avalon Peninsula the Harbour Main Group contains rocks from both these periods, the implications of which are discussed in Section 1.9 (Geochronology).

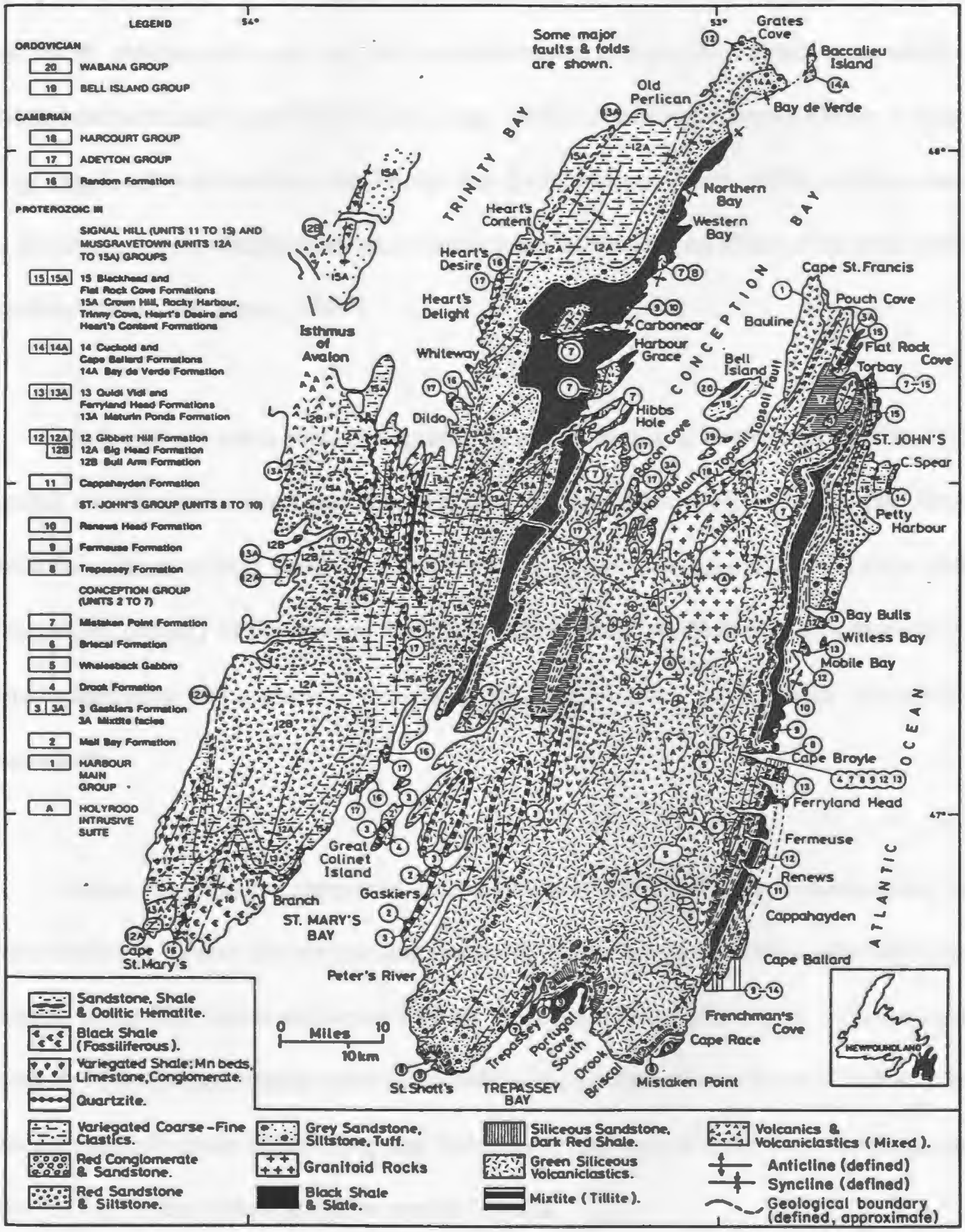
Assuming an age of 570 Ma for the basal Cambrian, the period of geological time represented by the Avalon Zone in Newfoundland is on the order of 190 Ma. The Avalon Peninsula itself, including the study area, has a Precambrian history extending over 60 Ma (from the oldest dated rocks). It is clear that the Avalon Zone has been the product of a complex orogenic history, yet the evidence on the Avalon Peninsula is obscured by interpretation. Unconformities such as those described by McCartney (1967), Rose (1948) or Dawson (1963) have been assigned little temporal significance by the original and are ignored by later workers. The following section will review the bedrock geology of the Avalon Peninsula and further detail the geological problems that are presented in the current data.

2.3 The Geology of the Avalon Peninsula

2.3.1 Introduction

The Avalon Peninsula is dominated by plutonic, sedimentary and volcanic rocks of Late Precambrian age unconformably overlain by a sequence of Cambrian to Ordovician sedimentary rocks (Figure 2.1). The bimodal volcanic rocks of the Harbour Main Group have been considered by previous workers to be the oldest rocks on the Avalon Peninsula (Rose, 1952; McCartney, 1967). The Harbour Main Group has been described as passing upwards either conformably (Rose, 1952; King, 1990) into the marine sedimentary rocks of the Conception Group or with a local angular unconformity separating the units (McCartney, 1967). The Conception Group is overlain conformably by deltaic sedimentary rocks of the St. John's Group which in turn are overlain conformably by alluvial sedimentary rocks of the Signal Hill Group (King, 1990). The Holyrood intrusive suite is described as either intruding the Harbour Main and Conception groups (Rose, 1952) or intruding only the Harbour Main Group (McCartney, 1967).

Figure 2.1. *Geology of the Avalon Peninsula (from King, 1990).*


LEGEND
ORDOVICIAN
20 WABANA GROUP
19 BELL ISLAND GROUP
CAMBRIAN
18 HARCOURT GROUP
17 ADEYTON GROUP
16 Random Formation
PROTEROZOIC III
SIGNAL HILL (UNITS 11 TO 15) AND MUSGRAVETOWN (UNITS 12A TO 15A) GROUPS
15 15A 15 Blackhead and Flat Rock Cove Formations 15A Crown Hill, Rocky Harbour, Trinny Cove, Heart's Desire and Heart's Content Formations
14 14A 14 Cuckold and Cape Ballard Formations 14A Bay de Verde Formation
13 13A 13 Quidi Vidi and Ferryland Head Formations 13A Maturin Ponds Formation
12 12A 12B 12 Gibbett Hill Formation 12A Big Head Formation 12B Bull Arm Formation
11 Cappahayden Formation
ST. JOHN'S GROUP (UNITS 8 TO 10)
10 Renews Head Formation
9 Fermeuse Formation
8 Trepassey Formation
CONCEPTION GROUP (UNITS 2 TO 7)
7 Mistaken Point Formation
6 Briscal Formation
5 Whalesback Gabbro
4 Drook Formation
3 3A 3 Gaskiers Formation 3A Mixtite facies
2 Mall Bay Formation
1 HARBOUR MAIN GROUP
A HOLYROOD INTRUSIVE SUITE
54°
53°
48°
47°
Some major faults & folds are shown.
Grates Cove
Baccalieu Island
Old Perlican
Bay de Verde
TRINITY BAY
Northern Bay
Western Bay
CONCEPTION BAY
Heart's Content
Heart's Desire
Heart's Delight
Cape St. Francis
Pouch Cove
Bauline
Carbonear
Harbour Grace
Flat Rock Cove
Torbay
Isthmus of Avalon
Whiteway
Bell Island
Dildo
Hibbs Hole
ST. JOHN'S
C. Spear
Petty Harbour
Bacon Cove
Harbour Main
Topsail Fault
Bay Bulls
Witless Bay
Mobile Bay
Cape Broyle
Ferryland Head
Fermeuse
Renews
Cappahayden
Cape Ballard
Great Colinet Island
Gaskiers
Branch
ST. MARY'S BAY
Cape St. Mary's
Peter's River
ATLANTIC OCEAN
Frenchman's Cove
Cape Race
Mistaken Point
St. Shott's
TREPASSEY BAY
Trepassey
Portugal Cove South
Drook
Briscal
NEWFOUNDLAND
0 Miles 10
10 km
Sandstone, Shale & Oolitic Hematite.
Black Shale (Fossiliferous).
Variegated Shale; Mn beds, Limestone, Conglomerate.
Quartzite.
Variegated Coarse-Fine Clastics.
Red Conglomerate & Sandstone.
Red Sandstone & Siltstone.
Grey Sandstone, Siltstone, Tuff.
Granitoid Rocks
Black Shale & Slate.
Siliceous Sandstone, Dark Red Shale.
Green Siliceous Volcaniclastics.
Mixtite (Tillite).
Volcanics & Volcaniclastics (Mixed).
Anticline (defined)
Syncline (defined)
Geological boundary (defined, approximate)

The western part of the Avalon Peninsula is underlain by bimodal volcanic and sedimentary rocks of the Musgravetown Group (McCartney, 1967; King, 1988). The lowermost sedimentary unit of the Musgravetown Group (Big Head Formation) is interbedded with the Signal Hill Group (King, 1988). The Musgravetown Group is folded along a regional synclinal axis, the Trinity Bay Synclinorium (King, 1988) and the core of the syncline contains Cambrian strata, indicating a relatively young (Silurian or later) period of deformation (McCartney, 1967).

No basement rocks were recognized by earlier workers, however, Papezik (1973) reported detrital garnet and muscovite within sedimentary rocks of the Signal Hill Group which he inferred to have been derived from a sialic basement. Essentially the view of the Precambrian geology of the Avalon Peninsula held by most workers is that of more or less contemporaneous deposition of volcanic and sedimentary rocks with synvolcanic magmatism.

Despite the apparent simplicity of the geology it has fostered much controversy due to the conflicting observations regarding the geological setting and contact relationships of bedrock units. The major problems include the chemical affinity of the volcanic rocks (Harbour Main Group), stratigraphic relationships and genetic relationships of volcanic and plutonic rocks (Harbour Main Group and Holyrood Intrusive Suite) and also the relationship between the Harbour Main and Conception Groups.

2.3.2 The Harbour Main Group Subdivision and Chemical Affinity

The Harbour Main Group (Rose, 1952) consists of a mixed felsic–mafic volcanic sequence with associated sedimentary rocks. Papezik (1974) made the first subdivision of the Harbour Main Group and considered it to be disposed in three distinct blocks. These blocks were termed the Eastern, Central and Western blocks. These subdivisions have no clear stratigraphic significance. The Eastern Block included all those rocks exposed north of Topsail which were considered to have been deposited in a subaqueous (marine) setting given the presence of pillowed flows and well sorted sandstones. The Central Block, as described by Papezik (op. cit.) consists of mainly flow-banded rhyolite exposed along the eastern margin of the Holyrood Intrusive Suite. The Western block comprises the Colliers Peninsula and the immediate area which are underlain by ignimbritic rhyolitic rocks and associated subaerial basalt flows (Papezik, 1974).

King (1990) formally subdivided the Harbour Main Group in the St. John's Peninsula area into three formations, the St. Phillips, Princes Lookout and Portugal Cove Formations which are composed of volcaniclastic rocks, basalt flows and interbedded sedimentary and volcanic rocks, respectively (King, 1990). These units and rhyodacitic rocks forming domes exposed near Cape St. Francis correspond to Papezik's (1974) Eastern Block. The rhyolitic ash flow tuffs (Johnnies Pond Formation, this work) near the eastern margin of the Holyrood Intrusive Suite correspond to the Central Block. The Western Block crops out west of the

Holyrood Horst and according to the division of Papezik (1974) does not crop out within the study area.

Papezik (1970), studying the Western and Eastern Block, reported that the Harbour Main Group had a mildly alkaline geochemical affinity and was also distinctly sodic. The alkaline chemistry was taken to indicate that the rocks were erupted in an extensional setting analogous to the Basin and Range province. The distinct sodic compositions were obtained on samples of the rhyodacites near Cape St. Francis and appear peculiar to this rock type in the eastern Avalon. Hughes (1970) and Hughes and Bruckner (1971) considered the Harbour Main and Conception Group to have formed as part of an island arc-complex which shed detritus into an adjacent basin forming the Conception Group. Hughes (1973) disputed Papezik's (1970) interpretation based upon the petrological character of the volcanic rocks. He noted that the volcanic rocks contained albite phenocrysts, and that epidote was not uncommon as an accessory mineral. He reasoned, citing a paucity of plagioclase compositions less than An_{20} in similar volcanic rocks elsewhere, that the Harbour Main Group compositions were secondary, resulting from the low grade metamorphic breakdown of more calcic plagioclase to albite. Hughes (1972) proposed that volcanic rocks throughout the Avalon Peninsula were part of a spilite–keratophyre province and as such their major element chemistry is difficult to interpret with certainty.

It was clear from the early stages of mapping during this project that the units these authors compared had no equivalents in the study area. Furthermore, the units that Hughes compared actually represented a diversity of rock types, as they included the rhyodacites of Cape St. Francis (Harbour Main Group) being compared on the gross sense with rhyolitic ash-flow tuffs of the Bull Arm Formation (Hayes, 1985). In addition to recognizing that these rocks had no equivalents in the study area, mapping also indicated relationships which help establish that the rhyolites of the Eastern Block, are clearly younger than the rocks of either the Central or Western Blocks (see section 2.4).

2.3.3 Relationship of Conception and Harbour Main Groups

Volcanic rocks of the Harbour Main Group underlie sedimentary rocks of the Conception Group. The contact has been described as an unconformity (McCartney, 1967) in the Holyrood area and also as essentially conformable (Rose, 1952; Dawson, 1963). McCartney (1967) mapped the folded nature of the unconformity and described a moderately dipping sequence of interbedded volcanic and volcaniclastic rocks which strike into folded Conception Group rocks over a distance of less than 250 m. Locally the unconformity is exposed. Rose (1952) indicated that the Harbour Main volcanic rocks were deformed prior to the deposition of the Conception Group. Nevertheless he placed little temporal significance on the unconformity and concluded that the sequences were practically conformable.

Dawson (1963) mapped the Harbour Main Group and Conception Groups along the eastern margin of the Holyrood intrusive suite, including the present study area. He supported Rose's (1952) earlier contention that green-matrix conglomerates and fine greywackes interbedded in both units suggest that sedimentary rocks within the Harbour Main Group are in part equivalent to the Conception Group. Dawson (1963) subsequently included some of these rocks within the Conception Group and where an unconformity between these and some Harbour Main Group volcanic rocks[1] had been mapped, they were assigned to a new unit called the "Black Mountain Formation" (Dawson, 1963). Dawson (1963) postulated that the depositional environment of the Conception Group was partly submarine and partly subaerial and deposition of volcanic and sedimentary rocks of the Harbour Main Group was contemporaneous and transitional with deposition of "cleaner" Conception Group sedimentary rocks "in a large slowly subsiding basin" to the east (Dawson, 1963). King (1990), drawing comparisons between sedimentary rocks within the Portugal Cove Formation and the lower part of the Conception Group, inferred, like Dawson, that deposition was penecontemporaneous.

2.3.4 Holyrood Intrusive Suite and its Relationship to the Harbour Main/Conception Groups

The relationship of the Conception Group and Holyrood Intrusive Suite was not established with certainty by earlier workers. Rose (1952) postulated that there was a "pre-Conception Holyrood" and a "post-Conception Holyrood" to account for what he had suggested was locally an intrusive relationship. He appealed to an intrusive relationship

[1] This earned these rocks the informal designation of "Misconception".

largely to explain the local proximity of the Holyrood Intrusive Suite and the Conception Group. Dawson (1963) and McCartney (1967, 1969) did not indicate a clear intrusive relationship between the Conception Group and the Holyrood Intrusive Suite. Holyrood-like granite clasts are found in several localities in units considered to be part of the Conception Group (McCartney, 1967). Hughes and Brückner (1971) proposed that these units were penecontemporaneous and represented intrusive, extrusive and sedimentary facies of a volcanic island complex. The available geochronological data (section 2.4) and the work of King (1990, and references therein) refutes much of the interpretations offered on the relationship between the units.

2.3.5 Precambrian Sedimentary Rocks

Precambrian sedimentary rocks of the eastern Avalon Peninsula contain facies deposited in submarine to subaerial fluvial environments and are disposed in three main units, the Conception, St. John's and Signal Hill Groups. Detailed descriptions of individual formations may be found elsewhere (Williams and King, 1979; King, 1986, 1988, 1990). The following descriptions are adapted from these sources:

The Conception Group (Rose, 1952) is the lowermost unit within the sequence and consists of marine turbiditic siliceous siltstone and sandstones with locally interbedded coarse volcaniclastic rocks. The Gaskiers Formation near the base of the Conception Group records a Precambrian glacial event. Near the top of the group, the Mistaken Point Formation contains Precambrian metazoan fossils preserved beneath a tuff layer. The intermittent deposition of tuff throughout the sequence has been interpreted to represent a distal airfall facies related to ongoing volcanic activity to the west (King, 1979).

The St. John's Group (Williams and King, 1979) conformably overlies the Conception Group. It is composed of sandstone and shale with minor tuff within the lowermost formation. It appears to represent a period of transition from marine turbidite facies through to onset of the deltaic deposits of the Signal Hill Group (King, 1986).

The Signal Hill Group (Williams and King, 1979) consists of a sequence of thick-bedded sandstone with local siltstone, tuff and conglomerate that is overlain by a variety of generally coarser-grained siliciclastic sedimentary rocks. The basal unit (Gibbett Hill Formation) is interpreted to represent the distal delta-basinal setting that was eventually overlain by prograding coarser-grained delta plain to proximal alluvial fan sedimentation from a source area to the present northeast. The Lilly Unconformity represents a period of uplift and deformation late in this depositional cycle (King, 1986) and is marked by folded rocks of the Conception Group overlain by the Piccos Brook Member of Flatrock Cove Formation (Signal Hill Group) (King, 1979).

2.3.6 Cambrian and Later Evolution

Precambrian strata of the Avalon Zone are unconformably overlain by Cambrian and Ordovician sedimentary rocks. On the Avalon Peninsula, the unconformity cuts through the entire Precambrian stratigraphic sequence. In the western Avalon Peninsula Eocambrian quartzite (Random Formation) rests unconformably upon the Musgravetown Group and is in turn unconformably overlain by Cambrian strata (McCartney, 1967). In the Conception Bay area, the Random Formation is absent and basal Cambrian sedimentary rocks lie directly upon the Harbour Main and Conception Groups and the Holyrood intrusive suite (Rose, 1952; McCartney, 1967).

The absence of strata younger than Ordovician on the Avalon Peninsula implies that it has been an uplifted area since that time. Evidence from offshore investigations indicate that Silurian strata and a Devonian unconformity are present in the near offshore (King, 1988). Post-Cambrian movement on the Topsail fault evident at Topsail Head, may be in part or wholly related to the development of this unconformity. The offshore Palaeozoic sequences are bounded to the west by a linear feature striking subparallel to the coast which might be a result of the Precambrian structural grain.The Avalon Peninsula was affected by Triassic rifting along the Atlantic margin as demonstrated by the easterly trending Trans Avalon Dyke (Hodych and Hayatsu, 1980). It is possible that some structures on the Avalon Peninsula were active during tectonism associated with this rifting event, but such relationships are difficult to demonstrate. The dyke has a remarkably linear positive aeromagnetic anomaly along most of its length. The anomaly signature is perturbed as it crosses the Topsail Fault and this might actually provide evidence of an offset of the dyke, indicating that the fault has had post-Triassic displacements.

2.4 Geochronology

Geochronological studies of the Harbour Main Group volcanic rocks and the Holyrood Intrusive Suite have been conducted using the Rb/Sr and U/Pb isotopic systems. The Rb/Sr method was used primarily on the Avalon Peninsula before the 1970's and exclusively on whole rock specimens. Table 2.1 below provides a list of geochronological data from major units which crop out within the study area. These data indicate that the Harbour Main Group contains rocks with widely differing ages. Hughes (1972) had earlier postulated that the group was composite drawing analogy with the Basin and Range to explain the range in lithologies and this model was also proposed by Krogh *et al.* (1988) to explain the similar time span of volcanic activity in the Harbour Main, and its western equivalent the Love Cove Group as represented by U/Pb ages on various parts of these groups. Despite the gap in ages between the Holyrood Intrusive South and the rhyodacite of the Eastern Block of the Harbour Main Group of volcanic rocks the authors (Krogh *et al.*, 1988) did not consider the break represented any distinct tectonic event despite the general acknowledgment of regional workers that the Holyrood intruded the Harbour Main Group (Rose, 1941; McCartney, 1961). The available geochronological data is consistent with the presence of a significant unconformity in the study area between the Holyrood Intrusive

Suite and parts of the volcanic sequences presently mapped as the Harbour Main Group. Detailed mapping of these units (see Chapters 3 and 4) has resolved geological relationships and permits a clearer interpretation of the geochronological data.

Table 2.1. *Summary of geochronology data for the eastern Avalon Peninsula*

Unit/Description and Age (Ma)	Source
Harbour Main Group	
552 ± 29 Rb/Sr	Krogh et al., 1988 (recalculated from Fairbairn et al. 1966)
Ignimbrite (Western block)	
606 +3.7/−2.9 U/Pb	Krogh et al., 1988
Rhyolite (Western block)	
622.6 +3.2/−2.0 U/Pb	Krogh et al., 1988
Porphyry (Central block)	
631 ± 2 U/Pb	Krogh et al., 1988
Rhyodacite (Eastern block)	
585.9 +3.4/−2.4 U/Pb	Krogh et al., 1988
Holyrood Intrusive Suite	
590 ± 11 Rb/Sr	Krogh et al., 1988 (recalculated from Fairbairn et al., 1966)
620.5 +2.1/−1.8 U/Pb	Krogh et al., 1988
Conception Group	
563 ± 3 U/Pb	Benus et al., 1988

CHAPTER 3

BEDROCK GEOLOGY OF THE STUDY AREA

3.1 Introduction

The study area contains Precambrian volcanic, sedimentary and intrusive rocks unconformably overlain by Cambrian strata. In the course of mapping, bedrock units and unconformities were recognized that indicated the need for revision of the regional stratigraphy. The field area contains six major units, some of which can be further subdivided. Two of these are new units and were previously included in the Holyrood Intrusive Suite and Harbour Main Group. Detailed mapping also permits correlation of the Harbour Main Group and Conception Group in the study area with the stratigraphy of the units in the St. John's area where these units have been subdivided to the bed and member level (King, 1990). The aim of this chapter is to describe the bedrock units and their stratigraphic and intrusive relationships. A revised stratigraphy for the study area is presented based upon the new field observations. The data for this chapter are based upon detailed mapping of approximately 350 bedrock exposures supplemented with petrographic study.

3.2 General Stratigraphy and Relationships in the Field Area

The oldest bedrock unit in the field area is the Foxtrap Diorite which consists of foliated dioritic to tonalitic intrusive rocks containing conspicuous amphibolite xenoliths.

These rocks have been historically assigned to the Holyrood Intrusive Suite (McCartney, 1967; King, 1988). The Johnnies Pond Formation is also a new unit and it is composed of rhyolitic ash-flow tuffs and related rocks which had been considered to be part of the Harbour Main Group (King, 1988). Its contact relationship with the Johnnies Pond Formation is unknown, however both units are intruded by the Holyrood Intrusive Suite. The Johnnies Pond Formation is separated from the Harbour Main Group and Conception Groups by an unconformity.

The Harbour Main Group, passes upwards conformably into the Conception Group. Small intrusions of quartz porphry and diorite intrude the Harbour Main Group and are likely coeval with this unit. The Cambrian Harcourt Group sedimentary rocks crop out in the northern part of the study area and overly all older strata with unconformity. Figure 3.1 is a general geological map of the field area, showing the locations discussed in the text. Map 1 (in pocket) provides greater detail on unit boundaries and structural information. Table 3.1 is the Table of Formations for the field area; it indicates the geological relations as inferred from the present study.

3.3 The Foxtrap Diorite

3.3.1 Description

The Foxtrap Diorite (informal) is a unit of intermediate intrusive rocks containing abundant amphibolitic xenoliths that crops out in the western part of the map area. The

Figure 3.1. *Geological map of the Avalon High Alumina Belt.*

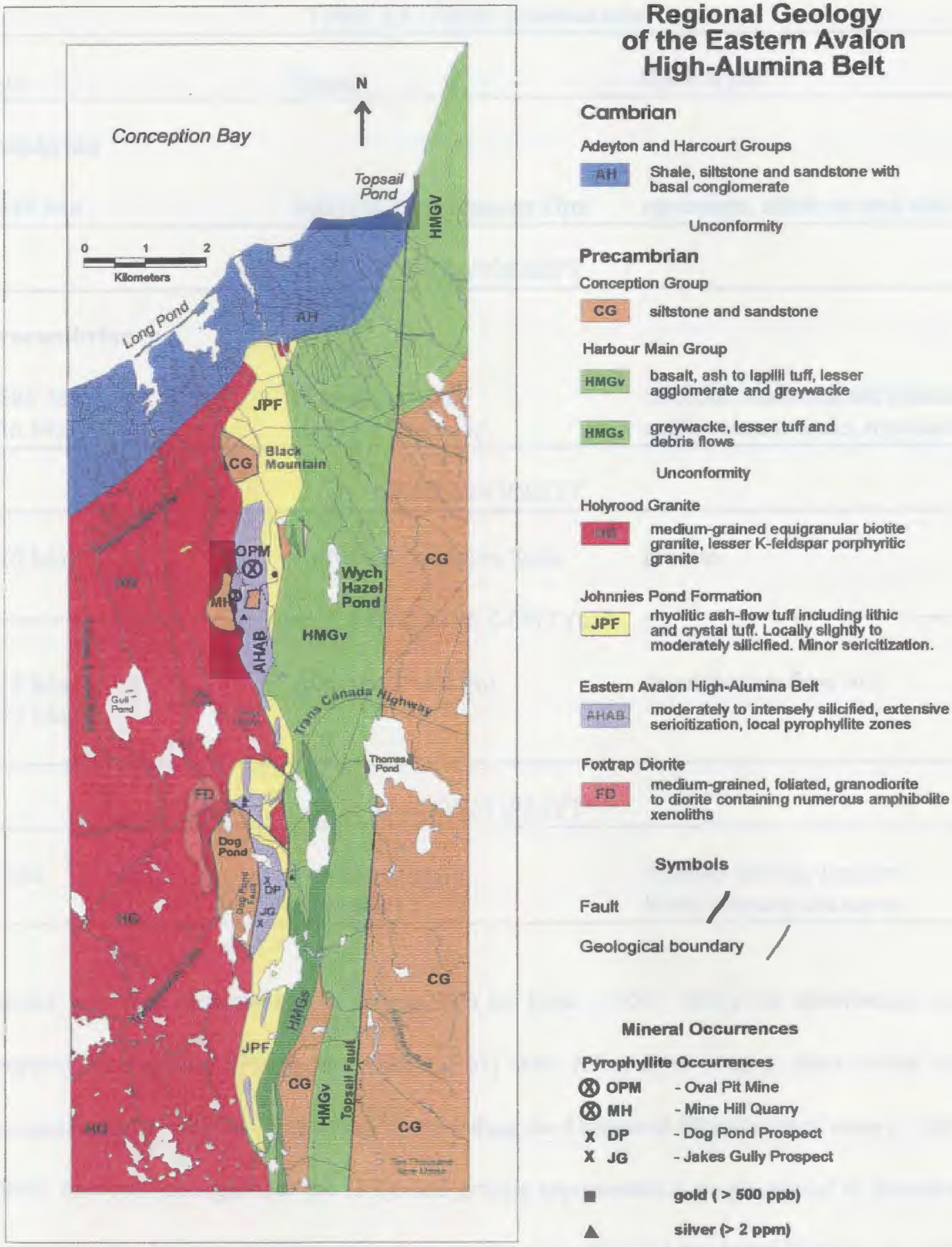

Regional Geology of the Eastern Avalon High-Alumina Belt
Cambrian
Adeyton and Harcourt Groups
AH
Shale, siltstone and sandstone with basal conglomerate
Unconformity
Precambrian
Conception Group
CG
siltstone and sandstone
Harbour Main Group
HMGv
basalt, ash to lapilli tuff, lesser agglomerate and greywacke
HMGs
greywacke, lesser tuff and debris flows
Unconformity
Holyrood Granite
HG
medium-grained equigranular biotite granite, lesser K-feldspar porphyritic granite
Johnnies Pond Formation
JPF
rhyolitic ash-flow tuff including lithic and crystal tuff. Locally slightly to moderately silicified. Minor sericitization.
Eastern Avalon High-Alumina Belt
AHAB
moderately to intensely silicified, extensive serioitization, local pyrophyllite zones
Foxtrap Diorite
FD
medium-grained, foliated, granodiorite to diorite containing numerous amphibolite xenoliths
Symbols
Fault
Geological boundary
Mineral Occurrences
Pyrophyllite Occurrences
OPM - Oval Pit Mine
MH - Mine Hill Quarry
X DP - Dog Pond Prospect
X JG - Jakes Gully Prospect
gold (> 500 ppb)
silver (> 2 ppm)
Conception Bay
N
Topsail Pond
0 1 2
Kilometers
Long Pond
AH
HMGV
JPF
Black Mountain
CG
OPM
MH
HG
Wych Hazel Pond
HMGv
AHAB
Gull Pond
Trans Canada Highway
Thomas Pond
FD
Dog Pond
DP
JG
HMGs
JPF
CG
HMGv
Topsail Fault

Table 3.1. *Table of formations*

Age	Group	Rock types
Cambrian		
>570 Ma	Adeyton and Harcourt Gps.	sandstone, siltstone and shale
	UNCONFORMITY	
Precambrian		
>586 Ma	Conception Gp.	siliceous, sandstone and siltstone
586 Ma	Harbour Main Gp.	mafic volcanic rocks, rhyodacite
	UNCONFORMITY	
620 Ma	Holyrood Intrusive Suite	granite
	INTRUSIVE CONTACT	
622 Ma 630 Ma ?	Johnnies Pond Fm.	rhyolitic ash flow tuff
	UNCONFORMITY	
? 680	Foxtrap Diorite Basement	foliated diorite, tonalite lower contact unknown

diorite was first described as a metagabbro by Rose (1950, 1952). Its distribution was mapped by Dawson (1963) and Gale (1963) who referred to it as a meta-diorite and recognized it as a distinct unit which is older than the Holyrood Granite. McCartney (1967, 1969), however, thought that the Holyrood granite represented a single period of intrusion. Consequently he had inferred that these rocks were formed by hybridization of mafic volcanic rocks and the xenoliths were formed by conversion of "basaltic roof pendants"

(McCartney, 1969, p. 122), presumably when the unit intruded Harbour Main basalts. Main basalts. Dawson's original recognition of the unit as being older than the Holyrood Intrusive Suite appears to have been ignored by subsequent investigators. The boundaries of the unit were mapped in detail by Gale (1963).

The unit is best exposed near the intersection of the Foxtrap Access Road and the Trans Canada Highway where outcrops consist of a variety of intermediate intrusive rocks of which diorite is most common. The diorite is a grey to white and black, massive to slightly foliated, medium grained rock containing variable amounts of hornblende and biotite. There is variation in the modal abundance of mafic minerals and in some places the rock approaches tonalite in composition. Biotite-rich (3 to 8%) phases have a weakly to moderately developed foliation and elongate xenoliths of hornblende diorite and amphibolite occur within the deformed diorite. The xenoliths are elongated parallel to the foliation. Dawson (1963) described the typical rock from this unit as mostly hornblende and plagioclase (An_{43-46}) with 3 to 4% biotite typically altered to chlorite.

3.3.2 Age Relations of the Foxtrap Diorite

The presence of a foliation and the elongation and flattening of the amphibolite xenoliths within the unit indicate ductile deformation (McClay, 1987). Such ductile fabrics are not exhibited by other units in the study area. Rhyolitic ash-flow tuffs of the Johnnies Pond Formation and the Holyrood Intrusive Suite in proximity to the Foxtrap Diorite exhibit dominantly brittle deformation. Ductile fabrics such as schistosity are only manifested in alteration zones. Both the Johnnies Pond Formation and the Foxtrap Diorite are intruded by massive granite of the Holyrood Intrusive Suite. These structural and intrusive relationships indicate that the Foxtrap Diorite is older than the Johnnies Pond Formation, which is clearly the oldest stratiform unit in the study area. Intrusive rocks older than 620 Ma have been identified in the Avalon Zone in Newfoundland, within the 685–670 Ma age range (O'Brien *et al.*, 1996). It is possible that these rocks are related to those units which are also similarily deformed having penetrative ductile fabric development (O'Brien *et al.*, 1996). No units older than the diorite are kown in the study area. This unit is probably part of a basement terrane to the Avalon rocks.

3.4 The Johnnies Pond Formation

3.4.1 Definition of the Johnnies Pond Formation

The Johnnies Pond Formation is composed of a sequence of rhyolitic crystal and lithic tuffs, with local intercalations of coarse volcaniclastic debris flows and fluvial conglomerate. It is exposed along a north trending ridge that extends from the Thousand Acre Marsh to the Conception Bay Highway (Map 1) and has an outcrop area bounded in the west by the Holyrood Intrusive Suite and to the east and south by mafic volcanic rocks of the Harbour Main Group and siliciclastic rocks of the Conception Group. The Johnnies Pond Formation strikes north to Conception Bay where it is overlain unconformably by Cambrian strata. The unit is named after Johnnies Pond which is located in the central part of the belt near the Oval Pit Mine. The formation is well exposed in the immediate area and most contact relationships can be observed despite the extensive alteration. The alteration is useful in determining the relationships of the formation to younger stratigraphic units.

The rocks which are recognized as the Johnnies Pond Formation have been removed from the Harbour Main Group. Potentially the entire sequence of Harbour Main Group rocks of the eastern block may have to be reassigned to a different group. This difficulty arises since the Harbour Main Group of the type area is intruded by the Holyrood Intrusive Suite (S. O'Brien, personal communication, 1995). Since the scope of the present study does not extend into extensive stratigraphic revision, the Johnnies Pond Formation is removed from the group. This seems the most prudent adjustment since the actual geochronological age of the unit is not known. It is expected, however, that the Johnnies Pond Formation is more closely allied with ash-flow rocks of the central Avalon Peninsula. The available geochronological data (Table 3.1) indicate that the Johnnies Pond Formation is actually older than much of the felsic volcanic rocks within the type area of the Harbour Main Group and on this basis it probably represents a distinct magmatic event.

3.4.2 Contact and Age Relationships

The base of the Johnnies Pond Formation is not exposed. No contact between the Johnnies Pond Formation and the Foxtrap Diorite was observed in the field area. Given the deformation within the diorite, and the absence of this style of deformation within the Johnnies Pond it is likely that an angular unconformity separates these units.

The Johnnies Pond Formation is intruded by the Holyrood Intrusive Suite. Xenoliths of rhyolitic ash flow tuffs typical of the formation occur in the granite near all contacts between the units. These xenoliths are progressively more altered near the high-alumina zone. An outcrop of granite on Country Path near the Oval Pit Mine contains xenoliths of rhyolite with hematite veins and a xenolith of silicified, brittly fractured and sericitized rhyolite. Roof pendants of the Johnnies Pond Formation occur within the Holyrood Intrusive Suite at White Mountain and are clearly intruded and recrystallized by the granite. On Mine Hill, silicified rhyolite is intruded by the Holyrood Intrusive Suite (Map 1).

A Precambrian unconformity is exposed in the Oval Pit Mine where a pronounced angular relationship between the Johnnies Pond Formation and the Conception Group is evident (see also Dawson, 1963). Highly altered and brittly fractured rhyolite is overlain by a boulder conglomerate derived from the alteration zone. The conglomerate passes conformably upwards into sedimentary rocks of the Conception Group (see Section 3.7). This unconformity is of regional significance and is named the Oval Pit Unconformity.

The Johnnies Pond Formation is everywhere in fault contact with the Harbour Main Group and consequently the original relationship appears nowhere to be preserved. The contact is difficult to trace in many areas due to poor exposure but the original contact relationship was clearly an unconformity since the Harbour Main Group and the Conception Group are in gradational contact, outside of the study area and also conformable in the southeast part of the map area, therefore the Johnnies Pond Formation and the Harbour Main Group must also be separated by the Oval Pit Unconformity.

3.4.3 Description of Rock Types

The Johnnies Pond Formation consists primarily of intensely welded rhyolitic and lithic ash-flow tuffs with lesser breccias and fluvial conglomerates. Poor exposure, alteration, faulting and the general discontinuous nature of the volcanic facies preclude formal stratigraphic subdivision of the Johnnies Pond Formation. The unit is, however, subdivided by rock type on Map 1. The main rock types are crystal tuff, lithic tuff and epiclastic rocks (reworked tuffs and conglomerates). Most of the rock types recognized in the Johnnies Pond Formation have counterparts in better exposed and more intact ash-flow successions. These lithologies are known to occur in multiple depositional cycles within the caldera environment and consequently these facies are likely diachronous within the unit and do not warrant recognition at the stratigraphic level. Much of the Johnnies Pond Formation is pervasively altered and primary features are obscured.

3.4.3.1 Rhyolitic Crystal Tuffs – Field Description and Relationships

Rhyolitic crystal tuffs are the most abundant rock type of the Johnnies Pond Formation. Rhyolitic crystal tuffs of the Johnnies Pond Formation are typically red to purple and grey, very fine-grained and siliceous. Relict pumice and shards are difficult to identify with certainty since most primary matrix textures and depositional features have undergone extensive devitrification and recrystallization. Flow-banding, lithophysal zones and local primary layering, marked by interbedded crystal and lithic tuffs, indicate that the bulk of the sequence probably originated from ash-flow tuff style volcanism (cf. Smith, 1960).

Lithophysal zones are often the only relict volcanic features recognizable in intensely altered rocks and outcrops of lithophysal rhyolite occur along most of the belt within recrystallized crystal tuffs, and locally defining crude north-trending zones. The zones are elongate horizons and locally continuous over 30 m in strike length. Lithophysal zones usually contain 40 to 80% lithophysae with a mean size of approximately 2 to 3 cm, set in a rhyolitic matrix. Some zones, are however, characterized by sparse (10 to 15%) concentrations of 4 to 5 cm lithophysae and these seem to be of more limited extent. Individual lithophysae appear in cross-section as circular to oval structures with an internal star shaped-region usually filled with cryptocrystalline quartz. In thin section the quartz appears as a fine grained mass of randomly oriented irregular crystals with variable extinction angles. The fine quartz is probably from the recrystallization of chalcedony as chalcedonic banding is clearly preserved in one lithophysae. Lithophysae are typically infilled with chalcedony in ash-flow tuff sequences (see Smith, 1960).[2]

The crystal tuffs have a variable crystal content and they comprise 1–2 to 10% of the rock. Bedding is recognizable in sequences containing crystal tuff. In these areas the tuffs appear to be medium to thick bedded (bedding thickness nomenclature follows Ingram, 1954, in King 1990). Grading is difficult to determine, primarily due to the recrystallization. Lithic fragments, mainly rhyolitic in composition, are found scattered in many exposures. The fragments are typically less than .5 cm in size and are red to purple coloured and angular.

Flow banding and crude tuffaceous layering are ubiquitous with variation in the scale and intensity of welding. Some of the intensely welded tuffs are flow-banded, and have wildly contorted layering perhaps indicative of early rheoignimbrite behaviour. Less welded rocks have a cm-scale colour banding, probably marking original ash-flow layering and bedding.

3.4.3.2 Petrography

In thin section the crystal tuffs generally consist of various proportions of feldspar and quartz crystals, .5 to 3 mm in length, set in a very fine-grained, felty matrix of quartz and

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[2] The references to "spherulites" in many of the previous geological descriptions of the area are actually misidentified lithophysae.

feldspar. Some of the feldspar grains are simply twinned. Locally the quartz grains are broken and partially recrystallized. The grains are generally sub- to euhedral and are commonly broken or cracked. Locally the groundmass is fluxioned, indicating some flow has taken place, yet the presence of relict pumice in some samples indicates the rocks are fragmental. The accessory minerals in the rhyolites consist of chlorite, sphene and zircon. Secondary textural features are developed in the rhyolites due to vapour phase activity and crystallization. The most dominant secondary feature noted are the lithophysae. Within the rhyolites, however, the spherulites are also developed, which locally define bands in thin section. These features indicate that the Johnnies Pond Formation likely underwent primary compaction and welding associated with the cryptic cycle by comparison to other ash-flow tuffs (Smith, 1960).

3.4.3.3 Lithic Tuffs

Lithic tuffs are green-grey and white weathering. They typically contain 10 to 40% lithic fragments in addition to abundant crystal material, set in a very fine-grained matrix. These were originally fragmental rocks but have been well indurated by welding and matrix recrystallization. The matrix of these rocks closely resembles the felsic crystal tuffs. Bedding features such as grading within the lithic tuffs are rarely evident, and probably indicates that many of these are also mass flow deposits, however, locally they are interbedded with welded lithic-poor crystal and ash tuffs. Lithic fragments are chiefly composed of rhyolite although some mafic fragments composed of plagioclase and iron oxides also occur.

3.4.4 Coarse Breccias

Coarse breccias composed of 0.20 cm to 0.5 m clast supported angular blocks with a coarse sand to pebble matrix form a minor component of the Johnnies Pond Formation. Some of the rocks included in this subdivision were mapped as autobrecciated rhyolite by earlier workers since they contain angular flow-banded clasts giving the appearance of autobreccia. However, there is also a population of massive, subangular clasts in these exposures indicating that these units represent reworking of a variety of volcanic rocks. These rocks are extremely thick bedded, unsorted and they share these features with mass flow deposits (cf. Smith, 1986). These facies were possibly fluidized by surface water and originating near topographic features in the volcanic environment such as the caldera margins. Most of the material in these rocks appears to have been glassy volcanic detritus. Devitrification has served to fuse the clasts and obscuring many of the primary features.

3.4.5 Conglomerate

The only example of extensively reworked sedimentary rocks in the Johnnies Pond Formation are known from a single outcrop of conglomerate south of Johnnies Pond. Although the exposure is extensively silicified, the outlines of individual clasts reveal that the conglomerate was clast supported and consisted of well rounded elongate cobbles in a fine grained matrix. Both clasts and matrix are silicified such that only traces of the cobbles are visible on broken surfaces of the outcrop. The presence of this facies indicates that some reworking of the ash-flow sheet occurred after deposition and prior to alteration, however, if there were significant amounts of reworked facies originally this is the only preserved example. The alternative possibility is that their was no reworking and the absence of reworked facies might indicate a lack of geomorphic influences on the volcanic terrane. Such conditions might exist in an arid terrane.

3.5 Holyrood Intrusive Suite

3.5.1 Introduction and Nomenclature

The Holyrood Intrusive Suite is a polyphase granitoid intrusion of batholithic dimensions that crops out in the western part of the study area. The name "Holyrood granite" was first used by Buddington (1919) for intrusive rocks in the central Avalon Peninsula. Rose (1952) referred to the rocks as the "Holyrood batholith". McCartney (1967) proposed that the unit be referred to as the "Holyrood Plutonic Series" disagreeing with Rose (1952) over the use of a structural term (batholith) in designating a name for the unit. The unit has been commonly referred to as the "Holyrood Granite" (e.g., O'Driscoll *et al.*, 1988) although Holyrood Intrusive Suite" is also in use (e.g., King, 1986, 1988, 1991; Hayes and O'Driscoll, 1989, 1990). The description of the batholith as an "intrusive suite" likely resulted from inclusion of the Foxtrap Diorite as a phase within the unit and the inclusion of monzonitic rocks which crop out in the western part of the Avalon Peninsula within the suite (McCartney, 1967). Based on modal proportions and feldspar composition in the northern part of the batholith, Strong and Minatidis (1975) defined the rock type as granite (sensu stricto) with subordinate granodiorite. Most outcrops of the unit within the study area are granite (sensu stricto).

The Holyrood Intrusive Suite within the field area comprises three phases divisible mainly by texture. Fine–medium grained porphyritic granite, medium grained equigranular granite and aplitic rocks associated with some of the finer grained phases are found in the study area.

3.5.2 Age of Intrusion

The Holyrood Intrusive Suite intrudes the Johnnies Pond Formation as a variety of Johnnies Pond xenoliths and roof pendants are contained within the granite along the contact. The xenoliths display a crude zonation from unaltered to silicified approaching the contact with the AHAB. On White Mountain (Map 1) ash flow layering is preserved in small (<100 m long) roof pendants of rhyolitic crystal tuff. Thin section examination reveals that the tuffs are completely recrystallized and cuspate bounded snowflake-like textures are developed in the mesostatis of the rhyolites. These textures are only known from that locale.

Altered xenoliths are common within the granite and indicate that alteration predates intrusion of the granite. Near Mine Hill, blocks of silicified rhyolitic ash flow tuff occur in the granite and an outcrop of Holyrood Intrusive Suite on Country Path, contains a xenolith of sericitized ash-flow tuff and also a xenolith cut by a quartz hematite breccia vein are enclosed by granite. The host granite shows no sign of veining or extensive hematitic alteration. Altered xenoliths, composed of silicified rhyolites were observed in a body of slightly chloritized granite northeast of Dog Pond. These features indicate that intrusion of the Holyrood Intrusive Suite postdates the alteration system.

No evidence for intrusion of the granite into the Harbour Main Group was found in the field area. Rose (1952), however, described clasts of granite in both the Conception and Harbour Main groups and hypothesized that these clasts were of an older granite since he thought the Holyrood granite intruded the Conception Group. With clear evidence of intrusion into the Johnnies Pond Formation and the presence of clasts in younger units, a more reasonable conclusion is that the Holyrood Intrusive suite does not intrude these units. Therefore, it must not cross the unconformity which separates the Johnnies Pond Formation from the Conception and Harbour Main groups. The Johnnies Pond Formation and the Holyrood Intrusive Suite form a basement for later basalt–rhyodacite volcanism and sedimentation associated with the Harbour Main and Conception, St. John's, and Signal Hill groups. The large scale anticlinoria that forms the central part of the Avalon Peninsula (King, 1988) has at its core a basement block.

3.5.3 Description of Phases

The dominant phase in the Holyrood Intrusive Suite is a massive, medium grained equigranular, biotite granite. Smaller plutons and dykes intrude the main phase. These include K-feldspar porphyritic biotite granite and aplite. They appear to be localized along the eastern margin of the Suite along Country Path.

Outside of the main body, the biotite granite itself forms plugs that intrude the Johnnies Pond Formation at Manuels River and Scout Pond. The granite is typically grey to black and white, locally pink, with a typical hypidiomorphic texture evident in outcrop. Along fault zones, the granitic texture is replaced by a pseudo-porphyritic texture in which feldspars form augen in a matrix of chlorite, that is replacing biotite, and ground feldspar and quartz. This imparts a greenish colour to the granite near fault zones. The granite is also typically pyritized along fault zones forming contacts with other units.

The medium-grained granite locally contains zones crosscut by tuffisite veins. Tuffisite was first described in the Holyrood granite by Hughes (1971) in pegmatitic granite west of the study area at Duffs. Similar tuffisite zones are common throughout the area and are not always associated with pegmatite but they are clearly less extensively developed away from pegmatites. Alteration does not appear to be associated with the veining. Some of the most profuse tuffisite veining in the study area occurs in the apophyses of granite exposed along the shore of Manuels River. In this area the veins network and anastomose throughout the exposure and in a well exposed part of the outcrop that forms part of the eastern riverbank, the granite is completely brecciated by tuffisite veins (Figure 3.2).

Figure 3.2. *Tuffisite veining in the Holyrood Intrusive Suite, Manuels River.*

On the basis of normative mineralogy, Strong *et al.* (1974) considered the Holyrood Intrusive Suite to represent compositions ranging from granite to granodiorite. Strong and Minatides (1975) later suggested, on the basis of modal mineralogy, that the suite is largely granite and refuted McCartney's (1967) contention that a monzonitic component was present. With the recognition of the Foxtrap Diorite as a distinct unit rather than a phase, the Holyrood Intrusive Suite within the study area is dominantly a homogenous granite body with local textural variation. The porphyritic phases are well exposed in the immediate area of the main tailings pile and settling pond of the Oval Pit Mine where the dominant phase is a fine- to medium-grained, variably porphyritic, biotite granite. The youngest phase of the Holyrood Intrusive Suite consists of very-fine grained aplite which intrude the porphyritic granite.

Phase relations within the Holyrood Intrusive Suite suggest that early components were intruded by successively quicker cooled, and hence finer-grained, phases. Cooling may have been by conduction or in part aided by the release of volatiles. The tuffisite veins in the coarser phases may have been produced by the release of volatiles from the finer-grained phase which intrude the coarser phases. The sequence granite–porphyritic granite–aplite suggests extensive, perhaps shallowing, intrusive activity. Intrusion of the granite into the AHAB alteration system indicates that final granite emplacement postdated the alteration system. This satisfies the field relations expected if a granite acting either as a source of volatiles for the alteration or a heat source intruded its alteration system.[3]

3.6 Harbour Main Group

3.6.1 Introduction

The mafic volcanic and related rocks in the field area can be traced north into the Topsail Head area (King, 1988) where they are continuous with the St. Phillips and Portugal Cove formations of the Harbour Main Group (King, 1986, 1991). These units are presumed to conform-ably underlie the Conception Group in the St. John's area. Mafic volcanic and epiclastic rocks in the study area occupy a similar stratigraphic position with respect to the Conception Group.

The Harbour Main Group represents a range in volcanic depositional environments. Within the field area, the group is composed of a variety of mafic tuffaceous, pyroclastic, epiclastic and coarse debris-style deposits. Much of the Harbour Main strata within the study area lie within the strained zone of the Topsail Fault, hence most exposures are extensively chloritized and have a strong penetrative foliation. Original features are not preserved in these chloritic schists. Features which would indicate clearly whether some of these rocks

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[3] Construction of a highway through the northern part of the study area began in 1994. Outcrops examined during the summer of 1995 included an example of a silicified rhyolite intruded by a leucocratic granite. At Mine Hill, workings along a new mine road indicate that some granite intrudes silicified, sericitized and pyrophyllitized rhyolites.

are flows (e.g., presence of pillows, vesicles) or sedimentary deposits (e.g., bedding, primary laminations) are also largely absent in the lesser deformed exposures and this is a problem that hampered past regional geological mapping. Much of the area presently considered to have been underlain by Harbour Main mafic volcanic rocks by McCartney (1967) and King (1988) was originally mapped as Conception Group by Rose (1952).

The Harbour Main Group within the field area has been divided into two facies in the present study. The volcanic facies consists of those rocks with features closely indicating a volcanic origin including vesicles, flattened and vesiculated lapilli and bombs. Basalt flows, agglomerates, and ash–lapilli tuffs have been recognized with these criteria. The second significant facies is dominated by immature sedimentary rocks but also contains a volcanogenic component. These are mostly fine-medium grained poorly sorted sandstones and coarse debris deposits. The sandstones are typically dark green, chloritic and gritty and appear to grade into better sorted siliceous sandstones of the Conception Group (see also Dawson, 1963).

3.6.2 Contact Relations

The Harbour Main Group is in gradational contact with the Conception Group and unconformably overlies the Johnnies Pond Formation. Medium–coarse sandstones, which are interbedded with Harbour main Group mafic volcanic facies grade into sandstone and siltstone of the Conception Group. These relationships are exhibited by the close association of these facies in exposures east of the Johnnies Pond Formation near the Thousand Acre Marsh. A mafic tuff also occurs within the Conception Group exposed in the Oval Pit Mine. Mafic volcanic detritus appears as a component in some sandy beds in the Conception Group such as in the inlier within the Oval Pit Mine and their presence indicates that some Harbour Main volcanism occurred during the Conception Group depositional cycle. Evidence of the basal unconformity may also be found in this exposure as clasts of silicified and/or quartz veined Johnnies Pond Formation occur within unaltered coarse debris deposits in the Harbour Main Group. These relationships indicate that altered Johnnies Pond Formation rocks were available as a source of detritus at the time of Harbour Main volcanism.

The volcanic rocks of the Harbour Main Group are unaffected by the alteration processes evident in the Oval Pit Mine, despite being in proximity to highly altered volcanic rocks of the Johnnies Pond Formation. For example undeformed and relatively unaltered basalt flows crop out within metres of extensively brittly fractured and altered Johnnies Pond rocks on Country Path (MAP 1). Similarly no distal parts of the alteration system such as quartz–hematite breccia veins are found in the Harbour Main Group. The absence of these features which pervade the Johnnies Pond Formation point to a young age for the Harbour Main Group in the area.

The contacts between the Harbour Main Group and the Holyrood Intrusive Suite are faulted and thus the original relationships are not apparent. The earliest record of detritus from the Holyrood Intrusive Suite occurs in the Conception Group (Vhay, 1936) and there may not have been an extensive depositional contact between the Harbour Main Group and Holyrood Intrusive Suite. Instead, the Harbour Main Group may rest largely on Johnnies Pond Formation beneath the Oval Pit Unconformity.

3.6.3 Volcanic Facies Association

3.6.3.1 Mafic Flows

Well-preserved lava flows are rare within the Harbour Main Group in the map area. Flows crop out near the main gate to the Oval Pit Mine and in an outcrop along the eastbound lane of the Trans Canada Highway, east of the Pastureland Road. Papezik (1974) had reported pillow basalt near Mine Hill but close examination of this exposure during the present study failed to reveal any reliable pillow structures. The outcrop is, however, divided by a conjugate fracture system into lozenge shaped blocks which may have been the structure identified as pillows. The exposure on the Trans Canada Highway is similar and also contains a wide (0.2 to 0.5 m) conjugate shear set. The flows in both localities are dark green, very fine grained and homogenous in appearance except for scattered vesicles. Most of the mineralogy has been replaced by chlorite. Their depositional environment is unknown, however, the lack of pillow structure might indicate they were locally erupted in subaerial environments. Pillow basalt is, however, known from other localities within the Harbour Main Group (King, 1990).

Other possible flow rocks preserved within the Harbour Main Group include a massive horizon within an outcrop of tuff and sediment on the Pastureland Road south of the TCH. The sequence consists of a pyroclastic flow, overlain by a thin siltstone (or tuff bed) having an irregular scoured lower contact with the pyroclastic flow. The siltstone is overlain by massive, reddened, basalt. The top of the flow is not exposed and the scoured basal contact indicates tops to the east. The coincidence of fine grained sediment and oxidized basalt may indicate a shallow water or subaerial depositional environment.

3.6.3.2 Agglomerates

Most of the agglomerates in the study area are associated with fine-grained tuffs, lapilli tuff, or flows. The agglomerates are typically red to purple and green fragmental rocks composed of partly welded bomb and lapilli sized pyroclasts. The flattening and welding of the pyroclastic debris indicates deposition of hot juvenile material. Many of the pyroclasts are vesiculated and are, therefore, distinct from the massive, green, fine-grained chloritic groundmass which encloses them. These rocks are inferred to represent a proximal volcanic facies based upon the size and monolithic, juvenile nature of the fragmental debris. The clast to matrix ratio is on the order of 4–5:1, however, it is variable on the outcrop scale and generally these rocks are clast supported. The agglomerate grade into other facies at the outcrop scale.

3.6.3.3 Ash and Lapilli Tuffs

These rocks are green, purple and red and similar in appearance to the agglomerates, however, the tuffs differ in the size of the pyroclastic components and in the clast to matrix ratio. Typically the pyroclasts are flattened, with some showing vesiculation, and are largely supported in a dark green chloritic matrix. The matrix is indistinguishable from most other mafic tuffaceous rocks in the field area. On the average, clast to matrix ratios are on the order of 1:4–5 and, like the agglomerates, are extremely variable within the same outcrop.

3.6.3.4 Felsic Rocks

Felsic volcanic rocks of the Harbour Main Group are represented by a suite of thin rhyodacitic dykes. A small outcrop of diorite contains dark grey siliceous rhyodacite dykes where it crops out along the Trans-Canada Highway near Scout Pond. The dykes are approximately 1 m wide and are faulted. Fractures in the dykes contain a soft asbestiform pale grey blue amphibole which probably formed as a result of thermal metamorphism of the host rocks (amphibole of Dawson (1963)). The dykes are also well exposed in the bed of Manuels River. Geochemical analysis of the dykes indicates that they are highly sodic and most likely part of the same magmatic event that has produced extensive dyke and dome formation in the eastern Avalon Peninsula.

3.6.4 Sedimentary Facies

The sedimentary facies consist of coarse debris-flow style sedimentary rocks and fine to medium grained greywackes. The coarse rocks are distinguished from the volcanic debris flows by the lack of juvenile volcanic material in the clast or coarse fraction of these rocks. The coarse fraction consists of lithified felsic, mafic volcanic rock fragments and/or in some localities sedimentary clasts are also evident. The matrix ranges from a fine-grained chloritic mud- to crystal- and rock fragment-rich poorly sorted sandy detritus. Rocks included in this category likely represent a variety of depositional environments and processes.

Fine–medium grained greywackes are the most abundant rock type of the Harbour Main Group in the field area. The finer grained rocks within this unit closely resemble some of the sedimentary rocks that are interbedded with the Conception Group. These rocks appear transitional between the Harbour Main and Conception Groups.

3.6.4.1 Coarse Debris-style Deposits

Coarse debris flows containing 0.2–4 m boulders crop out close to the boundary with the Johnnies Pond Formation. These units are typically matrix supported and composed of cobbles to boulder sized clasts that are clearly derived from the Johnnies Pond Formation set in a dark green matrix that is similar to the greywackes elsewhere in the Harbour Main Group. The contacts, where exposed, are faulted, however, these units probably occur near the base of the Harbour Main Group given their coarse clast content. Some well-exposed examples of this facies are present in the study area.

At Mine Hill, blocks of silicified rhyolite typically ranging from 10 to 50 cm in diameter are enveloped by a dark green sand–pebble conglomerate matrix. Some cm scale fragments composed entirely of quartz also occur as clasts. The largest clast in the deposit is over 3 m in length and is composed of silicified rhyolite. The matrix contains 20 to 40% of 2 to 10 mm fragments of rhyolite and silicified rhyolite with the remainder composed of dark chloritic material. Generally many fragments have the size and shape of fracture bounded fragments in the alteration zone indicating very little reworking of the coarse fraction. The blocks show variable degrees of internal fracturing. The deposit appears to be coarsely graded over a 50 m distance with some larger blocks appearing closer to the contact. This deposit appears to have formed as a cohesive grain-flow or mudflows with large entrained blocks and a characteristic of this type of debris flow is that they emplaced en masse (cf. Smith, 1986).

Northeast of the Oval Pit Mine, near Black Hill Pond, 2 to 3 m blocks of relatively unaltered rhyolite occur in green, fine- to medium-grained greywacke. The blocks are matrix supported and also contain quartz veins which do not cut the enclosing greywacke. This deposit also is massive having no indication of bedding structures and the matrix is finer grained and better sorted than the Mine Hill debris flow but these deposits are essentially similar. The bulk of the Johnnies Pond Formation in the vicinity of Black Hill Pond is unaltered with the exception of quartz veins so these blocks also appear to be of local derivation.

These deposits are significant in that they confirm the timing of alteration in the Johnnies Pond Formation with respect to the Harbour Main Group. Since these deposits contain fragments of quartz and quartz veined material they imply that sedimentary rocks of the Harbour Main Group were sampling an already altered Johnnies Pond Formation. Further, since quartz veins are known to occur distal to the main alteration in the Johnnies Pond Formation it might also indicate that the upper parts of the alteration system were begun to be eroded during the early part of the Harbour Main Group volcanic cycle. This would, therefore, be consistent with the fact that later sedimentation clearly samples deeper levels of the alteration system (see section 3.7).

3.6.4.2 Greywacke Facies

This facies includes immature fine-medium grained sedimentary rocks and associated tuffs. These rocks are included within the Harbour Main Group since they appear to represent reworking of unconsolidated volcanic deposits and on the whole they are associated with volcanic facies within the Harbour Main Group. These rocks contain rhyodacite dykes, hence they were deposited prior to cessation of Harbour Main volcanism. As a field term for these rocks, greywacke is most appropriate (following the suggestion of Blatt *et al.*, 1980, p. 375) since the rocks are aerially extensive, `dirty' (i.e., immature) sandstones. In hand specimen the greywackes are green and purple having a fine–medium grained matrix flecked with whitish sand-sized fragments. In thin section the greywackes contain variable amounts of rounded to partly rounded quartz and feldspar crystal fragments along with mafic volcanic detritus set in a fine-grained matrix of plagioclase laths, chlorite, epidote and carbonate. The greywacke facies grades into better sorted sandstones which are in turn interbedded with siltstone. Locally the greywackes contain 1 to 2 m blocks of green, fine-grained siliceous siltstone. These clasts are indistinguishable from similar rocks in the Conception Group and imply firstly that there was a overlap in their depositional period. Some deposition of this siltstone facies, which is typical of the Conception Group, had occurred and was clearly reworked by Harbour Main Group sedimentation. The second important insight that can be gained from this relationship is that the early environment of deposition of Conception Group was unstable and that periods of quiet sedimentation as indicated by early fine grained siltstones could change rapidly as coarse clastic material was shed into the basin, perhaps associated with volcanism.

3.6.5 Correlation

The types of sedimentary and volcanic facies within the Harbour Main Group in the field area broadly resemble those of the St. Phillips Formation of King (1990). The St. Phillips Formation has many features of the Harbour Main Group within the study area including tuffs containing disrupted beds of siltstone (see King, 1990, p. 24). The St. Phillips Formation, therefore, continues across the Topsail Fault and within the field area unconformably overlies the Johnnies Pond Formation and, by implication, the Holyrood Intrusive Suite. This correlation permits the observation to be made that the post-620 Ma geological history of the eastern Avalon Peninsula records the development of a rift basin, accompanied by extensive volcanism (Harbour Main Group) and turbiditic sedimentation (Conception Group) that was eventually infilled by subaerial volcanism (see King, 1990 for details on facies within the basin). Essentially, the basement upon which the rift developed is represented by these earlier units.

3.7 Black Mountain Formation, Conception Group

3.7.1 Introduction

Sedimentary rocks of the Conception Group are best exposed in the vicinity of St. John's (King, 1990). Within the field area, the Conception Group forms isolated outliers in fault contact with the Johnnies Pond Formation and older units, and also occurs as large lenses having a gradational contact between the Conception and the Harbour Main groups.

The Conception Group facies in the field area are comparable with some recognized stratigraphic subdivisions of the Conception Group (King, 1990). However, stratigraphic relation-ships as exposed in these outliers and some of the rock types cannot be accommodated by existing subdivisions. The Black Mountain Formation is the name proposed for the Conception Group sedimentary rocks in the study area. Black Mountain forms a prominent feature composed of siltstone with some sandstone and conglomerate is typical of the formation through the study area. The Black Mountain Formation rests unconformably upon the Johnnies Pond Formation and is interbedded with facies broadly equivalent with the Harbour Main Group. Upper parts of the formation appear to be lithologically similar to the Broad Cove River Member of the Drook Formation which King (1990) defined as the basal unit of the Conception Group. The base of the Drook Formation is not known from the St. John's study area (King, 1990) and since the Black Mountain Formation has depositional contacts with the Johnnies Pond Formation and the Harbour Main Group it is thought that the Black Mountain Formation is the lowermost formation of the Conception Group. There is no evidence for an intrusive relationship between the Holyrood Intrusive Suite and the Black Mountain Formation.

Rocks assigned to the Black Mountain Formation include the Black Mountain sequence (informal) of Dawson (1963) and Conception Group siltstone and siltstone–sandstone interbedded with Harbour Main Group greywackes (Dawson, 1963; King, 1988). Dawson (1963) had considered the Black Mountain sequence to be younger than the Conception Group and that the rocks were unconformable upon the Harbour Main Group[4] and Holyrood Granite. With the recognition of the contemporaneous nature of Harbour Main and Conception group sedimentation and the nature of the basement rocks, it is clear that all

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[4] Dawson considered the Johnnies Pond Formation rhyolitic rocks to be part of the Harbour Main Group. Thus these sedimentary rocks were divided into two units to account for their basal contact relationships.

of these facies and relationships occur at the same stratigraphic level. It is therefore appropriate that they be grouped in the same formation.

3.7.2 Contact Relationships

The Black Mountain Formation unconformably overlies the Johnnies Pond Formation and is interbedded with the St. Phillips Formation of the Harbour Main Group. The unconformable relationship is clearly visible in the Oval Pit Mine where sheared and altered volcanic rocks of the Johnnies Pond Formation are overlain by boulder conglomerate of local derivation. The con-lomerates occur at the base of a section of sedimentary rocks which grade upwards into green siliceous siltstone. This siltstone unit occurs at the top of each exposed section of the Black Mountain Formation and is also interbedded with greywacke. It locally grades into massive greywacke and volcanic rocks of the Harbour Main Group. In the southeast part of the field area outcrops containing thick interbedded siltstone and greywacke which pass abruptly into mafic lapilli tuff. These patterns and field relations indicate that the Black Mountain Formation forms part of a conformable sequence with the Harbour Main Group volcanic facies. Some local facies relationships have been observed which support these correlations.

An outcrop along the Pastureland Road contains a pyroclastic flow, with a scoured top infilled and overlain by a thin (5 cm) bed of reddish siltstone. The siltstone is in turn overlain by a massive basalt flow. This close association of the Harbour Main Group volcanic facies and sedimentary facies that typify the Black Mountain Formation further indicates a temporal relationship between these facies and that local periods of sedimentation represented by the siltstone intervened between episodes of volcanic activity.

The base of the formation is, as indicated on Map 1, recognized and defined as the first appearance of interbedded siltstone and sandstone where the unit overlies Harbour Main Group greywackes and it is marked by boulder conglomerate where it overlies the Johnnies Pond Formation. Essentially the Black Mountain Formation, as preserved in the Oval Pit Mine above the unconformity, probably represents a marine transgressive sedimentation of the Conception Group onto the Holyrood Horst. In some sense it maybe diachronous since the earlier Black Mountain sedimentation may have occurred within the basin and the transgressive sedimentation onto the Horst could be slightly later.

3.7.3 Facies Relationships and Lithologies

The Black Mountain Formation is comprised of light green, fine grained siliceous siltstone, green to dark green fine to medium grained sandstone, and fine to medium grained greywacke. Locally the formation contains conglomerate and sandstone, particularly where it overlies the Johnnies Pond Formation, as at the Oval Pit Mine and at Black Mountain.

The dominant depositional facies in the Black Mountain Formation was chiefly turbiditic since much of the units consisting of rhythmically bedded sandstone and siltstone.

Thinly planar and wavy laminated siltstones are found interbedded with the Harbour Main Group greywackes on the regional scale and outcrop scale (see above). Laminated siltstones also crop out at the Oval Pit Mine and Black Mountain. These facies styles are consistent with B, C, and D divisions of the Bouma sequence (Bouma, 1962 in Walker, 1992). Facies vary from exposure to exposure within the Black Mountain Formation, and each outcrop likely lies within a distinct structural block. Consequently variation in the stratigraphic level coupled with rapid facies variation could account for the different facies preserved in each block imbricated with older rocks.

Many outcrops of the Black Mountain Formation also feature rhythmically interbedded siltstones and sandstones. The sandstones range from medium-grained greywackes to well-sorted fine grained sandstone. In the Dog Pond area, most exposures of this unit are composed of alternating beds of siltstone and medium to fine grained wacke. The rocks vary from metre- to decametre-scaled fine-grained greywacke interbedded with siltstone to medium grained greywacke interbedded with centimetre scale bedded siltstone. At Dog Pond the siltstone is clearly associated with greywacke. The greywackes in this locality are less chloritic than most greywackes of the Harbour Main Group and perhaps more mature (i.e., less clay fraction). The siltstone contains syn-sedimentary deformational features including slump folding and faulting and within some of the greywacke beds there are clasts of siltstone indicating disruption and reworking of pre-existing units. At the Oval Pit Mine slump folds are visible along the uppermost trenches in the pit and are marked by thin (3 to 5 cm) interbeds of medium to coarse grained pebbly sandstone. The sandstone contains pebbles of very fine-grained crystal tuff and extensively chloritized vesicular basalt.

Although there are differences in the depositional style and facies within the Black Mountain Formation and the Conception Group there are also similarities. Sequences at the Oval Pit Mine, west of Mine Hill, Dog Pond and Black Mountain all contain rhythmically bedded facies which may be related to a similiar facies described by King (1990) throughout the Drook Formation. The inlier at Black Mountain is composed of white weathering green thinly laminated siltstone. This siltstone is interbedded on the outcrop scale with black–green fine- to medium-grained siliceous sandstone. The interbedded greywacke sandstone–siltstone facies appears to be related to facies within the Broad Cove River Member as described by King (1990). Some of the rhythmically bedded siltstones may have affinities to the Mannings Hill Member of the Drook Formation (op.cit.).

3.8 Conclusions

The existence of a single volcanic unit of group status representing a single, extensive volcanic episode, prior to the deposition of the Conception Group is rejected by the present study. King (1990, p. 24) had offered this as a possibility to explain the range in ages presented by the group. It is clear from the present study that the large gap in ages reported by Krogh *et al.* (1988) are due to the fact that there is a major regional unconformity separating an older volcanic–intrusive terrane from a younger sequence that includes the

Harbour Main Group. Substantial revision of the pre-Conception Group stratigraphic nomenclature will be required if the Johnnies Pond Formation relationships can be traced over much of the volcanic sequence currently mapped as Harbour Main Group.

Recognition of the stratigraphy permits a detailed examination of the structural history of the study area. The structural geology of the belt requires examination to establish the distribution of structural zones within the belt and the relationship of the belt to its country rocks at the deposit scale. This has new implications for the development of exploration models for pyrophyllite and mineralization within the Johnnies Pond Formation.

CHAPTER 4

STRUCTURAL GEOLOGY AND GEOLOGICAL HISTORY

4.1 Introduction

The bedrock geology of the study area records structural events which provide insight into Precambrian crustal development of the Avalon Zone. The basement units within the Holyrood Horst and the cover rocks of the Harbour Main and Conception Groups illustrate the development and interaction between a Precambrian arch and a flanking, yet younger, Precambrian volcano-sedimentary basin. There is also evidence of their continued tectonic interaction since Cambrian time. This chapter presents the evidence for the timing of deformation within bedrock units and explains the present distribution of units. An understanding of the structural geology is important in developing genetic and exploration models for pyrophyllite. The structural features associated with high-alumina alteration system aid in unravelling the complex structural history of the region. Previous studies on the Avalon Peninsula did not fully explain the complex outcrop patterns or structural relationships observed in the study area. Consequently, the interpretations presented in this section are new.

4.2 Main Structural Elements in the Study Area

The most important regional-scale structures in the study area are the Topsail Fault (Rose, 1952; King, 1988) and the Holyrood Horst (McCartney, 1967). The Johnnies Pond Formation crops out along and forms the eastern boundary of the Holyrood Horst. The Topsail Fault and its secondary structures juxtapose major units and consequently control the outcrop pattern. Much of the northerly strike of the geology is more structural than it is depositional. The Holyrood Horst and the younger Topsail Fault appear to both occupy the same zone of crustal weakness.

Previous workers have made somewhat similar observations. Rose (1952) noted the deformation marking the Topsail Fault and thought the Holyrood Intrusive suite acted as "a buttress against which the less competent rocks were thrust or as the causative agent of thrusting" (Rose 1952, p. 41). No tectonic context was provided for the deformation, since the mapping and interpretation preceded modern concepts of plate tectonics. He also recognized that there were Precambrian to post-Cambrian movements on the Topsail Fault, however, the timing of the Precambrian movement was not specified. Rose (1952, p. 40) mapped a number of thrust faults, including two near Johnnies Pond, and on this basis considered the overall structural regime to have been compressive. McCartney (1967, 1969) described the structural geology of the central part of the Avalon Peninsula and inferred that, after deposition of the Harbour Main (include his definition the Johnnies Pond Formation) and Conception Groups and the intrusion of the Holyrood Intrusive Suite, the area was uplifted and became the source of sediment for the Signal Hill Group thus implying that the Holyrood Horst is a post-Conception Group feature.

The revised stratigraphy presented in Chapter 3 also permits refinements of the structural history of the region. Seven periods (D_1–D_7) of tectonism can be recognized. Not all produce penetrative deformation. Most are brittle in style and their deformational effects may be apparent in zones as narrow as a few centimetres in width.

4.3 D_1–Foxtrap Diorite

The D_1 in the study area is the foliation defined by the biotite and hornblende in the Foxtrap Diorite. The foliation is vertical and strikes northeasterly and amphibolite xenoliths are elongated in about a 3:1 length to width ratio subparallel to the foliation. This is considered the oldest deformation since no nearby units exhibit any evidence of strictly ductile fabrics developed by alignment of primary mineralogy. Its extent is limited to the outcrop area of the Foxtrap Diorite.

4.4 D_2–Pre-AHAB Deformation of the Johnnies Pond Formation

D_2 is restricted to the Johnnies Pond Formation and is represented by a period of syn to late volcanic deformation prior to the development of the AHAB. Vertical AHAB structures cut inclined Johnnies Pond Formation strata, hence tilting of bedding occurred prior to the development of the AHAB. Despite the intense alteration throughout the Johnnies Pond Formation the effects of this deformation are apparent at a number of localities within the unit. Some examples of these relationships include:

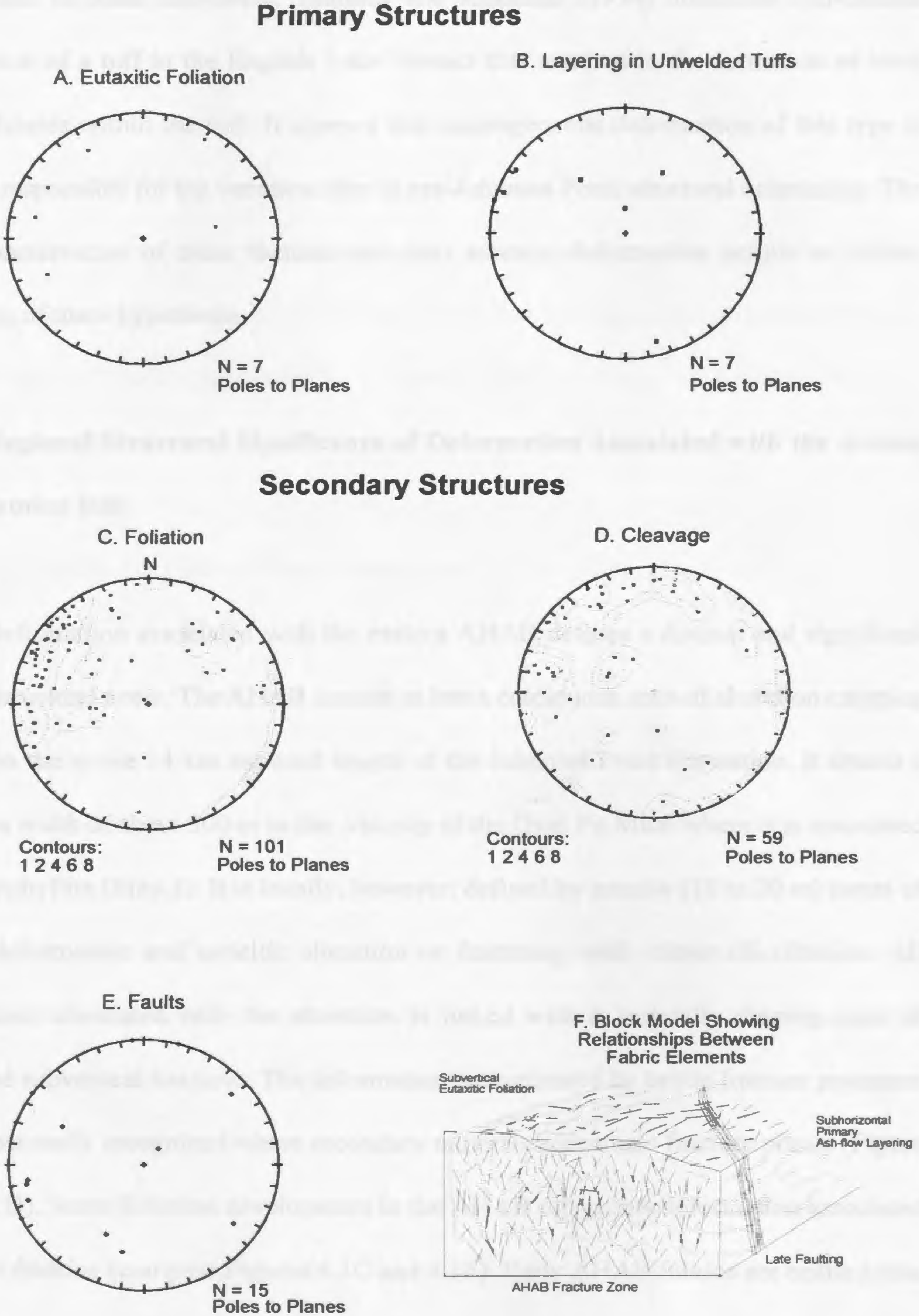
(1) Northeast of the Oval Pit Mine, northwest to north trending and vertically dipping quartz– hematite breccia veins cut steeply (80°) northwest dipping tuffs.

(2) At Mine Hill steeply to subvertically dipping ash-flow layering and flow banding is overprinted by a subvertical fracture system associated with the AHAB.

(3) Interbedded rhyolitic and crystal tuffs crop out in a large exposure north of TCH near the intersection with the Foxtrap access. Bedding strikes 60° and dips 70° southwest, is cut by a north trending zone of silicification containing a sericitic core which appears to be vertically dipping.

The relationships of the AHAB to these structures are depicted in Figure 4.1. No regional cleavage development is associated with this phase of deformation as the deformation appears to involve mostly moderate to steep tilting of the volcanic pile as both eutaxitic foliations (Figure 4.1A) and unwelded tuffs (Figure 4.1B) show a range in orientations. The eutaxitic foliations generally have a greater tendancy to be inclined than the unwelded rocks. This may be indicative of an original relationship. The deformation in the Johnnies Pond Formation may be the result of broad regional caldera collapse structures or deformation related to the volcano-tectonic environment. This may be analogous to the deeply dissected caldera described by Branney *et al.* (1992) in the Lake District. The deformation within the Johnnies Pond Formation is also analogous to the style of defor-

Figure 4.1. *Primary and secondary (AHAB-related) structures in the Johnnies Pond Formation.*



Primary Structures
A. Eutaxitic Foliation
N = 7
Poles to Planes
B. Layering in Unwelded Tuffs
N = 7
Poles to Planes
Secondary Structures
C. Foliation
N
Contours:
1 2 4 6 8
N = 101
Poles to Planes
D. Cleavage
Contours:
1 2 4 6 8
N = 59
Poles to Planes
E. Faults
N = 15
Poles to Planes
F. Block Model Showing Relationships Between Fabric Elements
Subvertical Eutaxitic Foliation
Subhorizontal Primary Ash-flow Layering
Late Faulting
AHAB Fracture Zone

mation seen in other ash-sheets. Branney and Kokelaar (1994) document syn-caldera deformation of a tuff in the English Lake District that resulted in the formation of local vertical fabrics within the tuff. It appears that heterogeneous deformation of this type is probably responsible for the variation seen in pre-Johnnies Pond structural orientation. The limited preservation of these features and later tectonic deformation permit no further evaluation of these hypothesis.

4.5 D_3–Regional Structural Significance of Deformation Associated with the Avalon High Alumina Belt

Deformation associated with the eastern AHAB defines a distinct and significant regional structural event. The AHAB is more or less a continuous zone of alteration cropping out within the entire 14 km exposed length of the Johnnies Pond Formation. It attains a maximum width of about 500 m in the vicinity of the Oval Pit Mine where it is associated with pyrophyllite (Map 1). It is locally, however, defined by narrow (10 to 20 m) zones of intense deformation and sericitic alteration or fracturing with minor silicification. All deformation associated with the alteration is linked with a vertically dipping zone of networked subvertical fractures. The deformation is dominated by brittle fracture processes and is most easily recognized where secondary minerals accentuate fracture planes (Figure 4.1C and D). Some foliation development in the AHAB represents deformation associated with later faulting (compare Figures 4.1C and 4.1F). Early AHAB fabrics are brittle joints with cleavage development (Figure 4.1D). With increased alteration, foliations are developed within the altered rocks (Figure 4.1C). Kinematic analysis is rendered impossible due to the alteration processes and the fine-grained nature of the replacement assemblages which overprint earlier features that would serve as a guide to the deformation history. The relationship of fabric development within the AHAB and its relationship to hydrothermal processes are discussed in Chapter 5. The most important regional geological features of the AHAB structure are its continuous nature and vertical orientation. The alteration serves as a distinct temporal marker, since the alteration system is intruded by the massive Holyrood Intrusive Suite, the deformation must be pre-Holyrood (ca. 620 Ma) in age.

4.6 D_4–Post-AHAB Uplift and Basin Development

The Oval Pit Unconformity (see Chapter 3) is important since it demonstrates a significant stratigraphic break between sequences of rocks that have a 40 Ma age difference. It represents a transition from the ca. 620 Ma continental, felsic ash-flow style volcanism to marine volcanism and development of major marine basin (Conception–St. John's Groups). The age of this basin is probably about the same age as the volcanic sequences which include rhyodacite domes dated at 586 Ma. The tectonism associated with this event was closely coupled with the volcanism in the Harbour Main Group and this largely extensional event is recognized as D_4 within the study area.

Basement rocks to the eastern Avalon Peninsula must have underwent extensional tectonic regimes which led to the development of the basin in which the Harbour Main and

Conception groups were deposited. It is difficult to identify structures associated with this period of uplift and extension, however, the Johnnies Pond Formation does not crop out east of the Topsail Fault, implying that this structure controls distribution of the formations. This might be explained if the fault was initially a basin controlling structure. This interpretation is supported by stratigraphic data as the Conception and Harbour Main groups thicken rapidly to the east of the Topsail Fault. In the Paddy's Pond and Cochrane Pond Anticlines, the Drook Formation is about 1000 m thick (King, 1988). In contrast, the section of Black Mountain Formation rocks exposed at Dog Pond is on the order of 200 m thick. Although the degree of preservation of the Dog Pond section may be called into question, there is a significant difference in the thickness of the unit at both these locations which are separated by the Topsail Fault. The rapid thickening of sedimentary units, and the presence of coarse clastic debris within the thinner section at the basin margin is consistent with the Topsail Fault being a strike-slip basin bounding fault early in its history.

The Conception Group stratigraphic section at the Oval Pit Unconformity represents a marine transgression onto the Holyrood Horst and sedimentation in the Conception Group is also closely sourced from the Harbour Main volcanism. Throughout much of the study area there appears to have been a close depositional relationship between the typically interbedded siltstones of the Conception Group and greywackes and tuffs of the Harbour Main Group.

Along the unconformity in the Oval Pit Mine, the main source of detritus was the Johnnies Pond Formation. The basal conglomerate is overlain by successively finer-grained pebble conglomerates and pebbly sandstones and the beds of altered fragments diminish in thickness. Near the top of the section, the coarse beds contain altered and unaltered rhyolite fragments. The fine-grained rhythmically bedded siltstone–sandstone sequence that forms at the top of the Oval Pit Mine section occurs in all outliers of the Conception Group and appears to be correlative with parts of the Drook Formation (Chapter 3).

The distribution of Black Mountain Formation outliers along the eastern margin of the Holyrood Horst, and in particular the thickness and facies variation as compared with typical Drook Formation, which elsewhere is the lowermost formation of the Conception Group (Williams and King, 1979), indicates that the margin of the Holyrood Horst was subject to local inundation during basin development. Importantly these inundations are spatially coincident with high-alumina zones in the AHAB and result in the preservation of high-alumina alteration beneath the Conception Group. This pattern indicates fundamental basement control on the presence of the outliers. The contact on these outliers may be a result of differences in subsidence rate of reactivity of basement structures. The subsidence rate in areas of high-alumina alteration may have been greater due to structural control as the weakening of the rock by alteration may have localized deformation into these zones or the pre-existing AHAB-related structures may have been exploited by basin structures facilitating greater extension and consequently more inundation in these areas. Clearly some of the faults have the same orientation as foliations within the AHAB (compare Figures 4.1C and 4.1F).

Extension throughout basin development appears to have been closely tied to uplift in the source area as reflected in the variation in the source of coarse clastic material within major stratigraphic units. Within the field area the type of clasts found in debris flows within both the Harbour Main Group and Conception Group differs with stratigraphic level. In the Harbour Main Group the clasts in the debris flows are either unaltered, quartz veined or silicified and clearly of Johnnies Pond/AHAB derivation. The Conception Group contains clasts of pyrophyllitized rocks, implying that further uplift and erosion had occurred to such an extent that this material was accessible.

The record of detrital input from the Holyrood Intrusive Suite into the basin is somewhat more complex. Granitic detritus is rare in the Conception Group, however, clasts were reported by Rose (1948) from Black Mountain and a mixtite unit within the Conception Group cropping out on the Witless Bay line. The Signal Hill Group also contains abundant rhyolite and granite clasts (King, 1990). This sourcing pattern is consistent with continued uplift of the Holyrood Horst and that signified unroofing of the Holyrood Intrusive suite through the Johnnies Pond Formation did not occur until the deposition of the Signal Hill Group. On the opposite side of the Holyrood Horst, near Holyrood, Holyrood Granite clasts are found within the Harbour Main Group (McCartney, 1967) requiring that unroofing of the granite was not contemporaneous throughout the area. Further work is needed along the margins of the Horst to develop a regional understanding of the uplift history. However, it is clear from this investigation that a significant structural event was responsible for the formation of the basin and it is manifested in the depositional record within the study area.

4.7 D_5–Topsail Fault and Related Structures

4.7.1 Topsail Fault

The Topsail Fault is marked by a linear zone of intense deformation in rocks of both the Harbour Main and Conception groups (Map 1). The fault can be traced north to the Topsail Head area where latest movement on the structure juxtaposes Cambrian sedimentary rocks of the Adeyton Group with the Harbour Main Group. This indicates a period of post-Cambrian deformation.

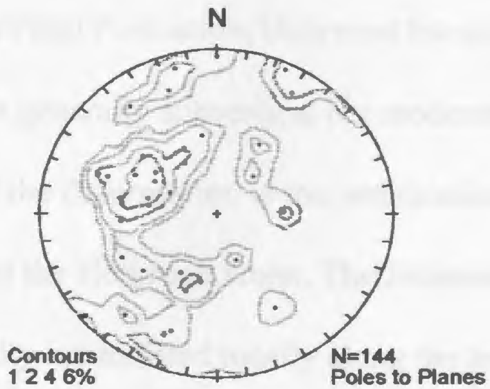
The fault is marked throughout much of the field are by a zone of secondary fabric development marking the D_5 deformation. In the southern part of the map area, greywackes, basalts and mafic tuffs of the Harbour Main Group are extensively chloritized and schistose. Early quartz veins in these exposures are disaggregated and boudinaged and few primary features of the host rocks are recognizable. Within the fault zone relatively competent green silicic siltstones of the Conception Group have a millimetre spaced fracture cleavage, oriented perpendicular to the schistosity seen in the more chloritic rocks. In coastal exposures at Topsail Head, the host rocks are extensively quartz veined along the fault. Rhyodacitic dykes which intrude the Harbour Main Group are boudinaged and enveloped by a schistose fabric in their host rocks, which appear to be greywacke and tuffs that are extensively sheared and chloritized..

Figure 4.2 shows a series of contoured equal area stereographic projections constructed from cleavage and bedding data for the Harbour Main Group and Conception groups. The data illustrates the strong northerly orientation of secondary structural features and bedding has an angular relationship to the secondary structures. Bedding in the Harbour Main Group is subvertical and strikes northwest while bedding within the Conception Group is moderately to shallow dipping. Bedding is rotated into the main cleavage direction within the Harbour Main Group (compare Figure 4.1B and D) while the same cleavage orientation crosscuts the subhorizontal bedding in the Conception Group. These observations indicate that within the cover sequence the lower parts of it are more intensely deformed. This is consistent with the flower structure model for the Topsail Fault (see below). Upper parts of the structural complex have undergone less rotation (Conception Group) but are cut by the same structures (hence the same orientation is evident on cleavage in both units). Since the map pattern of major units parallels the structural data on the gross scale, it is reasonable to infer that the outcrop pattern is structurally controlled by the Topsail Fault.

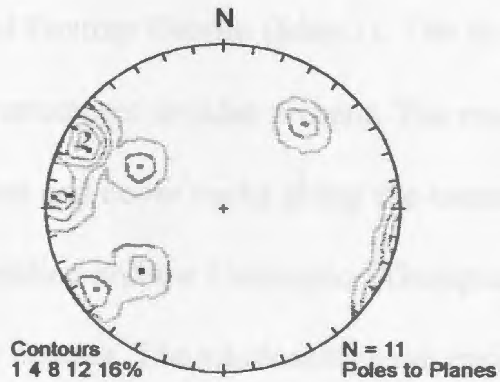
4.7.2 Structures Related to the Topsail Fault

The effect of the deformation along the Topsail Fault is not restricted to the fault zone itself as several other major faults in the study area appear to be related to this event. The

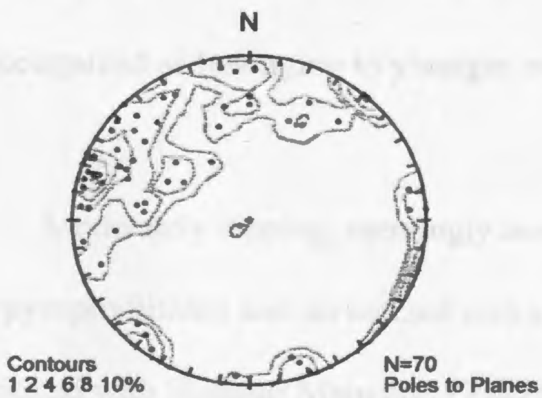
Figure 4.2. *Bedding and cleavage relationships within the Harbour Main Group.*



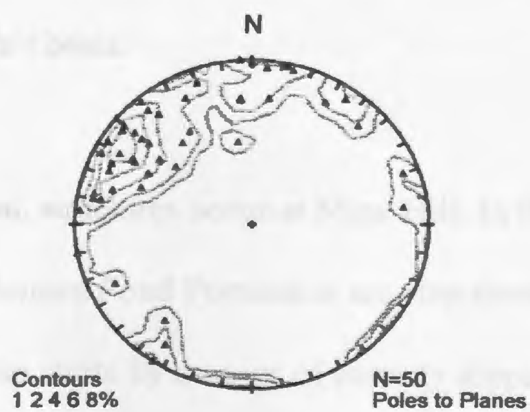
A. Bedding orientation in the Conception Group



B. Bedding orientation in Harbour Main Group



C. Cleavage orientation in the Conception Group



D. Cleavage orienatation in the Harbour Main Group

Dog Pond, Trout Pond, Mine Hill, Oval Pit Mine and Black Hill faults place cover sequences of the Conception and Harbour Main Group in fault contact with the basement rocks of the Johnnies Pond Formation, Holyrood Intrusive Suite and Foxtrap Diorite (Map 1). The fault zones are generally subvertical but moderately dipping structures are also present. The main effect of the deformation is the imbrication of basement and cover rocks along the eastern margin of the Holyrood Horst. The Johnnies Pond Formation and the Conception Group are structurally intercalated locally along the length of their contact. The relationships are easily seen in the vicinity of Mine Hill (Figure 4.3). The deformation is marked by a penetrative fabric in fault zones and by a weak secondary fabric in some high-alumina rocks. The primary AHAB structures are brittle and do not have the penetrative fabrics. These foliations are recognized as belonging to younger events on this basis.

Moderately dipping, seemingly compressional, structures occur at Mine Hill. In this area pyrophyllitized and sericitized rocks of the Johnnies Pond Formation are structurally imbricated with Harbour Main and Conception Group strata by a series of easterly dipping faults. These faults appear to be compressional since on the gross scale they appear to cut out parts of the stratigraphic section. Basement rocks appear in both the footwalls and hanging walls of thin slices of cover rocks. A clear example of this type of relationship is exhibited in Figure 4.4. This pattern is also reflected to some degree by the distribution of large Conception Group outliers.

Figure 4.3. *Detailed geological map of the Mine Hill area.*

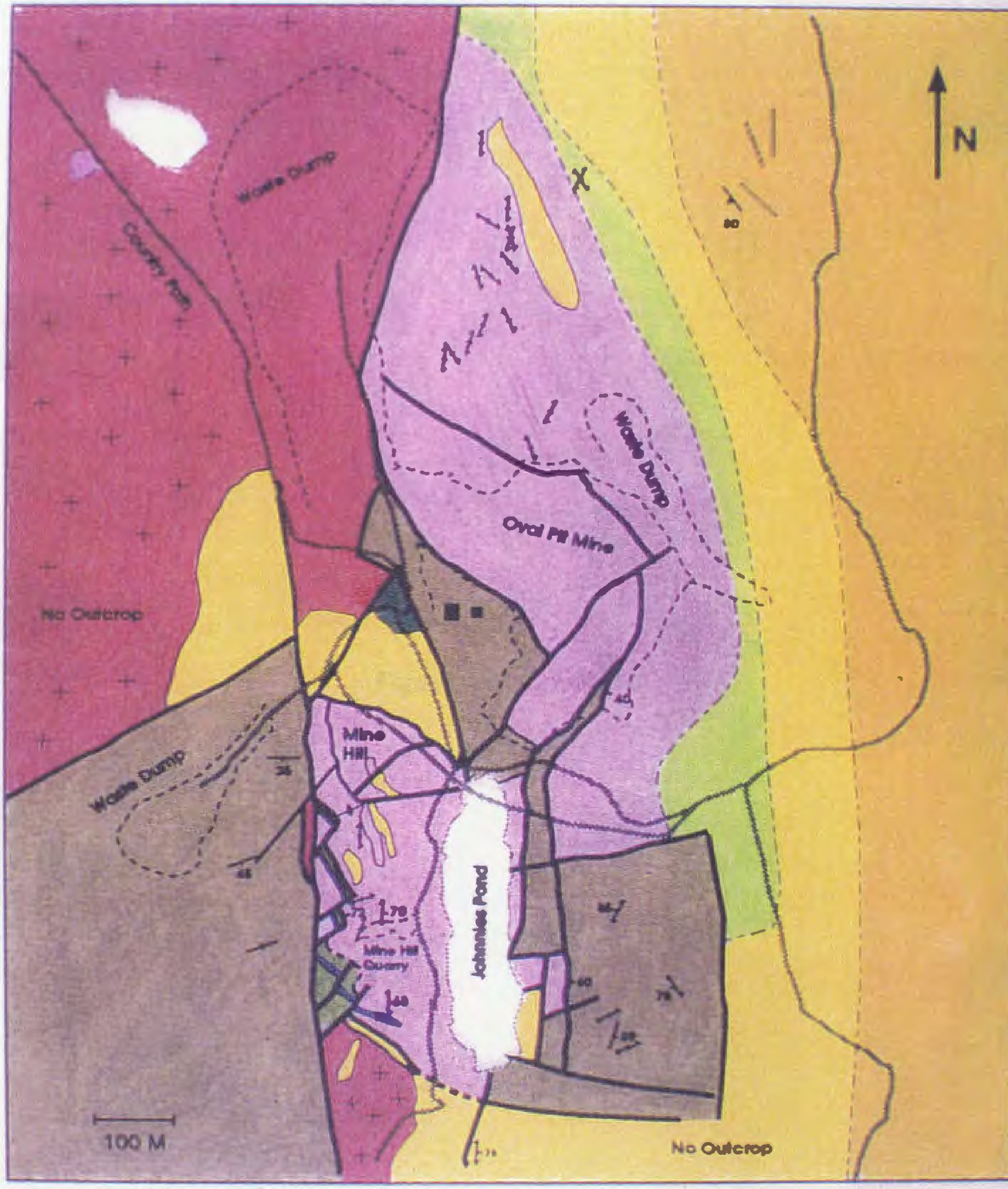

N
Waste Dump
Country Path
X
80
Waste Dump
Oval Pit Mine
No Outcrop
40
Mine Hill
Waste Dump
35
65
70
Mine Hill Quarry
Johnnies Pond
60
75
100 M
No Outcrop

Figure 4.3. *Continued.*

GEOLOGY OF THE OVAL PIT MINE AREA

LEGEND

Precambrian — circa 585 Ma

Diabase dyke

Quartz-feldspar porphyry

Conception Group

Fine-grained siliceous siltstone interbedded with medium-grained sandstone, pebble to boulder conglomerate and minor tuffaceous sandstone

Harbour Main Group

Massive basaltic lava flows

Chaotic pebble to boulder debris flow

Precambrian — circa 620 Ma

Holyrood Intrusive Suite

Medium-grained, equigranular and K-feldspar porphyritic, biotite granite and aplite

Johnnies Pond Formation

Intensely welded and recrystallized crystal and crystal-lithic tuff, local volcanic breccias and lithophysal zones

unaltered

silicified

silicified and sericitized

pyrophyllitized and sericitized

Geological Symbols

Fault

Geological boundary (defined, approximate)

Unconformity

Foliation (vertical, inclined)

Bedding (vertical, inclined)

Flow banding (vertical, inclined)

Breccia veins

Topographic Symbols

Gravel roads

Mine workings

Waste Dump

(From Hayes, In prep.)

Figure 4.4. *Thrust fault in roadcut at Mine Hill. The hanging wall consists of AHAB pyrophyllite zone and the footwall contains relatively unlaltered Harbour Main Group basalts.*

At Mine Hill, a Harbour Main breccia unit forms cover imbricated into the Johnnies Pond Formation. The fault structures bounding the breccia unit trend north and dip towards the east approximately 70°. A weak secondary fabric is developed in the pyrophyllite schist which dips easterly 60 to 70° and is consistent with the structures produced the imbrication.

To the east of Johnnies Pond, a block of Conception Group strata is relatively undeformed internally yet an intense foliation is developed where the unit is in contact with the Johnnies Pond Formation. The zone of deformation marks the fault contact between the units strikes north and dips 60° east and thus has the same general orientation as the second foliation in the rhyolites at Mine Hill. The easterly dips and compression of the sections indicate westward directed component to the sub-horizontal fault movements. The outcrop patterns are further complicated in the area by high angle faults. One of these faults exposed near the south end of Johnnies Pond terminates a block of Conception Group strata and is marked by a vertically dipping zone of intense shearing and penetrative fabric development. This particular fault may be related to the main compressional faults and its style and spatial relationship indicates it could be a lateral ramp.

This fault system also affects contact relationships between the Johnnies Pond Formation and the Holyrood Intrusive suite. Despite having an original intrusive relationship, many contacts of the Johnnies Pond Formation and the Holyrood Intrusive Suite are now marked by vertical faults. Deformation in the granite results in chloritization of biotite, some cataclastic reduction of grain size and, locally, the development of a weak schistosity.

Pyritization of the granite and the Johnnies Pond Formation adjacent to the fault zones is ubiquitous and gives these outcrops a rusty appearance.

The compressional faults in the Mine Hill area and all of the vertical structures intercalating the pre-580 Ma basement and cover rocks are components of the same regional fault system. Although the bulk of the structures are subvertical, the east dipping faults occur to the west of the Topsail Fault and hence dip into the plane of this structure. On the eastern side of the Topsail Fault in the Portugal Cove area, thrust structures in the Harbour Main and Conception Group Rocks are easterly directed (King, 1990). The sense of dip direction on each side of the Topsail Fault is similar to flower structures which form in strike slip fault systems (Sylvester, 1988). Thus the Topsail Fault likely represents a regional transpressional structure and there is clear implication of movement on this structure having influenced the present distribution of rock units within the study area.

The pyrophyllite deposits are influenced by the deformation associated with the Topsail Fault. The primary effect appears to be that the deposits are exhumed through the Conception cover. The deformation may also imbricate ore zones within these deposits, as indicated by the pattern of faulting in the cover rocks of the Conception Group, however there are no suitable markers in the altered rocks to facilitate reconstruction. Much of the schistosity seen in some outcrops of altered rock is probably related to subsequent (post-alteration/deformation) and may be related to the Topsail Fault. The deformation of pyrophyllite at Dog Pond, for example, occurs along the Dog Pond fault which is clearly related to this fault system.

Based upon the foregoing structural and stratigraphic analyses the potential, exists for blind deposits of pyrophyllite wherever Conception Group rocks are in fault contact with altered Johnnies Pond Formation. The large area of Conception Group strata in fault contact with the Johnnies Pond Formation west of the Dog Pond Fault may be underlain by pyrophyllitic rocks. It should be recognized that the true thickness of the cover in the block is unknown and if the estimate of 200 m of exposed strata is correct, a potential occurrence might be too deep to exploit economically. The Dog Pond prospect, however, warrants further exploration by diamond drilling through the Conception Group since here as at the Oval Pit Mine the cover may be thin near the fault.

Deformation in all major units affected by this deformational event is accompanied by extensive pyritization along fault contacts (see Chapter 5). The fault contacts provided fluid pathways for sulphur-bearing fluids to invade the rock masses. Some minor quartz veins containing galena and chalcopyrite were found at Topsail Head in the fault zone and these may equally be related to this event.

4.7.3 Timing of Deformation along the Topsail Fault Zone

The age of the movement on the Topsail Fault that produced the main deformation within the Conception and Harbour Main Groups is most likely Precambrian as there is no similar inter-calation of Cambrian cover and Precambrian basement. Had the Cambrian been deposited before the deformation it would be reasonable to conclude that at least locally the basement and the Cambrian cover would have the same structural relationships locally as the Johnnies Pond Formation and the Conception Group. The movements on the Topsail Fault may be related to late Precambrian event that produced broad regional folding in the St. John's area (see King, 1990).

The Topsail Fault is probably responsible for the formation of a graben which was ultimately infilled by Cambrian and Ordovician sedimentary rocks in present-day Conception Bay. This hypothesis requires further evaluation through the examination of similar structures in western Conception Bay. It should be noted that the Cambro–Ordovician sequence is roughly bounded by the Topsail fault system in the east and also along a similar fault system that bounds the Holyrood Horst to the west (King, 1988).

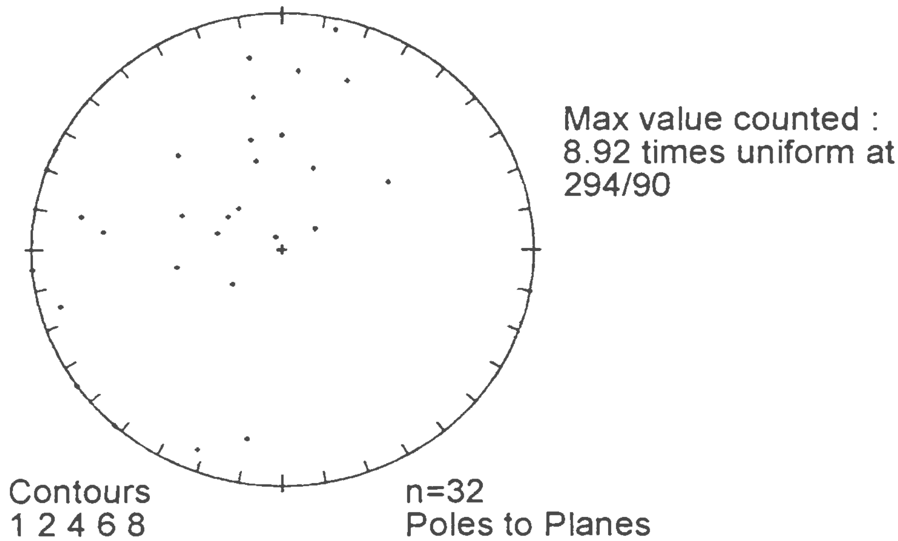
4.8 Veins and Metamorphic History

A variety of quartz veins cut the Precambrian rocks and can be broadly divided into vertically and horizontally dipping groups of veins.

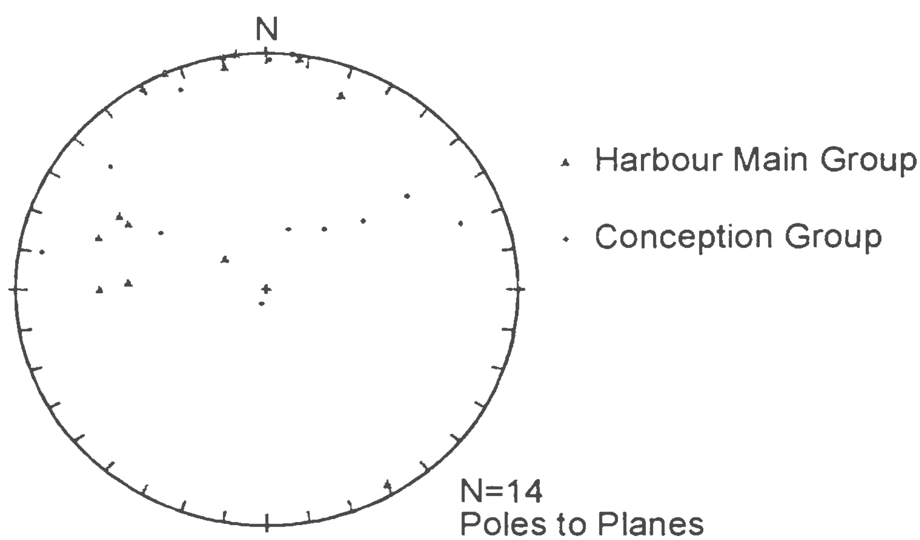
The vertically dipping set includes quartz–hematite and quartz–specularite veins cutting the Johnnies Pond Formation are clearly related to the AHAB. Another vertically dipping vein set of quartz veins contains no accessory minerals. These veins are found within the Johnnies Pond Formation, Holyrood intrusive suite and Harbour Main Groups and hence may have no affinity to the AHAB.

Horizontally dipping quartz veins cut the pyrophyllite zone at the Oval Pit Mine. Horizontal-subhorizontally dipping quartz, quartz–chlorite and lesser quartz–chlorite–epidote veins occur throughout the study area. The veins are 2 to 5 cm thick and contain milky quartz and large clots of green chlorite and locally epidote. The horizontal veins form a suite which are related to the post-Conception, Precambrian deformation and they appear to form as dilatant zones near thrust planes. Evidence for this relationship can be seen in the south east wall of the Oval Pit Mine where sub-horizintally dipping quartz veins cut pyrophyllitized rocks in the hanging wall of the thrust. Similar veins were also examined along the northwest face, also having the same relationship to major compressional structures traversing the Pit. The sub-horizontal quartz–chlorite veins found on a regional scale and probably occur in the hanging wall of regional structures. The mineralogy of the quartz veins metamorphic grade is the same as that of the Harbour Main and Conception groups within the field area. Figure 4.5 shows equal area projections of poles to planes of the orientation of quartz vein assemblages within the study area. The dominant subhorizontal nature of the veins within the Johnnies Pond Formation are clearly evident (Figure 4.5A). The veins within the Harbour Main and Conception groups are both horizontal and moderately inclined. Although both

Figure 4.5. *Orientation of veins within the Johnnies Pond Formation and the Harbour Main and Conception groups.*



A. Equal area projection of quartz veins within the Johnnies Pond Formation



B. Equal area projection of quartz veins within the Conception and Harbour Main Groups

groups are sub-horizontal veins, the moderately inclined veins dip westward in the Harbour Main and dominantly eastward in the Conception. The vein orientations are not coincident with cleavage in these units, consequently the difference may reflect local structural environments, or be of different generations.

4.9 Post-Cambrian Deformation

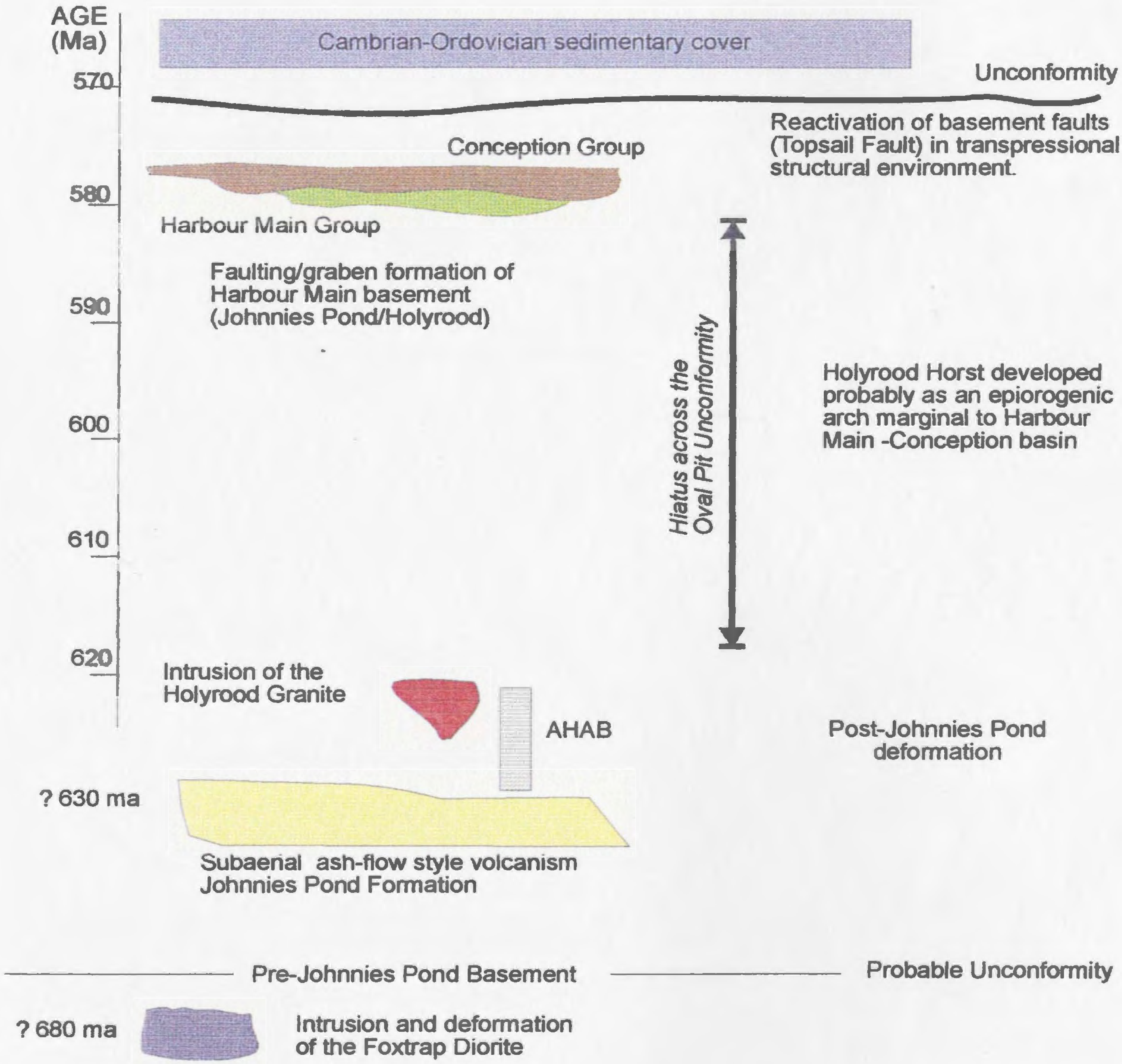
The Cambrian and Precambrian rocks in eastern Newfoundland have been affected by a period of deformation marked by re-activation of existing fault structures. Fossiliferous Cambrian strata are deformed and faulted against Precambrian rocks at Topsail Beach (Rose, 1952; Boyce and Hayes, 1990). McCartney (1967) noted the presence of faults cutting the Cambrian strata. North of the study area, an outcrop of intensely deformed Cambrian shale is exposed on the access road to the bulk fuel terminal and ore dock at Long Pond. The deformation is of such intensity that the material in the exposure is mostly fault gouge and as the outcrop is on strike from Conways Valley it provides an indication that this and other valleys in the field area are likely controlled by post-Cambrian faults.

4.10 Summary of Structural and Depositional History

The structural history of the eastern Avalon Peninsula as determined from this study are shown in Figure 4.6 and are summarized as follows:

D_1. Deformation in the Foxtrap Diorite (pre-630 Ma).

Figure 4.6. *Age relations and timing of structural events in the eastern Avalon Peninsula.*


AGE (Ma)
Cambrian-Ordovician sedimentary cover
570
Unconformity
Reactivation of basement faults (Topsail Fault) in transpressional structural environment.
Conception Group
580
Harbour Main Group
Faulting/graben formation of Harbour Main basement (Johnnies Pond/Holyrood)
590
Hiatus across the Oval Pit Unconformity
Holyrood Horst developed probably as an epiorogenic arch marginal to Harbour Main -Conception basin
600
610
620
Intrusion of the Holyrood Granite
AHAB
Post-Johnnies Pond deformation
? 630 ma
Subaerial ash-flow style volcanism Johnnies Pond Formation
Pre-Johnnies Pond Basement
Probable Unconformity
? 680 ma
Intrusion and deformation of the Foxtrap Diorite

D_2. Pre-AHAB post-depositional block faulting of the Johnnies Pond Formation. These are syn- and pre-Johnnies Pond Formation structures related to the caldera setting and recognized by the tilting of volcanic stratigraphy prior to the AHAB fracture zone.

D_3. Development of the AHAB in a north trending fracture zone.

D_4. Major extension during basin formation as evidenced by syn-sedimentary structures and volcanism in the Harbour Main Group In the later stages it involves unroofing of the Holyrood Horst (partly in conjunction with 4). Transgressive sedimentation on Horst margin in response to extension.

D_5. Development of Topsail Fault flower structure.

D_6. Deposition of Cambrian and Ordovician rocks.

D_7. Reactivation of the Topsail Fault.

CHAPTER 5

DETAILED DESCRIPTION OF ALTERATION AND STRUCTURES WITHIN THE AVALON HIGH-ALUMINA BELT

5.1 Introduction

The Eastern Avalon High-Alumina belt is a brittle structural zone (D_3) along which migrating hydrothermal fluids caused extensive alteration of the Johnnies Pond Formation. The AHAB has mappable alteration zones (Map 1) which parallel the structural grain of the belt and a variety of alteration minerals were produced through the redistribution of elements of the original host rock concomittent with the D_3 fracture zone. In this section the types of alteration are described along with their inter-relationships and their dependencies upon the structural evolution of the AHAB.

5.2 Alteration Types

5.2.1 Overview

The main types of alteration exhibited by the Johnnies Pond Formation are silicification, sericitization, pyrophyllitization, diasporization and hematization. Detailed mineralogical investigations have been completed by previous workers which indicate the bulk mineralogy is dominated by these minerals (Keats, 1970; Papezik, Keats and Vhatra, 1978; Papezik and Keats). These types of alteration are visible in hand specimen scale although many of the features are best seen in outcrop. A propylitic alteration zone marked by the chlorite-coated fractures is developed locally. Features indicative of metasomatism are also exhibited by feldspar phenocrysts in the rhyolites as small patches of secondary feldspar (adularia?).

5.2.2 Alkali Feldspar Metasomatism and Adularia

Exposures of Johnnies Pond Formation, exhibiting no obvious signs of alteration, crop out along the outer margins of the silicified zone. Samples of these rocks were studied petrographically and found to contain features indicative of alkali metasomatism. The metasomatism is marked by the development of chessboard feldspar. This exsolution structure has been reported from rhyolites elsewhere on the Avalon Peninsula that have undergone extensive metasomatism (Malpas, 1971; Hayes, 1985) and are known elsewhere to occur in metasomatized rocks.

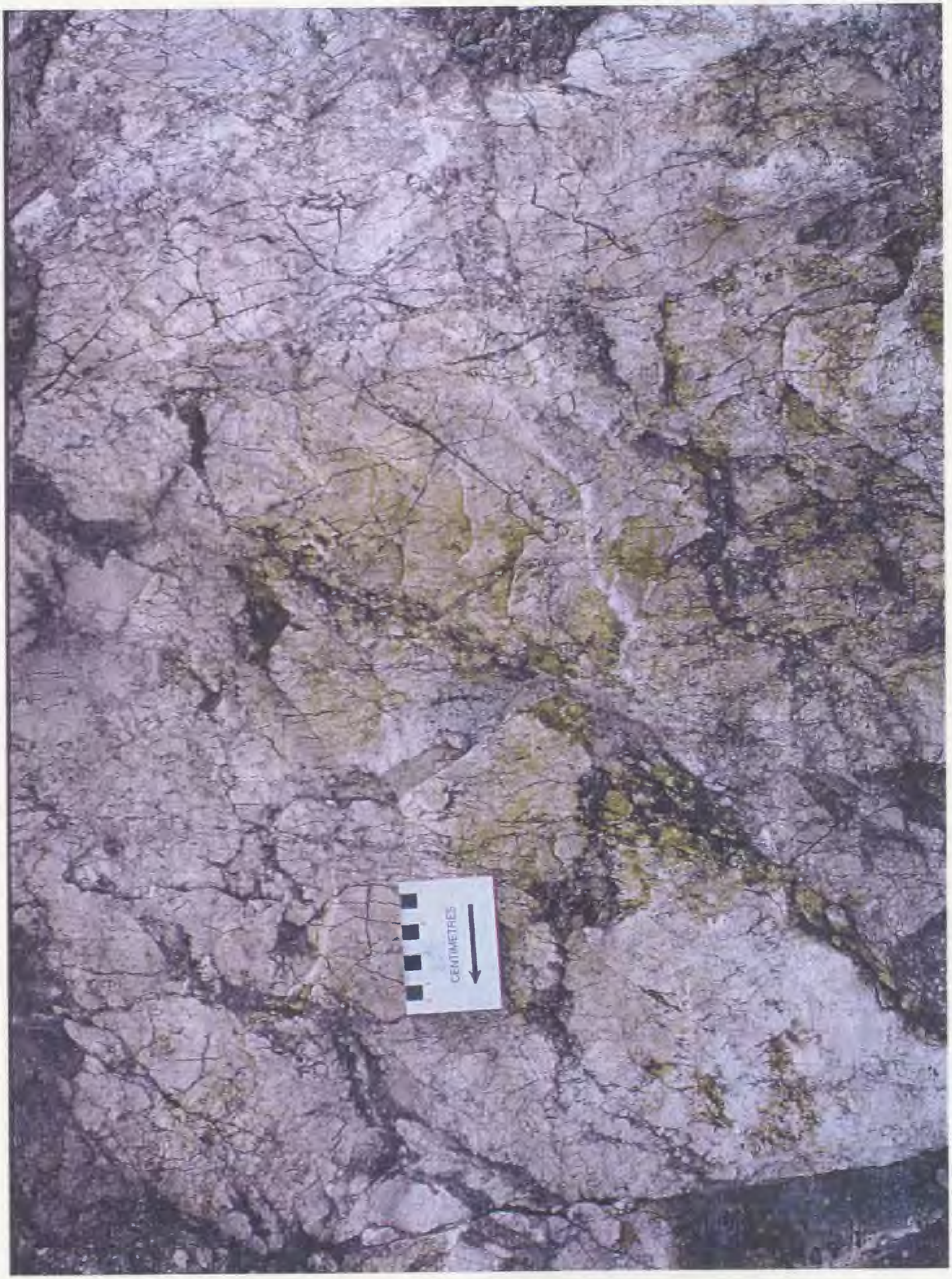
One sample examined contained patches of secondary potassium feldspar as indicated by sodium cobaltinitrate staining. The feldspar appeared to be pore filling, having no discernable crystal shape/form and the entire patch had radial undulatory extinction. These patches are likely adularia, which is a common phase in low sulfidation-type hydrothermal systems (Heald *et al.*, 1987).

5.2.3 Silicification

Silicification is the most regionally extensive type of alteration within the AHAB. The silicified rocks are typically very-fine grained, light grey and typically white-weathering and in places they are tinged reddish-brown by patches of hematite. With the exception of minor quartz associated with some breccias on the distal parts of the alteration system, most silica is present as amorphous chalcedony. The chalcedony forms the matrix to breccias zones throughout the alteration system and commonly fills profuse net-veined fractures within the rhyolites. These fractures are undoubtedly produced by hydrothermal brecciation of the host rock and as there is no evidence of banding this further indicates that silica was introduced during a single brecciation event along each fracture. An example of hydro-thermal brecciation in a silicified zone is shown in Figure 5.1 which shows a silica net vein system cutting rhyolite. Cross-cutting silica veinlets occur in several exposures throughout the belt and indicate that overall silicification involved multiple over printing brecciations and silica flooding events. This may be similar to the crack–seal process described by White and Hedenquist, 1990) From the hydrothermal fields of New Zealand.

Original textures, such as delicate layering features, have also been obliterated in the most intensely silicified rocks. The most intense silicification appears to promote extensive recrystallization of the tuffs and this recrystallization appears to be the fabric destroying stage of the alteration. Locally silicified rocks contain lithophysal zones and exhibit flow

Figure 5.1. *Hydrothermally brecciated and silicified rhyolite near Johnnies Pond.*


CENTIMETRES

banding or layering and as such these robust textures are the only identifiable features of the protolith that are preserved (Figure 5.2).

Silicification was concurrent with hematization along the outer margin of the alteration zone and in these areas hydrothermal breccias with matrices of both chalcedony and hematite are common. Near the Oval Pit Mine, silica–hematite breccias form vein-like zones cutting unaltered rhyolites. The largest veins are sub-vertical, up to 0.5 m wide and contain fragments of the host rock in a grey translucent very fine grained matrix with red hematitic patches (Figure 5.3) Some of the thinner, millimetre-scaled, veins in this locality have hematite-rich cores. The margins of the veins are lined with clear euhedral quartz rather than fine grained chalcedonic silica.

5.2.4 Sericitic Alteration

Sericite was the earliest structurally controlled alteration mineral developed in the AHAB. It occurs on the outer margin of the pyrophyllite zones adjacent to the silicified zone and forms zones overprinting silicified rocks between pyrophyllite occurrences along the belt (Map 1). As is evident on both small and large scales, sericite distribution is closely tied to the structural development of the host rock. The first indication of sericite in the silicified rocks is accompanied by the develop-ment of a weak penetrative fabric evident in hand specimen.

Figure 5.2. *View of silicified zone at the southern end of Mine Hill showing relict flow banding and layering.*


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Figure 5.3. *Quartz–hematite breccia vein near Oval Pit Mine.*

Similar features are also evident on the outcrop scale. Figure 5.4 shows a fracture system in silicified rhyolites which outcrop in a large hill between Little Pond and Trout Pond.The fractures are millimetre to centimetre scaled in width and filled with pale green sericite. Some of the wider fractures contain fragments of comminuted silicified rock and sericite. Sericite locally forms massive schistose zones which crop out between pyrophyllite occurrences. A particularly sericite-rich zone crops out on the power line north of Black Mountain and sericite zones also crop out in the vicinity of Balls Marsh. The sericite zones are also the sites of intense shearing, perhaps some of which is related to post-AHAB deformation focused into these less competant zones.

Sericite also occurs within high-alumina zone rocks in mixtures with pyrophyllite. In the Oval Pit Mine rocks, the typically whitish grey silicified rocks are tinged green when sericite is present and sericitic rocks are marginal to pyrophyllite-rich zones on the scale of the pit walls. Some parts of the pit walls contain a mixture of sericite and pyrophyllite. Keats (1970) found through detailed XRF study that the rocks of northern face of the Oval Pit contained a mixture of sericite and pyrophyllite. This area was examined during the present study and found to be typical of the partly to completely pyrophyllitized rocks in terms of colour, texture and degree of alteration.

Figure 5.4. *Fracture hosted sericitic alteration in silicified rhyolites north of Trans Canada Highway.*

5.2.5 Pyrophyllite

Pyrophyllite occurs as a soft pale-yellow, slightly translucent, very fine-grained mass within fractures and pod-like zones within silicified rhyolitic rocks. The pyrophyllite is locally stained rusty brown and yellow by hematite from the oxidation of post-AHAB pyrite. In thin section individual pyrophyllite crystals are less than .1 mm and difficult to resolve even under high-power (40X) magnification. The distribution of pyrophyllite within most exposures is controlled by typically thin millimetre-scale fractures, however, larger centimetre- to decametre-scale zones are formed by coalescing of fractures. Other metre-scale zones of relatively pure pyrophyllite appear to form by accumulation of pyrophyllite material.

Many of the features of pyrophyllite mineralization can be seen on Mine Hill which is composed, for the most part, of white silicified rhyolitic ash-flow tuff cut by a system of pyrophyllite-bearing fractures. Near the south end of the hill, a small pure pyrophyllite pod is developed within a mass of sheared and silicified pyrophyllitized rhyolite (Figure 5.5). The pod is hosted in a zone of intense fracturing. Where the zone is most fully developed it hosts a 0.5 m wide pod containing abundant centimetre scale, subangular fragments of silicified rhyolite, which are clearly remnants of host rock with their angular shape having been derived from the fractures. The boundaries of the pod are gradational and marked by a reduction in the density of pyrophyllite-bearing fractures. The development of this pyrophyllite zone is clearly influenced by the fracture history of the host-rock.

Figure 5.5. *Pyrophyllite in sheared rhyolite, Mine Hill.*

Elsewhere within the AHAB, pyrophyllite is found in pods which appear to have formed by accumulation rather than *in situ* fracturing and alteration. The boundaries of these pyrophyllite lenses appear sharper than the intensely sheared zones hosting pyrophyllite and the pods are wider on the scale of 1 to 2 m. Less comminuted material is found within the pods and instead large pieces of silicified rock are entrained within the massive pyrophyllite. These indicate that the degree of fracturing was relatively low in these areas. Some of the inclusions of silicified material are, however, conspicuously fractured and this observation is consistent with some pre-pyrophyllite fracturing. These structures terminate at the boundary of the silicified fragment and cannot be traced into the pyrophyllite. Figure 5.6 from Mine Hill is an example of a typical piece of entrained silicified rock. The pods are in most cases influenced by the pattern of intersecting fractures produced by the style of deformation and are often associated with comparatively massive rhyolite rather than the finely commutated material of the smaller fractures. These accumulations are not the result of mere increasing deformation and alteration. Instead these are more likely to have originated as zones of accumulation of pyrophyllite material (Figures 5.7 and 5.8) and imply that physical remobilization of the pyrophyllite is occurring within the alteration system. Examination of the textures within the pyrophyllite zones reveals that there is a fundamental process at work.

Within the largest masses of pyrophyllite, some having exposed areas of over 10 m^2, there are no variations in grain size. In fluid-rich environments one might expect that

Figure 5.6. *Pod of pyrophyllite from Mine Hill with block of silicified rhyolite.*


EXACT

Figure 5.7. *Example of pyrophyllite pod from north of Oval Pit Mine. The pod is located in the interstices of large diamond-shaped fractured blocks of pyrophyllite. The pyrophyllite pod in the photo appears dark-grey to black due to lichen (pen knife is resting on pod). The white coloured rocks are massive silicified rhyolite.*

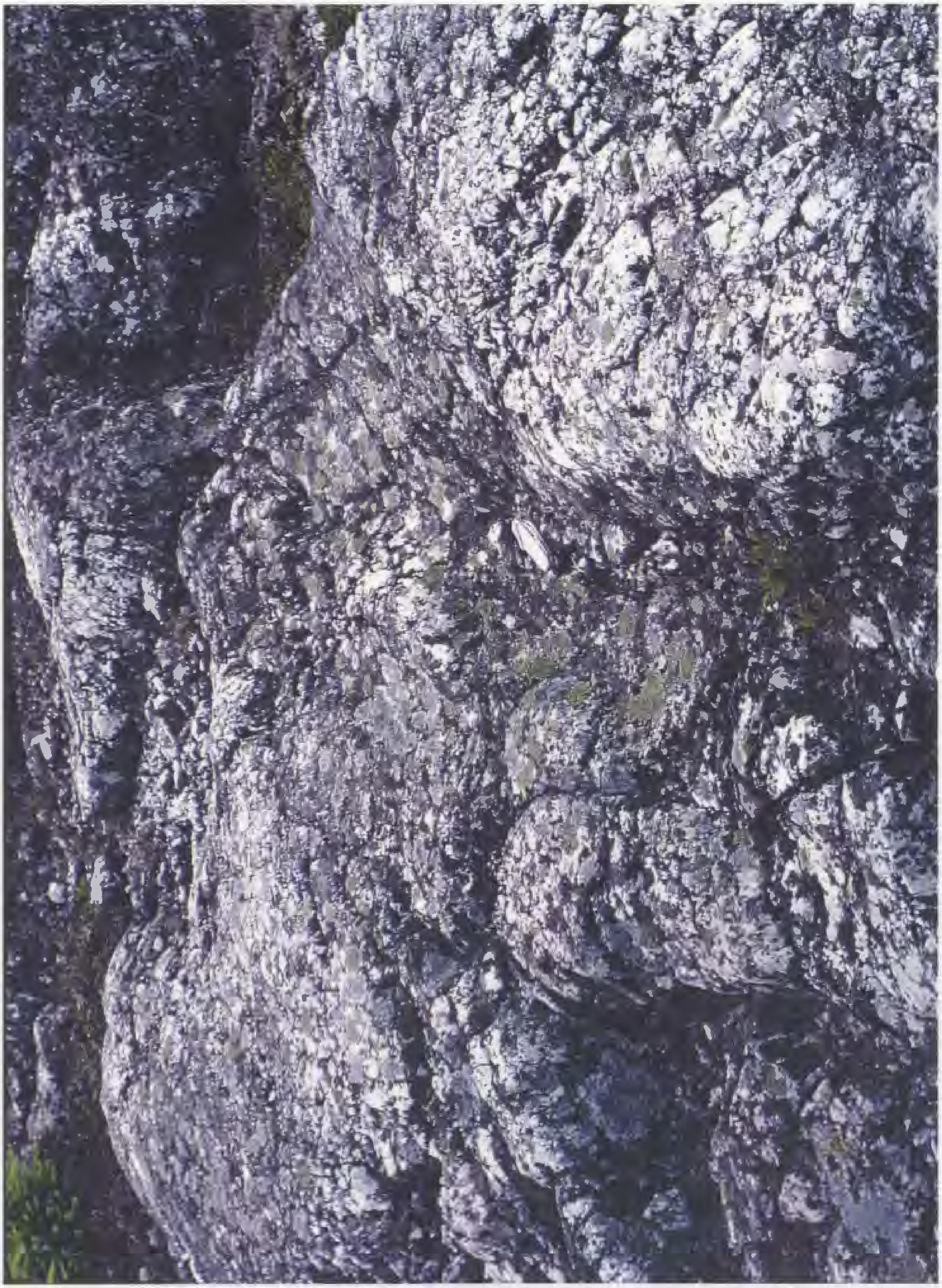


Figure 5.8. *Example of pyrophyllite pod near south part of Oval Pit Mine. Pyrophyllite pod is irregularly shaped and appears to be infilling between blocks of silicified rock.*

crystallization would produce a range in grain sizes and textures leading to a coarsening of individual crystals such as in a pegmatite. Instead the pyrophyllite zones are texturally homogenous and pyrophyllite coarsening only occurs with associated diaspore nodules. This homogenous fine-grained texture indicates that there was little individual crystal growth, yet abundant crystal nucleation. The explanation for this behaviour involves the recognition that the absence of large crystals may imply that there is a kinetic influence inhibiting crystal growth or another mechanism is responsible for controlling crystal growth in the system. One hypothesis is that these zones have originated by the crystallization of a pyrophyllite colloid rather than *in situ* growth of pyrophyllite along fractures. In the colloid model, a colloid with the necessary composition to form pyrophyllite and diaspore would form first in the fracture system and at some stage collect in large fractures or migrate to dilatancy zones. This behaviour would explain why masses of pyrophyllite form irregularly distributed pods rather than being located throughout the fracture system as predicted by the structural relations and also goes far to explain the genesis of the diaspore nodules. The role of colloids or materials with colloidal properties have not been widely documented in natural hydrothermal systems, although there is sufficient evidence to document their existence. The presence of a colloid probably indicates that there are some complexities with the crystallization of pyrophyllite in natural systems. It is known that crystallization is a function of both thermodynamics and kinetics.

Crystal growth mechanisms were discussed by Steefel and Van Cappelen (1990), with particular attention to processes operating when there is a kinetic inhibitor to prevent the crystallization of the thermodynamically preferred phase. Rock dissolution and the crystallization of secondary phases are clearly controlled by solubility relations and the stability of mineral phases. It is noted by Steefel and Van Cappelen (1990) that stable, insoluble minerals can have slow precipitation that is kinetically inhibited even on geological time scales.

Within the AHAB, the main process is the dissolution of quartz and feldspar followed consequently by the precipitation of sericite, pyrophyllite and diaspore. Helgeson (1979) pointed out that dissolution–precipitation systems are rate dependant upon their slowest step. In the case of the AHAB it would imply that the dissolution of feldspar would be largely dependant on the crystallization rate of pyrophyllite. Steefel and Van Cappellen (1990) carry this thinking forward to systems where the crystallization of secondary phases is slow and would inhibit the reaction were it not for the existence of compensatory mechanisms that provide alternative pathways for crystallization. Two mechanisms described are precursor phases and Ostwald ripening.

A precursor crystallizes instead of the more stable phase and is subsequently scavanaged and replaced by the slower crystallizing stable phase. The precursor minerals are usually amorphous or poorly crystalline and may not have the same chemical composition as the stable mineral by which it is replaced by solution in mediated processes (Steefel and Van Cappellen, 1990). Ostwald ripening is also an alternative strategy to inhibitory crystallization kinetics and involves the crystallization of a large number of smaller crystals that are subsequently redissolved and the material transferred to larger crystals (Steefel and Van Cappellen, 1990).

Under near neutral conditions most high-alumina minerals have reduced solubilities and alumina is practically immobile (see Chapter 6). This would mean that the rate of feldspar dissolution in the AHAB would be controlled largely by the crystallization rate of secondary products (cf. Helgeson, 1979). Solubility data for pyrophyllite is not available, so it is difficult to assess the relative solubility relations between feldspar and pyrophyllite quantitatively. There are, however, analagous minerals and behaviours throughout the high-alumina minerals that may help explain the textures within the AHAB. The massive crystallization of pyrophyllite withn the AHAB probably involves precursor processes, however, the local coarsening might involve Ostwald ripening.

Based upon the crystal distribution in the pyrophyllite zones and the pooling of pyrophyllite in large masses within the alteration zones there is a physical role for a precursor in the process of pyrophyllite crystallization. The massive fine grained nature of the pyrophyllite might also be consistent with an early stage Ostwald-like process involving massive nucleation of fine-grained pyrophyllite directly with little or no subsequent crystal growth (with the possible exception of diaspore nodules, see next section). It is unlikely, however, that anything other than massive nucleation could produce monotonous, very fine grained crystals as that seen in the pyrophyllite in the AHAB.

Steefel and Van Cappellen (1990) note that the observation of Parham (1969) that kaolinite forms in weathering profiles as a replacement of halloysite, which in turn, had replaced allophane. This is a naturally occurring example of a precursor and these transformations provide a clear analogy as to processes suspected to have occurred in the AHAB. Kaolinite and pyrophyllite form at about the same pH conditions, the main difference being that pyrophyllite is stable at a higher temperature than kaolinite. The behaviour exhibited by kaolinite at low temperatures can likely be extrapolated to pyrophyllite since the control on the kinetics of crystallization is the solubility of the crystallizing phase. It is expected that pyrophyllite will also have a kinetic barrier to crystallization tending to form supersaturated solutions because most aluminum minerals have poor solubilities, especially within the near neutral to slightly acid conditions envisioned for the hydrothermal fluids of the AHAB. Most pure alumina hydroxides exhibit similar relations. For example, gibbsite ($Al(OH)_3$) is least soluble in the 4.5 to 6 pH range at 100°C (Wesolavski and Palmer, 1994). Bohemite (AlOOH) is also relatively insoluble over this pH range (Caslet *et al.*, 1993). Both are less soluble at higher pH and lower temperatures and at pH $\geq \sim 3$ both these minerals become more soluble by 2 or more orders of magnitude. The behaviour of bohemite is important since it forms an aqueous species during the dissolution of feldspar (Helegson *et al.*, 1984; Walker and Woodland, 1993) such that if a solution were to become supersaturated with bohemite it would impair the dissolution of feldspar. It is also recognized that silica and alumina form complexes at low temperatures in the pH range 4.5 to 8 (with the higher pH restricted to low silica concentrations). The mineral allophane is known from waters outflowing from a hydrothermal alteration system in New Zealand (Wells *et al.*, 1977). Despite the scarcity of data on the presence and behaviour of these minerals at higher temperatures it is clear that allophane, or a mineral like it, could act as a precursor to pyrophyllite crystallization. Importantly it would serve as a sink for alumina and silica, reducing the concentration of these compounds in solution and thereby promoting further dissolution of feldspar.

An alternative mechanism to allophane crystallizing first and being replaced by pyrophyllite is the direct crystallization of pyrophyllite from solution. This is difficult to envisage given the fact that little variation in grain size occurs and there seems to be no plausible way to transport crystallized material to the zones of accumulation. It might be expected that some reduction in rock fragment size be favoured due to the fact that the alteration system is hosted by a fracture zone, however, this must be balanced against the fact that as a hydrothermal system with open spaces controlling fluid flow there should be little further influence on the fragment size by strain where fluids are flowing. Since later Ostwald ripening of the grains does not widely occur this can be interpreted as further evidence for the inference that there is a considerable kinetic barrier to pyrophyllite crystallization. There may be, however, a role for Ostwald processes associated with the coarsening of pyrophyllite in diaspore zones. Unfortunately, there are not any detailed studies of pyrophyllite deposits in which crystallization mechanisms have been addressed on which to make comparisons. This is especially true of the mechanism by which the pods or pyrophyllite form in the dilatency zones. No detailed studies of these types of zones are available.

It would seem from the data gathered in this study that extensive alteration occurs along fractures in the pyrophyllite zones with the immediate phase precipitated being an amorphous allophane with the extraction of silica and alkalis from the host rock.. The allophane largely remains in the fracture systems and the massive pods appear to form by the migration of this material into zones of dilatency where pyrophyllite then crystallizes from allophane.

5.2.6 Diasporization

Diasporization is an alteration/remobilization process occurring within pyrophyllite zones and is marked by the formation of diaspore nodules. The diaspore nodules are accompanied by an increase in the size of pyrophyllite crystals. The pyrophyllite surrounding the diaspore zones is light tan in colour and is somewhat distinct compared to the pyrophyllite found in lower grade zones. The diaspore nodules themselves are typically spherical and contain coarse (5.0 mm) patches of radial pyrophyllite blades and in terms of the hydrothermal system represent small scale zones of pyrophyllite coarsening and the development of a new mineral phase. Since diaspore contains no silica, the diaspore nodules mark the zones of most intense silica depletion. Their presence indicates that alumina is chemically immobile at this stage of the alteration. The spherical nature of the nodules probably reflects that nodule growth occurred within the host pyrophyllite, and were not influenced by other features such as fractures or other dilatencies. Within the context of kinetic mechanisms the coarser pyrophyllite might represent true Ostwald ripening of the fine-grained pyrophyllite.

There are two possibilities for the timing of their formation; the first being that the earliest crystallizing phase in these zones may be allophane, then pyrophyllite to be replaced by coarser pyrophyllite and diaspore in the high-temperature zones. Alternatively, the diaspore nodules could have formed first in the allophane and their associated coarse pyrophyllite with the last stage being massive nucleoation of fine grained pyrophyllite throughout the high-alumina zone. The data from this study are unable to resolve this timing.

5.2.7 Hematization

Movement of Fe in the alteration system is associated with diffusion processes and zones of brecciation or veining and is indicated to occur by the differing styles of hematization associated with the alteration system. The controls on hematization are dependant on its proximity to the core of the high-alumina alteration and style of alteration. Within the Oval Pit Mine there are large patches of reddish brown hematite-stained material within the pyrophyllite zone. On the small scale it can be observed that the hematite zones actually fringe the pyrophyllite zones and consist of two parts. The part closest to the pyrophyllite zones consists of a zone of diffuse dusty hematite and the second part forms within 2 to 5 m from the pyrophyllite front and is marked by the coalescing of the dusty hematite into millimetre-scaled veinlets. Much of the hematite-stained areas on the pit walls contain both these styles of hematization (Figure 5.9). Enclaves of relatively unaltered pyrophyllite within the alteration system are typically fringed by veinlets of hematite.

Outside of the pyrophyllite zones dusty hematite of this type is increasingly rare and the hematite is mostly associated with hematite breccias (although some of the sericitic rocks are overprinted by hematite). The breccias form zones in less altered rocks, and are typically associated with silicified zones distal to high-alumina alteration. In these areas hematite occurs with silica in quartz–hematite breccias. Near the Oval Pit Mine three quartz–hematite breccia veins are exposed. The veins are 15 to 30 cm wide and can be traced for a distance of several metres (Figure 5.3). Much of the same outcrop contains numerous centimetre-scaled hematite veinlets with quartz margins. The largest veins in the area appear structurally controlled by the AHAB shear system. Their orientation suggests that they form in zones of extension oriented obliquely to the overall trend of the alteration system.

5.3 Structural Control on Secondary Mineral Development

5.3.1 Introduction

Much of the apparent complexity in pyrophyllite distribution within outcrops of altered rock has its origin in the structural style of the alteration system. The rhyolitic rocks have no pore space and consequently little inherent porosity, hence development of secondary porosity in the silicified felsic volcanic rocks is necessary to permit fluid flow. The fracture style and pattern influence the shape of the pyrophyllite zones as evident in

Figure 5.9. *Hematite alteration zones proximal to pyrophyllite zones in the Oval Pit Mine.*

many some exposures and the lensoid shapes of the silicified fragments within the alteration system are artifacts of the D_3 fracture system. Not all factors controlling the distribution of alteration assemblages are directly related to variations in fluid composition, temperature or pressure within the zone or the source of fluid. The AHAB demonstrates that in a structurally controlled alteration system the development of the fracture system likely controlls these variables significantly.

5.3.2 Alteration Zonation and Structural Style

The mechanism and type of structural failure is variable throughout the alteration system. In the silicified zones, the presence of hydrothermal breccias indicates that increases in fluid pressure above lithostatic pressure were the causative mechanism of secondary porosity generation. The pathways generated by the hydraulic fracturing were essentially infilled by chalcedony. These zones are located along the margins of the system and also within the core of the system in rocks that have subsequently been overprinted by the pyrophyllite alteration. Brecciation therefore occurs along the outer margin of the system and also at the advancing front of the propagating fracture zone.

The sericite and pyrophyllite in the AHAB are controlled by secondary porosity developed from a fracture system (see below). The coincidence of the alteration style and structural style may be explained in terms of fluid flow rates. The sericite zones are characterized by widely-spaced fractures or a narrow fracture system. In the sericite zone, the fracture system probably did not support sufficient enough a fluid flow to cause a significant elevation in isotherms and/or did not permit large mass transfer from these areas. In contrast the pyrophyllite zones are characterized by the greatest degree of fracturing. This implies that the fluid flow rate was higher in these zones, hence, causing elevation of isotherms and greater mass transfer. These zones were conducive to the formation of pyrophyllite by the mechanisms outlined in Section 5.2.5.

The hydrothermal brecciation episode is not accompanied by sericitic alteration probably indicating that the fluid flow regime was not sufficiently established by this style of deformation to produce either the elevation of isotherms or transfer of material necessary to produce a significant alteration mineralogy. Infilling of the hydrothermal breccias by quartz or chalcedony, also indicates that the fluids were supersaturated with respect to these phases. In essence the style of rock failure and the fluid composition are similarly zoned. Figure 5.10 shows a generalized view of these relationships. The mechanism of fracture may have a large effect on the efficiency of the hydrothermal alteration process. This is explored in the following section.

5.3.3 Role of Fractal Fracture

A noticeable feature of the fractured and altered rocks is the presence of discrete subrounded blocks of silicified rock in a sericite/pyrophyllite matrix. These were called "ellipsoidal schists" by Vhay (1936). In the lesser altered areas, fractures subdivide the host

Figure 5.10. *Overview of alteration zonation and structural development of AHAB.*

Original Rhyolite

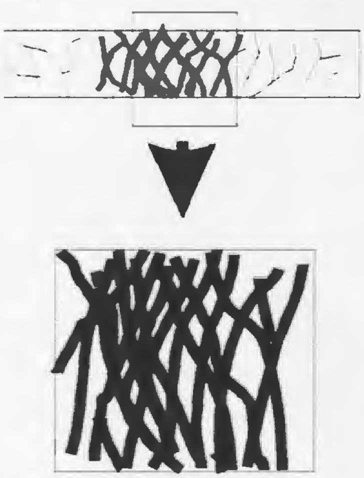
Silicification Stage

Silica added through multiple brecciations and injections of silica-rich fluid.

Sericitization

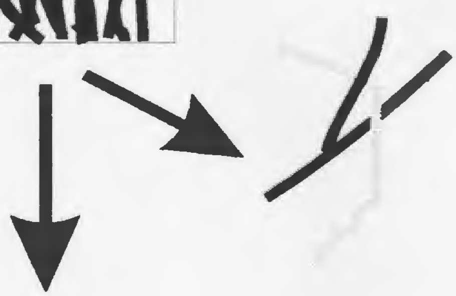
Incipient fracture development permitting restricted flow of hydrothermal fluid. Alteration of feldspar to sericite, K-metasomatism of feldspar

High-alumina Stage

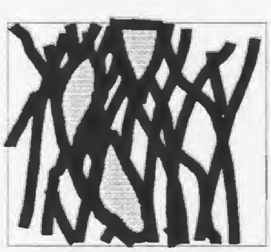


Increase in fracturing promotes higher fluid flow which elevates isotherms. Dissolution of feldspar proceeds, silica is removed from the rock in the hydrothermal fluid. Alumina minerals form in the fracture space.

Silica is removed from the host rhyolite and sedcondary phases form in the fracture spaces. Alumina complexes with silica to form allophane



Iron is mobilized along with some silia to form quartz hematite breccias in lesser altered rocks and as broad zones of hematization proximal to the alteration front



Allophane migrates through fracture system into zones of dilatancy and undergoes crystallization to pyrophyllite. Diaspore forms in high-alumina zones in response to increases in temperature.

rock into crude diamond-shaped blocks by a process that is scale-invariant as it persists from outcrop to hand specimen to thin section with little change in style or appearance. It is, however, becoming accepted that fracture systems display fractal geometries (Chiles, 1988; Chelidse and Gueguen, 1990; Steacy and Samms, 1991; Nagahama, 1993). Scale-invariant phenomena are a consequence of a fractal origin. Fractal geometries are restricted to a finite range (compare Wong and Lin, 1988), and outside of the more "fractal" parts of the fracture system Euclidean geometries are present.

Euclidean geometries are easiest to observe between the pyrophyllite deposits in areas dominated by sericitic alteration. This may be an artifact of preservation, or it may reflect a lower strain in these areas. It has been demonstrated that fractal dimension (or the degree of deviation from Euclidean geometry) increases with energy input in fracturing experiments (Poulton *et al.*, 1990). These observations might also indicate that fractal dimension will increase with increases in loading rates and strain in natural systems. In areas with euclidean geometries (i.e., fractures can be recognized over distances of 5 m or more), there appear to be fewer fractures, and those that are present are wider spaced. It has been demonstrated that the roughness of a fracture increases with fractal dimension (Lee *et al.*, 1990). Fracture roughness also influences the surface area of a fracture surface in that smooth fractures have less surface area than rough fractures.[5]

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[5] This can be intuitively demonstrated with a bucket of paint. It takes more paint to cover a rough surface than a smooth one since it has larger surface area.

Within the AHAB this relationship between roughness and surface area likely exerts a fundamental control on the alteration system. A rough fracture maximizes the contact area between the rock and water hydrothermal solution thereby facilitating the mineral–fluid interactions that produce alteration. In areas where there are few, narrow linear fractures, there is abundant sericitic alteration and this is consistent with low fluid flow (as will be demonstrated in Chapter 6). Pyrophyllite zones are characterized by abundant small scale fractures with no clear Euclidean features. These geometries are difficult to quantify due to local variation and modification of fracture surfaces during alteration. It is therefore improbable that an accurate estimate of their contribution to increased fracture surface area can be made. However, they represent a significant factor in determining the progress of hydrothermal alteration in this system as given by field relations. The greater degree of fracturing promotes greater infiltration of the hydrothermal fluid. Isotherms will be higher in these areas and consequently the highest temperature alteration assemblages are formed in the most fractured zones.

CHAPTER 6

THERMOCHEMISTRY AND SOLUBILITY RELATIONSHIPS BETWEEN PHASES IN THE ALTERATION SYSTEM

6.1 Introduction

The mineralogy of most significant aluminosilicate phases within the alteration system can be expressed in terms of the Al_2O_3–K_2O–Na_2O–SiO_2 system; phase relationships within this system have been studied in detail and provide some insight into the nature of pyrophyllite stability. It is important that these data be reviewed to fully appreciate the dynamics of material transport in relation to the hydrothermal fluid and the distribution of secondary phases. Knowledge of the mechanics and stages of feldspar dissolution is integral to the understanding of the process of pyrophyllitization and how the solution chemistry is reflected in the zonation of the alteration minerals. The mineral zoning reflects the fundamental solubility relations of alumina and silica minerals.

6.2 Review of Stability Data and Relations

6.2.1 Alteration Minerals in the AHAB

Most of the alteration minerals in the Avalon-High-alumina Belt belong to the system Al_2O_3– K_2O–N_2O–SiO_2. Table 6.1 lists the composition of phases that are of interest within this system as they either are present in the AHAB or their absence permits some immediate conclusion to be reached. It should be noted that the list of minerals that are present in the

Table 6.1. *Partial listing of minerals in the system*

Al_2O_3–K_2O–Na_2O–SiO_2

Mineral	Formula	Present in AHAB
Quartz	SiO_2	x
Chalchedony	SiO_2	x
Orthoclase	$KAlSi_3O_8$	1
Adularia	$KAlSi_3O_8$	o
Albite	$NaAlSi_3O_8$	1
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	x
Kaolinite	$Al_2Si_2O_5(OH)_4$	n
Muscovite	$KAl_3Si_3O_{10}(OH)_2$	x
Paragonite	$NaAl_3Si_3O_{10}(OH)_2$	n
Diaspore	$HALO_2$	x
Corundum	Al_2O_3	x
Topaz	$Al_2SiO_4(FOH)$	o
Andalusite	Al_2SiO_5	n
Kyanite	Al_2SiO_5	n
Sillimanite	Al_2SiO_5	n

x - present;
n - absent;
o - identifed optically in small grains;
1 - largely present as components of sanadine

AHAB includes phases that are solid solutions (sanadine) or represent great degrees of mineralogical disorder (adularia). Alunite is commonly associated with pyrophylite in many high alumina alteration systems (Hemley *et al.*, 1969) yet it is absent in the AHAB.

6.2.2 A Review of Stability Relations between Phases

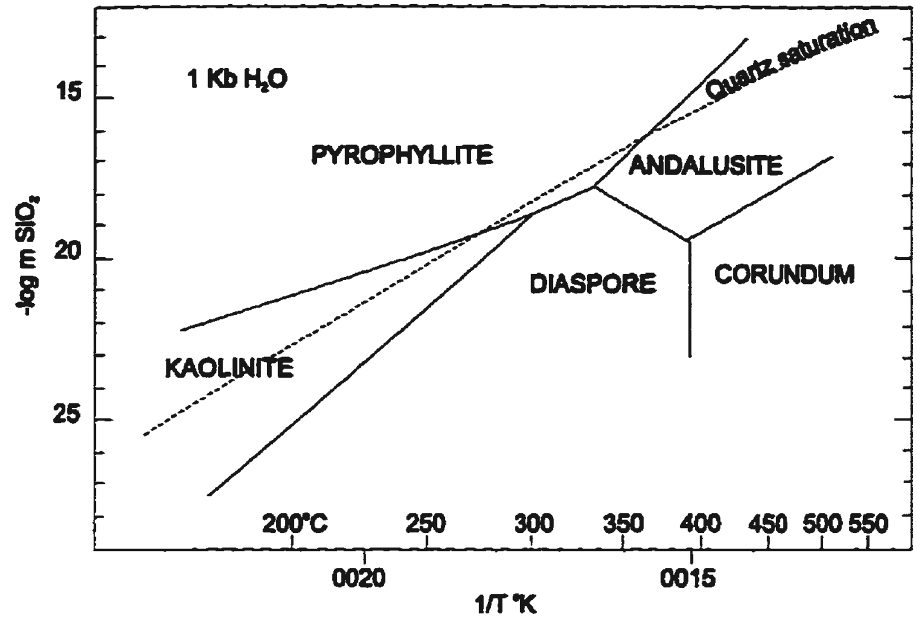
The stability relations of high-alumina minerals in natural hydrothermal systems have largely been extrapolated from studies of the topology and the stability limits of the phases in the system SiO_2–Al_2O_3–H_2O (Haas and Holdaway, 1973; Burt, 1976; Day, 1976; Hemley *et al.*, 1980). More recent sttudies aimed at determining the stability of feldspar and muscovite (Helgeson *et al.*, 1984; Sverjensky *et al.*, 1991) yield a more complete picture for the hydrothermal systems developed in felsic rocks. The choice of experimental technique and the subsequent application of the phase diagrams appears to have been the source of the belief that the presence of pyrophyllite in a hydrothermal system must indicate acidic conditions. This can be demonstrated to be an oversimplification.

Figure 6.1 illustrates the phase relations in the system SiO_2–Al_2O_3–H_2O. The main feature of the equilibrium relationships of importance to the AHAB in this system is the join between pyrophyllite–diaspore which exists from about 273° ± 10°C to 366° ± 10°C (Hemley *et al.*, 1980). It is characterized in this region by a sloping boundary indicating that at any given temperature the stability of diaspore is strongly influenced by the concentration of silica in the coexisting fluid. It can also be expected that for any point on the pyrophyllite–diaspore curve, an increase in temperature will shift the equilibrium towards diaspore, producing silica according to the reaction:

$$Al_2Si_4O_{10}(OH)_2 + 8\ H_2O \rightarrow 2\ AlO(OH) + 4\ H_4SiO_4$$

(from Hemley, 1980).

Figure 6.1. *Phase relations in the system Al_2O_3–SiO_2–H_2O (from Hemley* et al., *1980).*

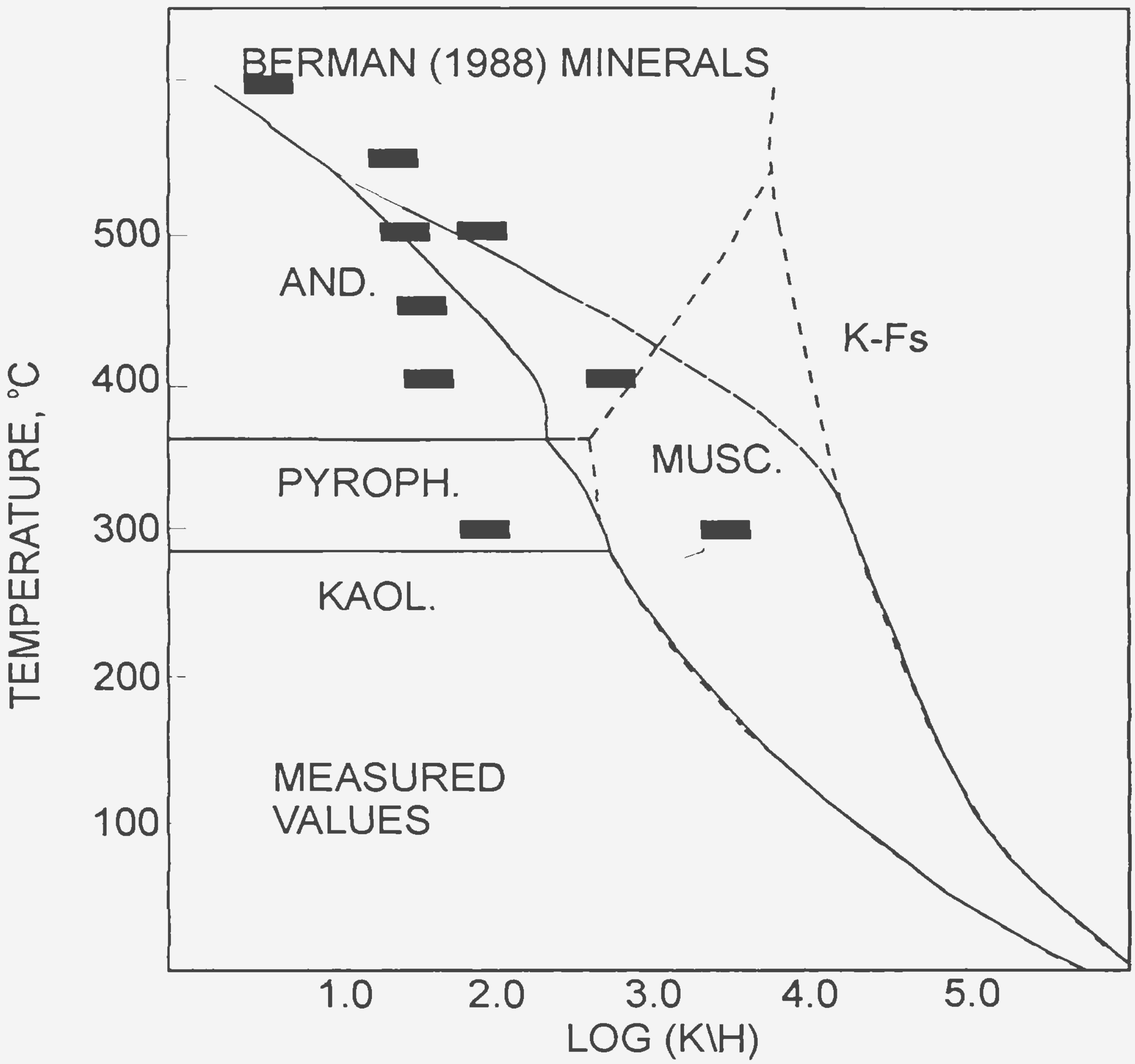

1 Kb H_2O
Quartz saturation
PYROPHYLLITE
ANDALUSITE
DIASPORE
CORUNDUM
KAOLINITE
-log m SiO_2
15
20
25
200°C
250
300
350
400
450
500
550
0020
0015
1/T °K

Sverjensky *et al.* (1991) conducted an assessment of feldspar–mica–aluminosilicate equilibria and provide a concise overview of relations of these minerals. Instead of examining stability as a function of SiO_2, as was the case with Hemley *et al.* (1980), the K/H composition of the fluid in equilibrium with the mineral assemblages during experimental runs were compared to calculated stability relations. The study also compared different internally consistent thermodynamic datasets (Helgeson *et al.*, 1978 and Berman *et al.*, 1988). The final adjusted data have topologies that are identical, however the position of phase boundaries differ. The pyrophyllite–kaolinite boundary calculated using the data of Berman *et al.* (1988) is closer agreement to the value determined experimentally by Hemley *et al.* (1980) than the data of Helgeson *et al.* (1978). It also places the lower thermal limit of pyrophyllite stability above 300°C (Figure 6.2).

The most significant feature of the relationships on this diagram is the boundary between muscovite and pyrophyllite. Most previous workers on the AHAB (Papezik *et al.*, 1978, Taras, 1989) consider the production of muscovite an intermediate phase. Essentially these diagrams indicate that the stability of pyrophyllite versus the stability of muscovite is controlled by both the narrow thermal stability field of pyrophyllite and the aK^+/aH^+ of the solution[6]. It would appear that the muscovite is stable at the expense of pyrophyllite when the activity of K is about 100 times that of H^+. Conversely pyrophyllite is stable at low K^+

[6] The calculated and experimental data for m_K/m_H (molal) concentrations in solution agree closely but are different from the calculated activity ${}_aK^+/{}_aH^+$ ratios at high temperatures due to complexing with chloride ion (Sverjensky *et al.*, 1991).

Figure 6.2. *Feldspar–mica–aluminosilicate equilibria (from Sverjensky* et al., *1991).*



The variation with temperature at 1.0 kbar of experimentally measured values of log ($m_{t,K}/m_{t,H}$) in 1.0 molal chloride solutions (solid symbols) and theoretically calculated values of log ($m_{t,K}/m_{t,H}$) and log a_{K+}/a_{H+} (solid and dashed curves, respectively), for the assemblages kaolinite-muscovite-quartz, andalusite-muscovite-quartz, andalusite-K-feldspar-quartz, and K-feldspar-muscovite-quartz.

activities with respect to H^+. Many authors describing hydrothermal alteration have considered pyrophyllite to be a hallmark of acid alteration and certainly acid solutions may have H^+ activities that are considerably higher than K^+. The phase relations indicate that the acid solutions that produce pyrophyllite merely satisfy the condition of having a low K^+/H^+ solution composition (see also Rose and Burt (1979)). Pure water has $aK^+ = 0$ and also satisfies this condition. Pyrophyllite may equally be a product of near neutral, or basic solutions having these relations when the temperature is above 275°C.

It is worthwhile to note that the data to produce the types of diagram in Figures 6.1 and 6.2 are typically determined using pressure vessels containing mixtures of pure reactants and subjected to varying P-T conditions until it is expected that a reaction has taken place. The starting materials are then removed and examined for new phases. Very little can be determined about the process of the reaction which takes place. Recently the reaction rate and process of dissolution of mineral phases in this system has been studied. These data provide more direct evidence for the mechanism and controls on hydrothermal alteration within the zone and the data relevant to this problem are explored in the next section.

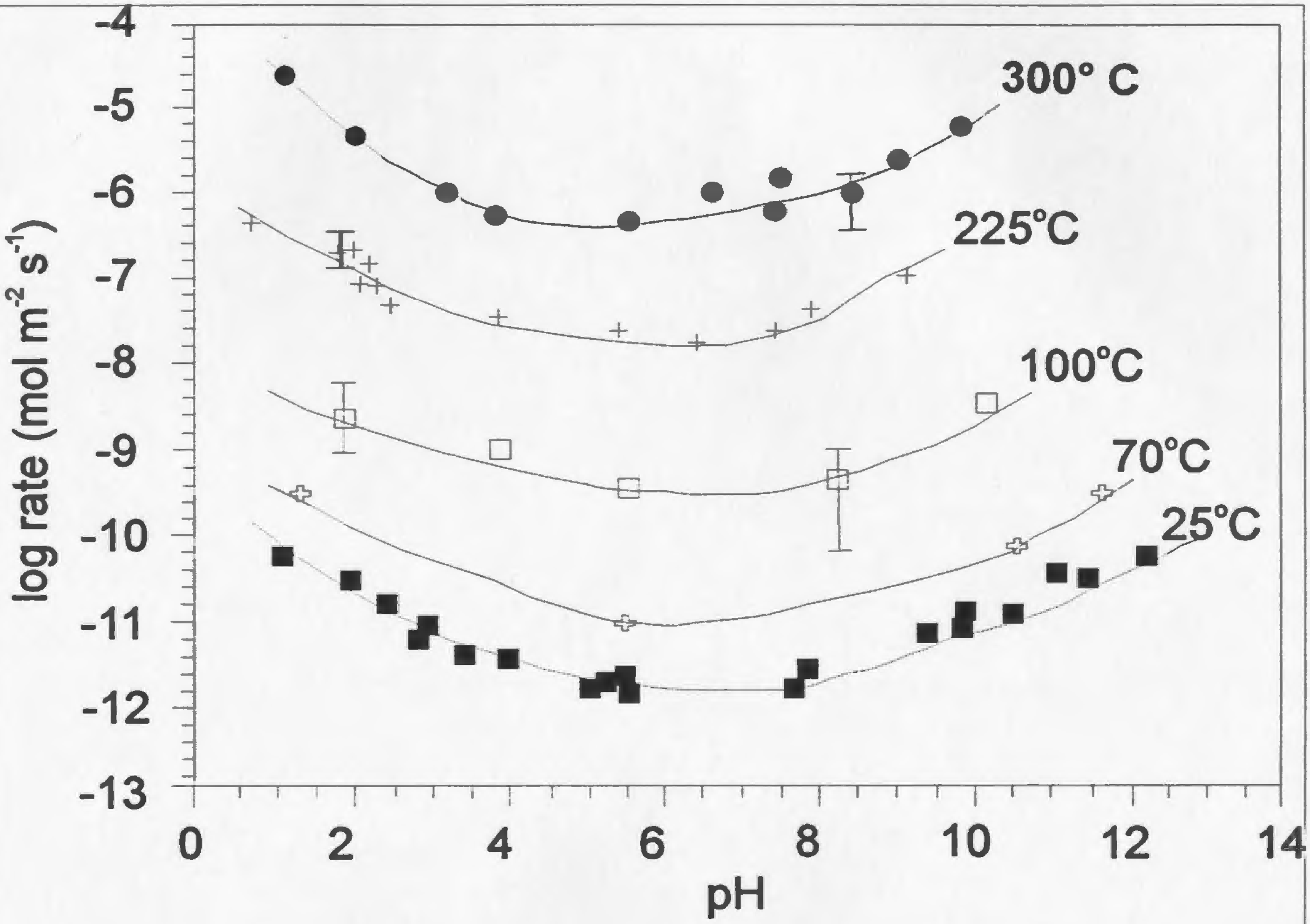
6.3 Mineral Dissolution Rates and Solubility

The dissolution process in the AHAB involved mass transfer between the host rock and the hydrothermal fluid which was localized in the fracture zone. The relative solubility of quartz and feldspar and the behaviour of alumina and silica in hydrothermal fluids appear to be the dominant influences upon the morphology of the alteration zoning.

Feldspar dissolution kinetics have been determined to be strongly pH dependant at any given temperature (Helgeson *et al.*, 1984; Hellmann, 1994; Hellmann *et al.*, 1990). Figure 6.3 (after Hellman, 1994, Fig. 4. p. 603) indicates that for the range of temperatures of interest in hydrothermal solutions, the dissolution rate of feldspar is lowest between near neutral and slightly acid solutions. It is also clear from dissolution studies that feldspars dissolve incongruently, with preferential release of K or Na cations, silica or Al dependant upon prevailing conditions. Studies aimed at understanding surface processes of feldspars subjected to hydrothermal conditions have determined that there is a leached surface layer which varies in thickness with pH (Chou and Wollast, 1984; Hellman *et al.*, 1990). These studies also indicate that the lack of an extensive leached layer development for near neutral experiments indicates that these solutions are poor solvents for feldspars. There have been different interpretations as to how feldspar hydrolysis kinetics operate. It has been suggested that the material transport through the leached layer may influence the dissolution rate of feldspar (Helgeson, 1971), however, studies of Chow and Wollast (1984) imply that the leached layer is not a process boundary.

Single, pure, well-ordered or completely disorded feldspars are often the subject of these experimental studies whereas feldspar in natural systems invariably exhibit more complex behaviour. Orville (1963) demonstrated that feldspars in contact with hydrothermal

Figure 6.3. *Feldspar dissolution rate after Hellman, 1994.*



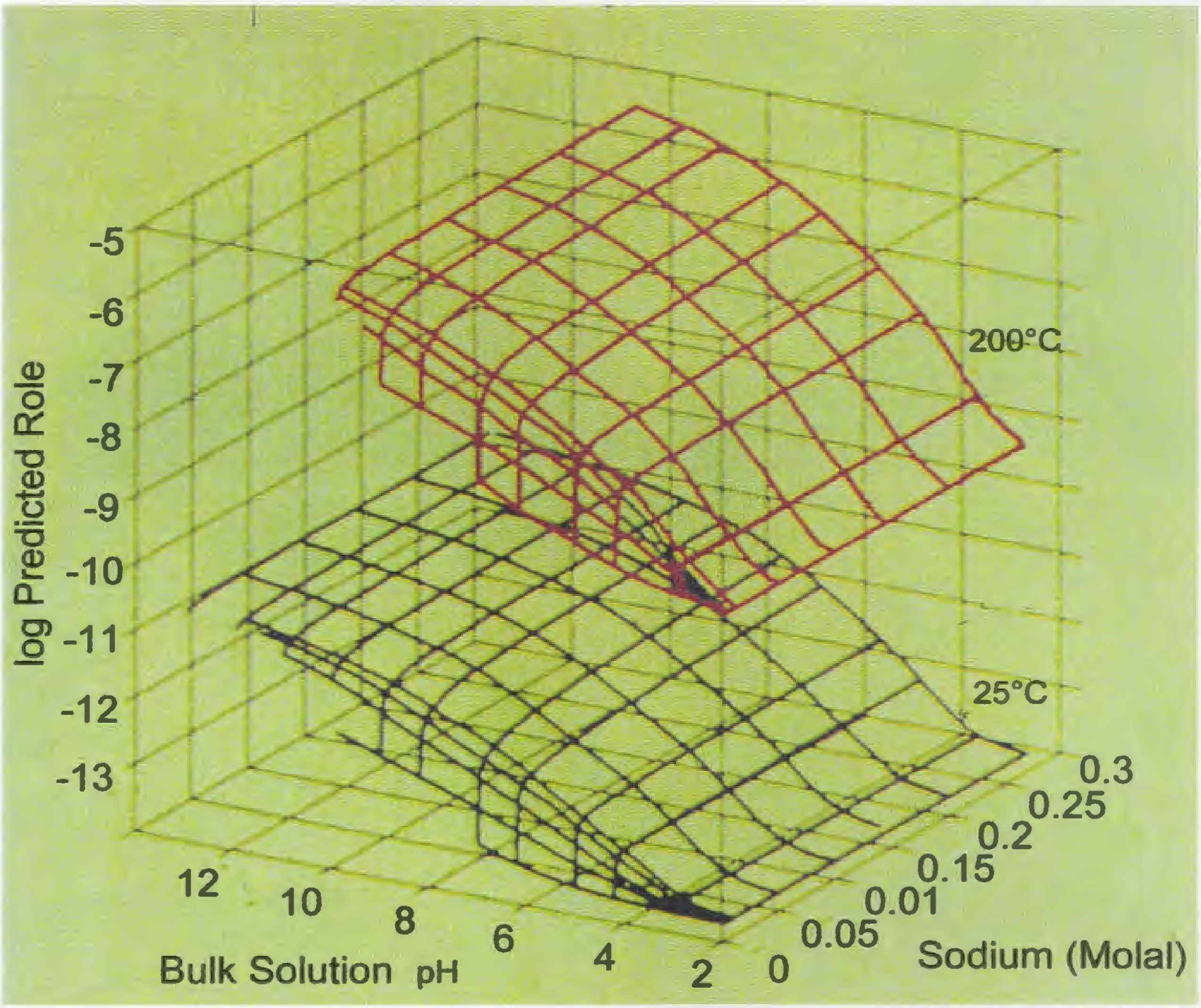
Comparison of albite dissolution rates.
Data from Hellman 1994 (fig 4)

solutions will preferentially exchange Na for K and this behaviour was recently confirmed by Walker and Woodland (1993). The process is extremely efficient and Na will be exchanged for K even when the abundance of Na is 400 times less than than of K.This type of exchange is unavoidable in feldspar-water systems and probably occurred early in the AHAB. The exchange reaction would tend to change the feldspars exposed in the fracture system producing a pure K-feldspar by removing Na. This may explain the persistence of sericite and the exclusion of paragonite within the pyrophyllite zone.

The dissolution of quartz also plays a significant role in the alteration system and its behaviour is controlled by a variety of factors including temperature, pH and the presence of other ions in solution particularly Na^+ and K^+ (Dove, 1994). At any given temperature and fluid composition the behaviour of quartz is largely antithetic to that of feldspar. Quartz is most soluble in solutions of near neutral composition and is particularly insoluble in acid solutions (see Figure 6.4 after Dove, 1994). This contrast in behaviour is the underpinning of the morphology of any zone of high alumina alteration in felsic rocks.

The importance of these observations in formulating models of pyrophyllitization is that simple replacement of feldspar by pyrophyllite has not been observed in any experimental procedure. In fact, feldspar dissolution is incongruent and even in natural systems may lead to the formation of secondary products. The evidence for sluggish dissolution kinetics at near neutral compositions by no means prohibits the dissolution of feldspar, yet it is suggestive that other processes may be aiding the dissolution process in the AHAB. This

Figure 6.4. *Solubility of SiO_2 after Dove (1994).*



log Predicted Role
-5
-6
-7
-8
-9
-10
-11
-12
-13
200°C
25°C
12
10
8
6
4
2
Bulk Solution pH
0
0.05
0.01
0.15
0.2
0.25
0.3
Sodium (Molal)

is a clear indication that the development of a fractal fracture system with a large surface area is the key process in producing pyrophyllite from hydrothermal solutions of near neutral pH.

6.4 Description of the Genesis of the Alteration

Hydrothermal fluids in disequilibrium with rocks which they contact will produce changes in the composition of both the fluid and host rock as the system tends towards equilibrium. This change be produced by exchange reactions, oxidation, dehydration, hydrolysis or dissolution of mineral phases. The alteration products within the AHAB appear to have formed principally by dissolution of and precipitation of the original host rock. The formation of alumina-rich zones, including the silica-depleted diaspore zones likely involves a series of reactions. An additional step in the process involved in transforming rhyolite into pyrophyllite is that the initial material might as well have been glass. It is known from experimental studies with rhyolitic glass that it can exist as a metastable phase and undergo K–Na ion exchange under hydrothermal conditions (Shiraki and Liyama, 1990). Fracturing introduces primary permeability and fluids are permitted to flow through the rock. The fluid both dissolves minerals and transfers heat to the rockmass elevating the isotherms along the fracture zone. Within the core of the alteration zone feldspars are dissolved, leaving a relatively insoluble alumina-rich residual phases and silica is transported along with alkalies to the extremities of the alteration system. Reaction of transported alkalis with unaltered feldspars promotes ion exchange, sericite forms in zones peripheral to the high-alumina zones in response to K/H ratios in the fluid and elevated isotherms. Silica, being carried by the hydrothermal fluid in high concentrations is injected into the surrounding rockmass during periods of hydrothermal brecciation. During the pyropyllitization process the fate of minor components is less well known. Fe and Mg may form chlorite in the outermost parts of the hydrothermal system. Iron moves in colloidal form (Papezik *et al.*, 1978) outwards from the pyrophyllite zones and coalesces forming veins in less-altered rocks. Some silica is carried into these veins in addition to the hematite. The hematite zones appear to be remobilized as the alteration front progresses.

Within the high-alumina part of the alteration system, an amorphous high-alumina phase, probably allophane, forms along the fracture planes. Zones of massive pyrophyllite form through intense fracturing and alteration locally although most large pods appear has formed by the migration allophane into dilatent zones. The allophane undergoes crystallization with earliest crystallization producing the coarse pyrophyllite associated with diaspore nodules. These areas probably have the highest temperature zones since diaspore is stable at higher temperatures than pyrophyllite. The coarse well-formed radiating clusters of pyrophyllite occurring with the diapore nodules is consistent with a longer period of crystal growth than that of the remaining pyrophyllite zones and perhaps involves recrystallization of early fine-grained pyrophyllite. The main masses of pyrophyllite crystallize en masse as very fine grain size and in all of the pyrophyllite pods indicate rapid crystallization.

CHAPTER 7

GEOCHEMISTRY OF THE AHAB

7.1 Introduction

The original mineralogy of the Johnnies Pond Formation is replaced by secondary minerals within the Avalon High-Alumina belt. The description of the field relationships within the altered rocks of the AHAB in Chapter 6 demonstrates that the replacement process occurs in stages, with silicification preceding both sericitization and pyrophyllitization. The alteration processes are not pervasive and consequently outcrops of the alteration system exhibit considerable heterogeneity at all scales. It is expectable that through the alteration process a rhyolite in the AHAB will have elevated values of silica during silicification and then through the sericitization and pyrophyllitization process contain less silica. At some point its silica composition will revert to its unaltered composition as the alteration vector approaches the high alumuna composition. The analyses of any partly pyrophyllitized rock will reflect both the silicification/desilicification processes to some degree. The geochemistry of immobile major elements will also be affected in this process through the constant sum effect. The challenge in extracting information about the alteration system through geochemistry is to select and apply methods of data analyses which will negate this effect.

In this chapter major and trace element and data are used to explore the alteration process. The topics to be addressed in this part of the study are the description of the composition of the altered rocks and unaltered rocks, comparisons of chemical and physical transport of material, the relative mobility of elements, and the original chemistry of the rhyolitic rocks as preserved in the geochemical data. The geochemical data are available in digital form from the Newfoundland Department of Mines and Energy as Open File NFLD/2377 (Hayes, 1994).

7.2 Trends in Major Component Composition

7.2.1 Overview of Alumina–Silica–Potassium Compositions

The major element geochemistry of the rhyolitic rocks within the Johnnies Pond Formation largely reflect the conversion of the igneous minerals to the secondary assemblage of the Avalon High-Alumina belt. The most apparent changes occur in the silica, alumina and pottasium contents since the chemical equilibria involve the stability of quartz, feldspar, sericite, pyrophyllite and diaspore.

Table 7.1 (data from Hayes, 1994) provides summary statistics for SiO_2, Al_2O_3 and K_2O and compares different types of alteration mineralogies. The most evident feature of the data is that there is considerable overlap in composition between rocks representing different parts of the alteration system. The overlap in the sample ranges reflects the heterogeneity of the samples and also the reversal of compositional vectors within the alteration system. This can be seen readily in the summary statistics for SiO_2 in the pyrophyllitized rocks, the l

Table 7.1. *A comparison of SiO_2, Al_2O_3 and K_2O grouped by alteration type*

Element	SiO_2	SiO_2	SiO_2	SiO_2	SiO_2	Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3	K_2O	K_2O	K_2O	K_2O	K_2O
Rocktype	all	P	S	SS	U	all	P	S	SS	U	all	P	S	SS	U
Mean	75.9754	70.9025	76.9343	74.626	77.3683	12.9483	22.0375	11.6228	13.028	11.87	4.6438	1.9613	5.3172	4.83	3.6183
Std Err	0.6096	3.6013	0.6195	1.6084	0.5869	0.5087	3.1692	0.2785	0.8895	0.4908	0.2851	0.5393	0.3601	0.5628	0.7983
Min	53.15	53.15	64.08	63.7	73.8	6.31	9.67	6.31	7.97	9.67	0.16	0.3	0.91	0.71	0.16
Skewness	1.3673	-0.4945	-0.4794	-0.5191	-0.4785	2.8818	0.2373	-0.3475	0.5247	-0.0398	0.1895	0.3314	0.2452	0.1526	0.1791
Median	77.37	72.33	77.45	77.45	77.525	11.78	21.84	11.66	11.74	11.985	4.45	1.76	5.405	4.21	3.405
Variance	30.1021	103.7567	17.6524	38.805	4.1338	20.959	80.3504	3.5674	11.8695	2.89	6.5859	2.3268	5.9636	4.752	7.6482
Max	87.79	84.52	87.79	83.75	79.98	36.62	36.62	15.71	18.85	14.19	11.26	4.29	11.26	8.27	8.34
S E Skew	0.2673	0.7521	0.3501	0.5801	0.6373	0.2673	0.7521	0.3501	0.5801	0.6373	0.2673	0.7521	0.3501	0.5801	0.6373
5% Trim	76.322	71.1322	77.0397	74.7261	77.4215	12.3359	21.9144	11.6674	12.9856	11.8633	4.5961	1.9242	5.2477	4.8678	3.5481
Std Dev	5.4865	10.1861	4.2015	6.2294	2.0332	4.5781	8.9638	1.8888	3.4452	1.7	2.5663	1.5254	2.4421	2.1799	2.7655
Range	34.64	31.37	23.71	20.05	6.18	30.31	26.95	9.4	10.88	4.52	11.1	3.99	10.35	7.56	8.18
Kurtosis	3.1695	-0.295	1.2363	1.0724	0.8529	10.7441	-0.792	1.1924	-1.0555	-1.8535	-0.5064	-1.5056	-0.3799	-0.4427	-1.1675
IQR	5.525	14.6925	5.385	11.2	3.84	3.2	13.8075	2.1425	6.47	3.005	3.74	2.905	3.965	3.21	5.525
S E Kurt	0.5287	1.4809	0.6876	1.1209	1.2322	0.5287	1.4809	0.6876	1.1209	1.2322	0.5287	1.4809	0.6876	1.1209	1.2322
n	81	8	46	15	12	81	8	46	15	12	81	8	46	15	12

all	all samples
P	Pyrophyllite-bearing rocks
S	Silicified rocks (rocks containing some brecciation and silica veining in outcrop)
SS	Silicified and sericitized (rocks containing fracture hosted sericite within a silicified host)
U	Various tuffs and welded rocks showing little or no evidence of alteration or veining

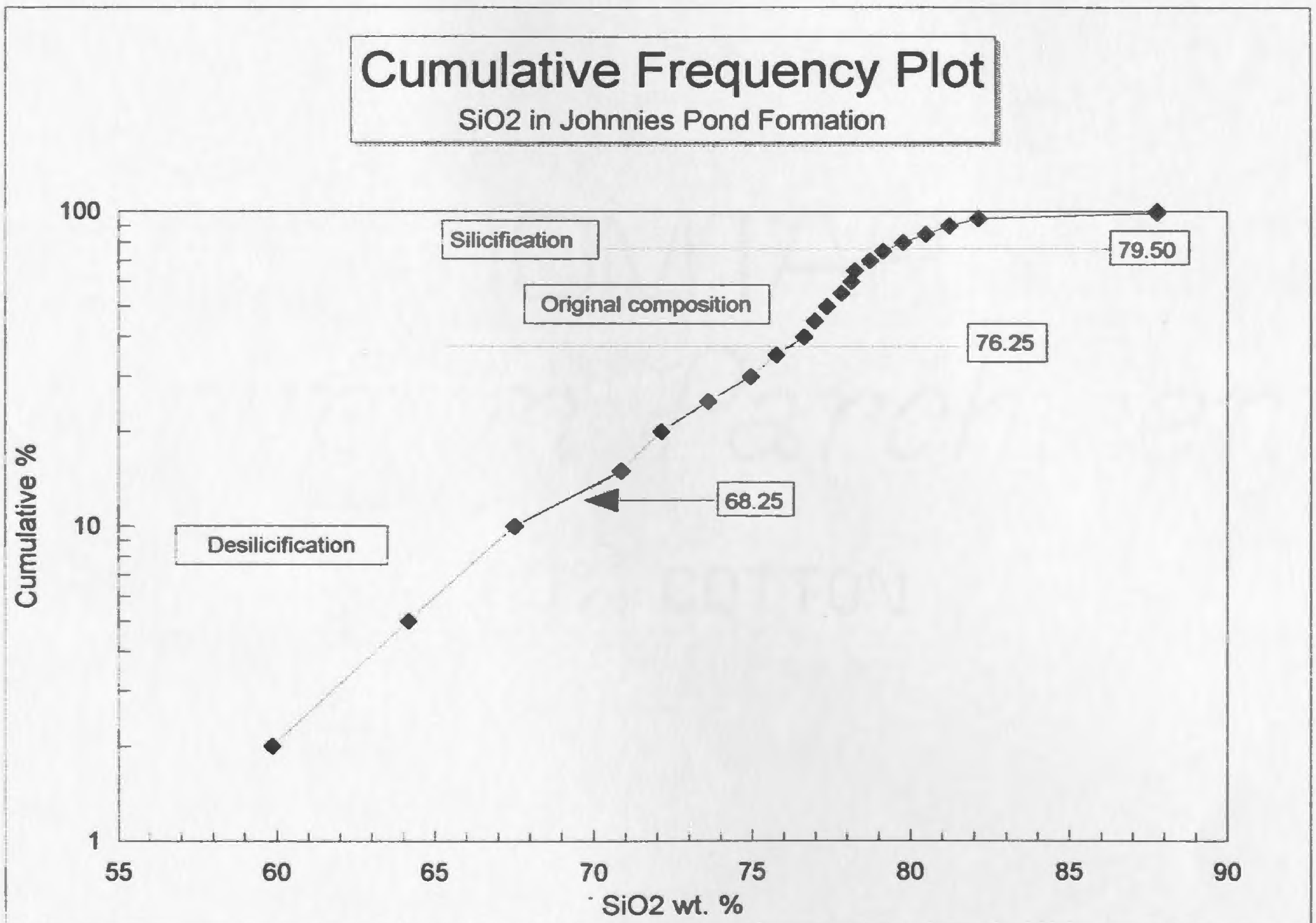
sigma error (10.18%) at 70.90 SiO_2 shows considerble overlap with the unaltered rocks (2.03 at 77.37% SiO_2).

Similar features are also present in the K_2O data. Silicified and sericitized rocks (SS) contain apparently less K_2O than rocks which are classed as silicified (S). The presence of greater Al_2O_3 and SiO_2 in the silicifed and sericitized rocks has likely produces lower values of other constituents (including K_2O) through the constant sum effect (see Section 7.2) and also through redistribution of K in the alteration system. The effects of these processes relative to each other cannot be obtained from univariate anaysis of the compositional data.

Another means of examining the distribution of these elements is through the use of cumulative frequency plots. Cumulative frequency plots of data representing a single normally distributed population produce a straight line. Those data which contain values from different populations when plotted in this fashion will reveal a series of inflection points along a curve. The inflection points mark the boundaries between differnt sub-populations. The distribution plots show curves indicating populations that represent the different types of alteration iont the altertation system. These groups established on the basis of these curves do not reflect the empirical field classifications.

Figure 7.1 shows the cumulative frequency curve for SiO_2. Three broad divisions are recognized probably representing the original, silicified and desilicified rocks. The original composition is likely a mixed group itself in that it might also include some silified rocks

Figure 7.1. *Cumulative frequency diagram of SiO_2 within the AHAB.*

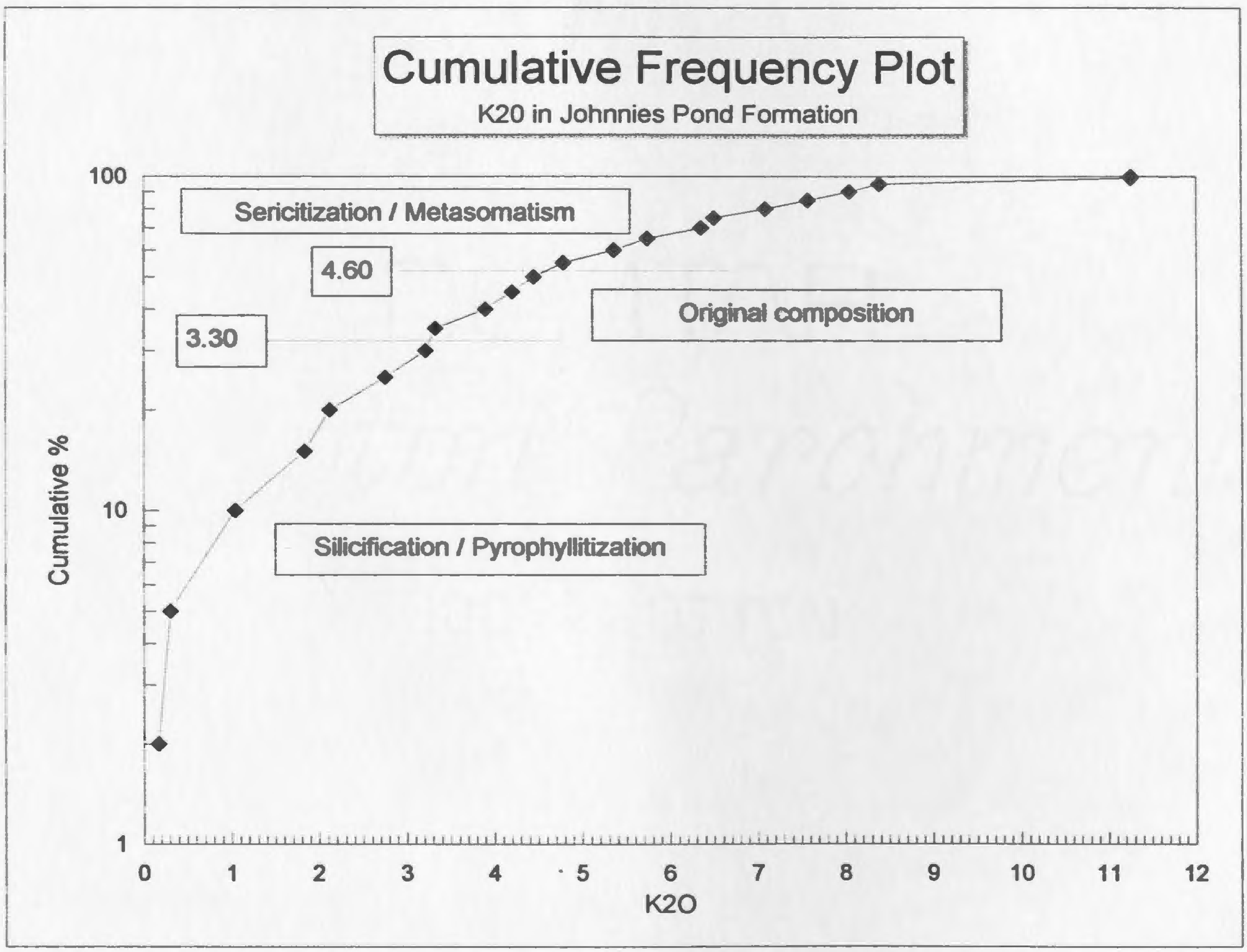

Cumulative Frequency Plot
SiO2 in Johnnies Pond Formation
Silicification
79.50
Original composition
76.25
68.25
Desilicification
Cumulative %
100
10
1
55
60
65
70
75
80
85
90
SiO2 wt. %

with pyrophyllite which are progressing from silicified to desilified. This illustrates the main problem with univariate analyses of the altered rocks. Rocks having complex alteration histories may move back through the unaltered composition to a different composition through reversal of the compsoitional vectors.

Figure 7.2 is a cumulative frequency plot for K_2O. Again three broad groups of data can be identified although the inflection points are not sharp. A range of compositions between 3.30 and 4.60% K_2O seem to represent the original composition. Values above 4.6 rise sharply and result from metasomatism and sericitization. Values below 3.30% can be attributed to silicification (gain of SiO_2, producing a lower value of K_2O through constant sum) or through pyrophyllitization (loss of K_2O). When silicification accompanies sericitication these can compete to lower the actual K_2O value.

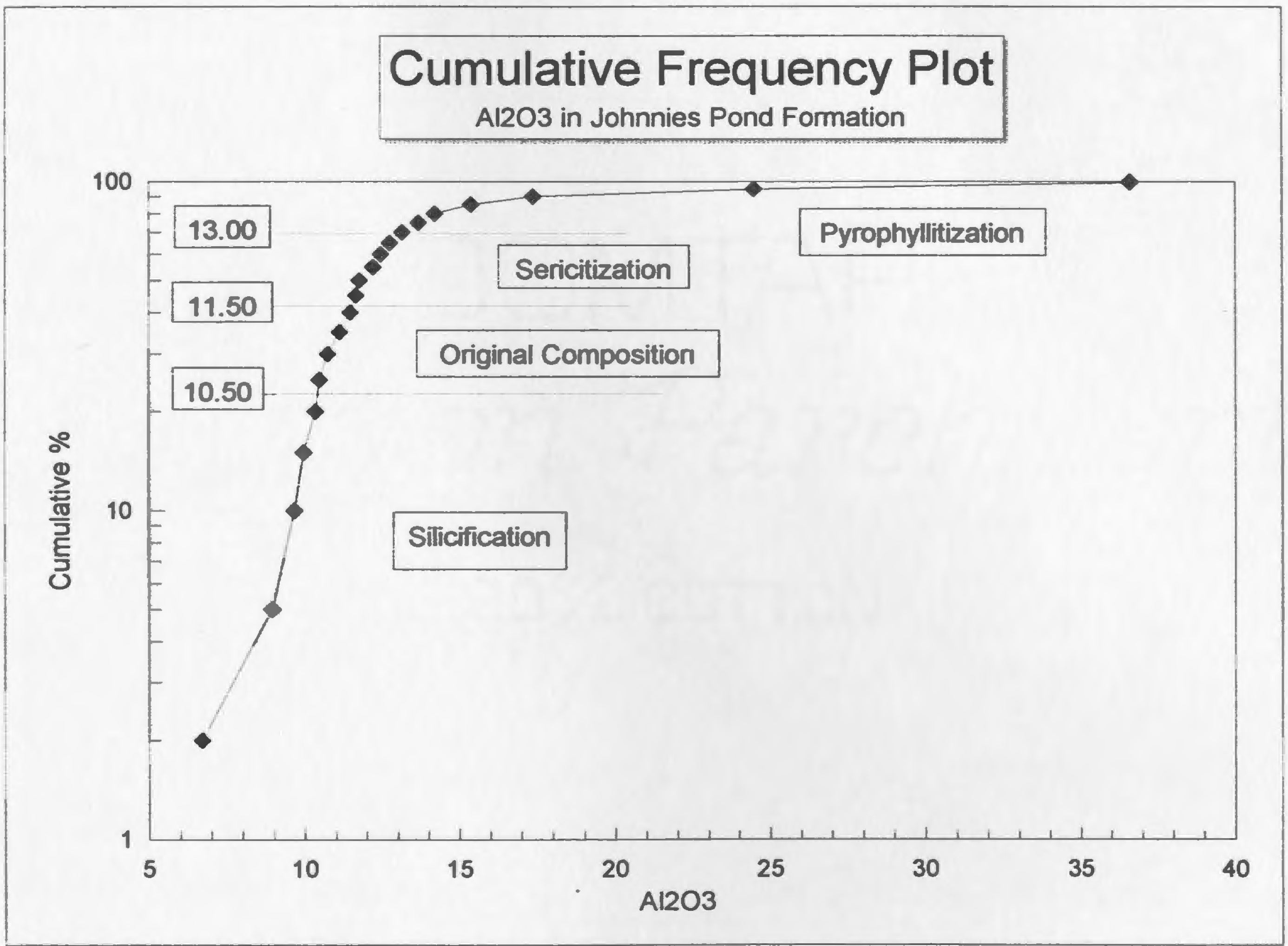
Figure 7.3 is the probablity curve for Al_2O_3. Unlike the K_2O and SiO_2 curves the curve is much smoother, likely due to its conservative behaviour within the alteration system and the ranges in Table 7.1 for different types of alteration can be more closely tied to different parts of the curve. The pyrophyllitized rocks can be identified by the sharp increase in Al_2O_3 above 13.00%. Below this a zone representing unlatered rocks is recognized. Values below 10.50 % Al_2O_3 most closely agree with the sericitized and silicified rocks. A striking feature of this curve is the arrangement of subpopulations that broadly correspond to alteration types. Potentially there may be a lack of samples bearing pyrophyllite that lie within the range of the unaltered rocks. If this is the case it would imply that the rocks are

Figure 7.2. *Cumulative frequency diagram for K_2O in the AHAB.*



Cumulative Frequency Plot
K20 in Johnnies Pond Formation
Sericitization / Metasomatism
4.60
3.30
Original composition
Silicification / Pyrophyllitization
Cumulative %
100
10
1
0
1
2
3
4
5
6
7
8
9
10
11
12
K2O

Figure 7.3. *Cumulative frequency diagram for Al_2O_3 in the AHAB.*



Cumulative Frequency Plot
Al2O3 in Johnnies Pond Formation
100
10
1
Cumulative %
13.00
11.50
10.50
Sericitization
Original Composition
Silicification
Pyrophyllitization
5
10
15
20
25
30
35
40
Al2O3

alumina enriched for other reasons than pure silica loss; it could equally indicate a gain such as by the mechanism of colloidal alumina mobility as proposed in Chapter 6.

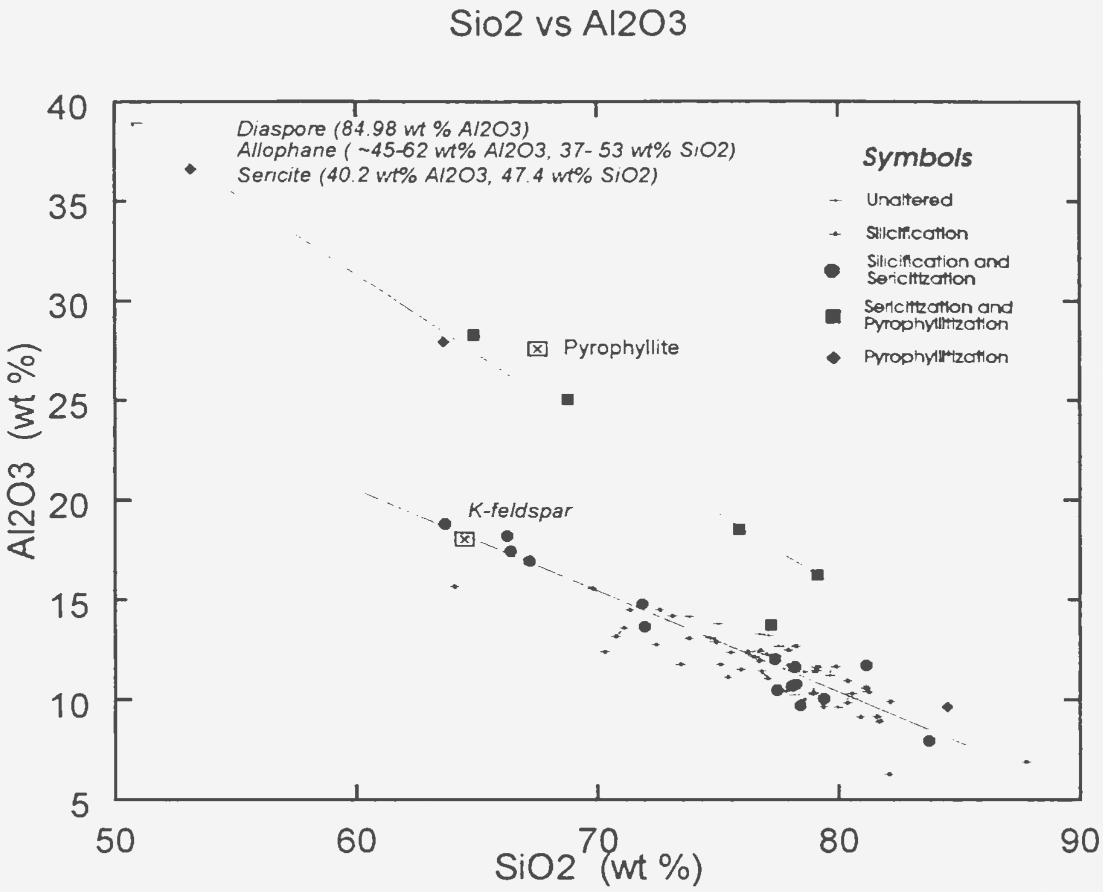
The weakness of the univariate analysis is that it does not provide information on the mechanism, or degree of alteration since changes in composition result from a gain or loss in more than one element simultaneousely. This kind of information can only be gained through bivariate and multivariate statistical analyses.

7.2.2 Bivariate Analysis of Major Element Data

7.2.2.1 Silica–Alumina Variation

A Harker variation diagrams was constructed using silica as the independant variable and alumina as the dependant variable (Figure 7.4). Significant correlation with SiO_2 was expected because of the wide range from 38 to > 90 wt% due to alteration, however, since all major elements by definition sum to 100%, a decrease in SiO_2 will consequently result in an increase in Al_2O_3. This relationship is known as "closure" (Russell and Stanley, 1990) and the strong correlations between Al_2O_3 and SiO_2 apparent in many geochemical datasets result from this statistical artifact. However in the case of the AHAB covariation in SiO_2 and Al_2O_3 due to geological causes is expected apriori since sericite, pyrophyllite and diaspore contain different amounts of these components than feldspar. Some evidence is seen on this diagram for geological causes, rather than purely statistical constructs.

Figure 7.4. *Al_2O_3 vrs SiO_2 for altered and unaltered rocks of the Avalon High Alumina Belt. Note the pronounced variation in slope of the pyrophyllitized rocks from the remaining samples and also the preponderanc of silicified and sericitized samples falling at the high alumina part of the main trend.*



Sio2 vs Al2O3
Diaspore (84.98 wt % Al2O3)
Allophane (~45-62 wt% Al2O3, 37- 53 wt% SiO2)
Sericite (40.2 wt% Al2O3, 47.4 wt% SiO2)
Symbols
Unaltered
Silicification
Silicification and Sericitization
Sericitization and Pyrophyllitization
Pyrophyllitization
Pyrophyllite
K-feldspar
Al2O3 (wt %)
SiO2 (wt %)
40
35
30
25
20
15
10
5
50
60
70
80
90

Along the main trend it can be noticed that the highest alumina rocks falling along that part of the trend are almost exclusively serictized. The position of the samples indicates that sericitization was responsible for the loss of silica in these samples (Si in sericite is less than Si in feldspar). Rocks containing sericite also plot within the main trend at various silica concentrations and these points are less readily interpreted. The contribution of sericitization to variation in silica in these samples is probably less than silica variation due to silicification.

An important feature of this graph is the prominent trend defined by a group of samples which contain pyrophyllite. These samples range in mineralogy from pure pyrophyllite, containing diaspore, to silicified rhyolite with abundant pyrophyllite along fracture planes which, respectively, plot near the high-alumina and high-silica ends of the range. Regression analysis on these two trends reveals that the data within each group are highly correlated ($R^2 > 8$). This high correlation is likely the result of closure. However the intercepts at high-silica values and the regression lines are otherwise significant. The slope of the regression line is -1.12191 for the pyrophyllite group and is gentler than the -1.79554 slope defined by regression of the silicified-sericitized group (Figure 7.4).

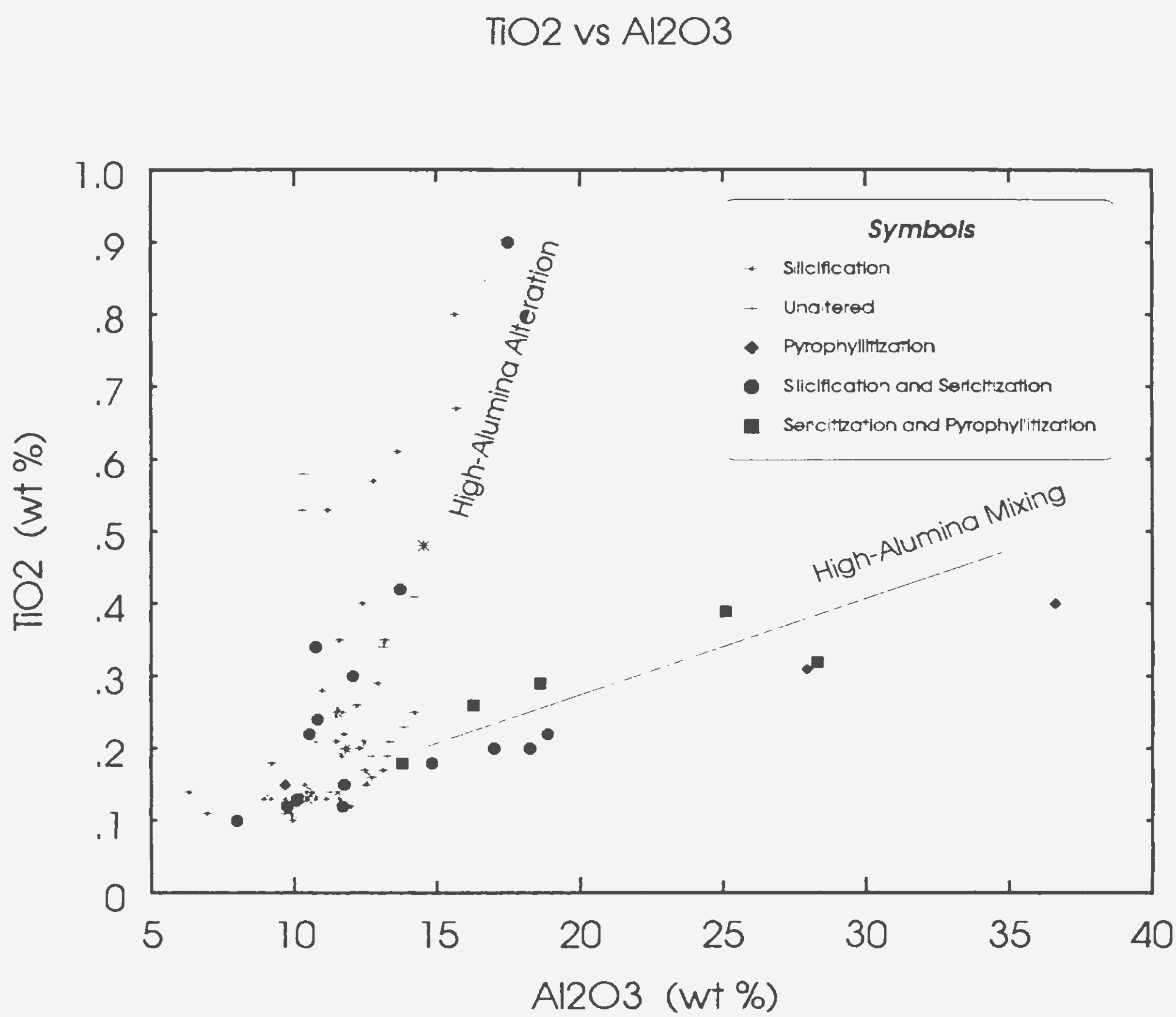
The trends on this graph indicate that the process of extensive pyrophyllitization is decoupled from progressive alteration processes such as sericitization. The pyrophyllite group trend has the form of a mixing line between a silicified rhyolite and pyrophyllite. The data reflects the coincidence of pyrophyllite zones and silicifed rhyolite since there are no known occurences of unaltered or slightly unaltered rocks having pyrophyllite on fracture surfaces. The geochemical data is consistent with the field observation that pyrophyllite appears physically mixed with silicified rhyolite through deposition of an amorphous aluminous precursor through the silicified zones.

The association of some pyrophyllite-bearing samples on the lower trend indicates that an extensively sericitized rhyolite can give rise to a slightly pyrophyllitized rock. However this process cannot account for pyrophyllite in rocks which contain more than 15% alumina. In essence the data show that rocks desilicified through extensive sericitization do not directly give rise to pyrophyllite-rich zones through further alteration.

7.2.2.2 Al_2O_3–TiO_2 Variation

Figure 7.5 shows a plot of TiO_2 versus Al_2O_3. These elements are considered to be immobile under most conditions of alteration and metamorphism. The data depicted in the figure show that these elements have two different patterns of behaviour in the AHAB. The first group of elements is characterized by Al_2O_3 <17.0 wt % and a range of TiO_2 from 0.1 to 0.9 wt%. This trend is defined cheifly by silicified rocks along with some unaltered and some sericitized rocks. A second trend is marked by a group of samples having TiO_2 less than 0.4 wt% and a range in Al_2O_3 from 14.0 to 37.0%. The low Al_2O_3 end of the line which these samples define is marked by a group of dominantly silicified samples having low TiO_2. The fact that both low and high TiO_2 contents are found in silicified rocks probably indicates

Figure 7.5. *TiO_2 vrs Al_2O_3 diagram for the AHAB revealing discrete patterns of covariation relative to type of alteration.*

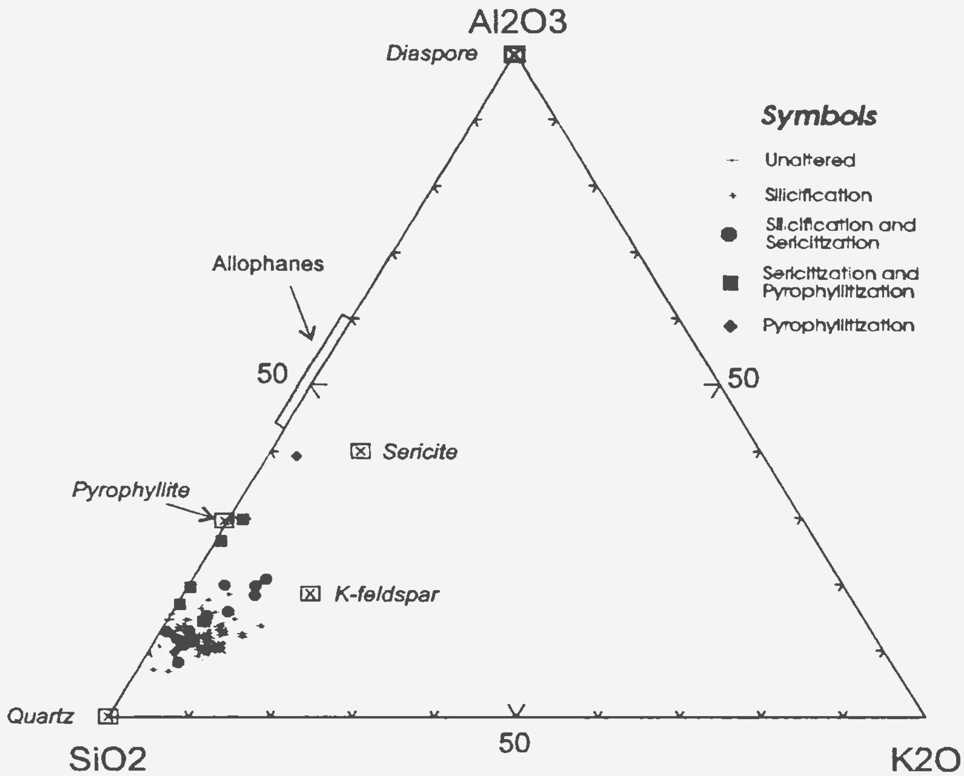

TiO2 vs Al2O3
Symbols
Silicification
Unaltered
Pyrophyllitization
Silicification and Sericitization
Sericitization and Pyrophyllitization
High-Alumina Alteration
High-Alumina Mixing
TiO2 (wt %)
Al2O3 (wt %)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
25
30
35
40

that the high TiO_2 may reflect primary compositional differenced within the Johnnies Pond Formation (this will be explored further using the trace element data). The covariance in TiO_2 and Al_2O_3 as indicated by the slope of the line defined by the high-alumina rocks indicates that TiO_2 also behaves as an immobile element in the alteration system. This interpretation also offers support for the idea that the high-TiO_2 trend reflects primary compositional differences since such trends might not be evident if TiO_2 was not conserved during the alteration process.

7.2.3 Ternary Diagrams of Major Element Data

Ternary diagrams offer the opportunity to examine groups of elements that are related to the major element chemistry of the alteration minerals. To more fully understand the redistribution of silica and alumina within the context of the original and alteration mineralogy a triangular plot of Al_2O_3–SiO_2–K_2O was constructed (Figure 7.6). K_2O is a component of both igneous minerals (feldspar) and sericite in the alteration assemblage. The main cluster of data lies between the composition of quartz and K-feldspar indicating that the bulk composition of the rocks for these elements is largely controlled by these minerals. Outliers from this cluster define crude linear arrays between secondary minerals. The sericitized rocks, fall on a crude line between quartz and sericite, the high alumina rocks fall on a distinct trend between the aluminous minerals pyrophyllite, allophane and diaspore. Interestingly the maximum alumina concentration in the sericitized and silicified rhyolites falls near the same concentration as seen in K-feldspar. This probably indicates that the

Figure 7.6. *Ternary diagram showing the relationship of* Al_2O_3*–*SiO_2*–K20 with respect to the major mineral phases.*



Al2O3
Diaspore
Symbols
Unaltered
Silicification
Silicification and Sericitization
Sericitization and Pyrophyllitization
Pyrophyllitization
Allophanes
50
50
Sericite
Pyrophyllite
K-feldspar
Quartz
SiO2
50
K2O

sericite associated with silicification results from a closed system-style alteration of feldspar with intrduction of H_2O only.

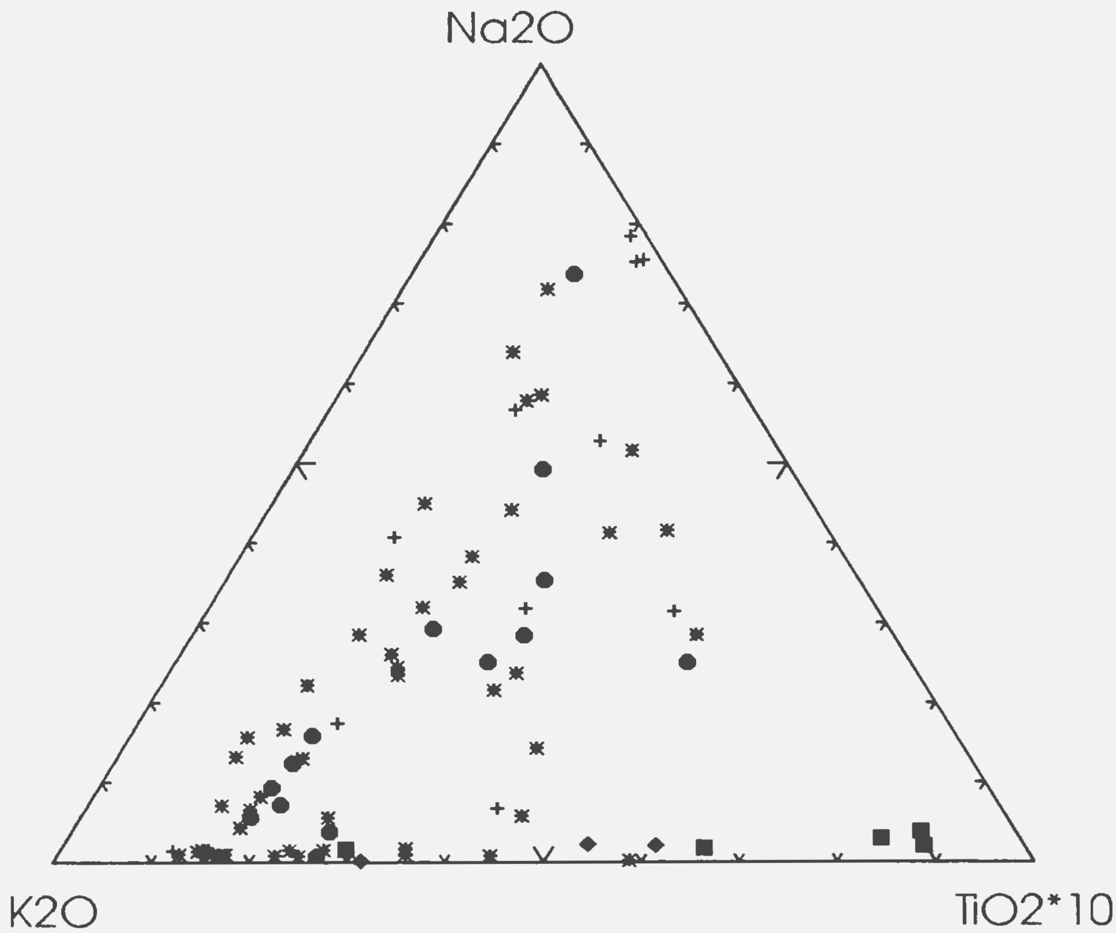
In a similar manner K_2O and Na_2O were examined on a ternary diagram with TiO_2, since it was previously indicated as reflecting variations in original chemistry, to examine the distribution of the major alkali elements between altered and unaltered rocks (Figure 7.7). The data show two principal groups of rocks divided in K_2O/Na_2O composition along with a group of TiO_2 rich high-alumina altered rocks. These rocks form a continuim with the high-K rocks on the diagram. The high and low K_2O rocks appear to form a continum wth the high-K rocks although there is a lower density of intermediate samples. The sericitized rocks are distributed between the high-and low K_2O groups indicating that sericitization alone does not influence the bulk alkali composition of the rocks and in fact it is more strongly influenced by the original chemistry.

7.3 Trace Element Chemistry

7.3.1 Introduction

Trace element geochemistry has the greatest potential to unravel the complexity of the alteration process and identify original geochemical features of the Johnnies Pond Formation that are distinct from hydrothermal processes. Elements within an alteration system are either conserved and reflect only apparent changes in composition predicated upon gains/losses in other constituents or are mobile and reflect inherent gains/losses in the

Figure 7.7. *Ternary diagram showing K_2O–Na_2O–TiO_2. The relationship between the alkalias and the immobile component TiO_2 demonstrates the influence of original chemistry of the rhyolite in controlling the distribution of K and Na.*


Na2O
K2O
TiO2*10

element. Most of the trace elements within the alteration zone appear largely conserved despite the high degree of alteration. This feature is attributable to the fracture controlled nature of the alterations system.

7.3.2 Classification Diagrams

An approach to trace element geochemistry that had dominated early endeavours in the field were the use of immoble elements to classify the rock association. Figure 7.8 (after Winchester and Floyd (1977) is such a diagram and it classifies the AHAB according to Zr/TiO_2 and NB/Y ratios. The main features of the diagram are that the Johnnies Pond formation is cheifly composed of rhyolite, the highly altered rocks define a line crossing into the Trachyte field and have near constant Zr/TiO_2 ratios. A number of samples fall within the Rhyodacite/Dacite field. It may be tempting to interpret these variations as solely due to original compositional variation, however, some features of the diagram indicate that some of the pattern is related to alteration, despite its apparent correctess with respect to rock classification. Firstly, with fiew exceptions the unaltered rocks (+'s) plot closely together near the rhyolite–rhyolite/rhyodacite field boundary. The more altered rocks are dispersed around this area and the highly altered rocks extend from this region with constant Zr/TiO_2 ratios. The samples which fall in the Rhyodacite/Dacite field appear to form a gross linear array with the bulk of the data (excluding the highly altered rocks). This array is consistent with the trace element concentrations being dispersed along the array by gains and losses in major elements. The most highly altered rocks are clearly displaced from this array.

Figure 7.8. *AHAB rhyolitic rocks plotted on the* Zr/TiO_2 *vrs. Nb/Y discrimination diagram of Winchester and Floyd (1977). See Figure 7.5 for legend of the symbols.*

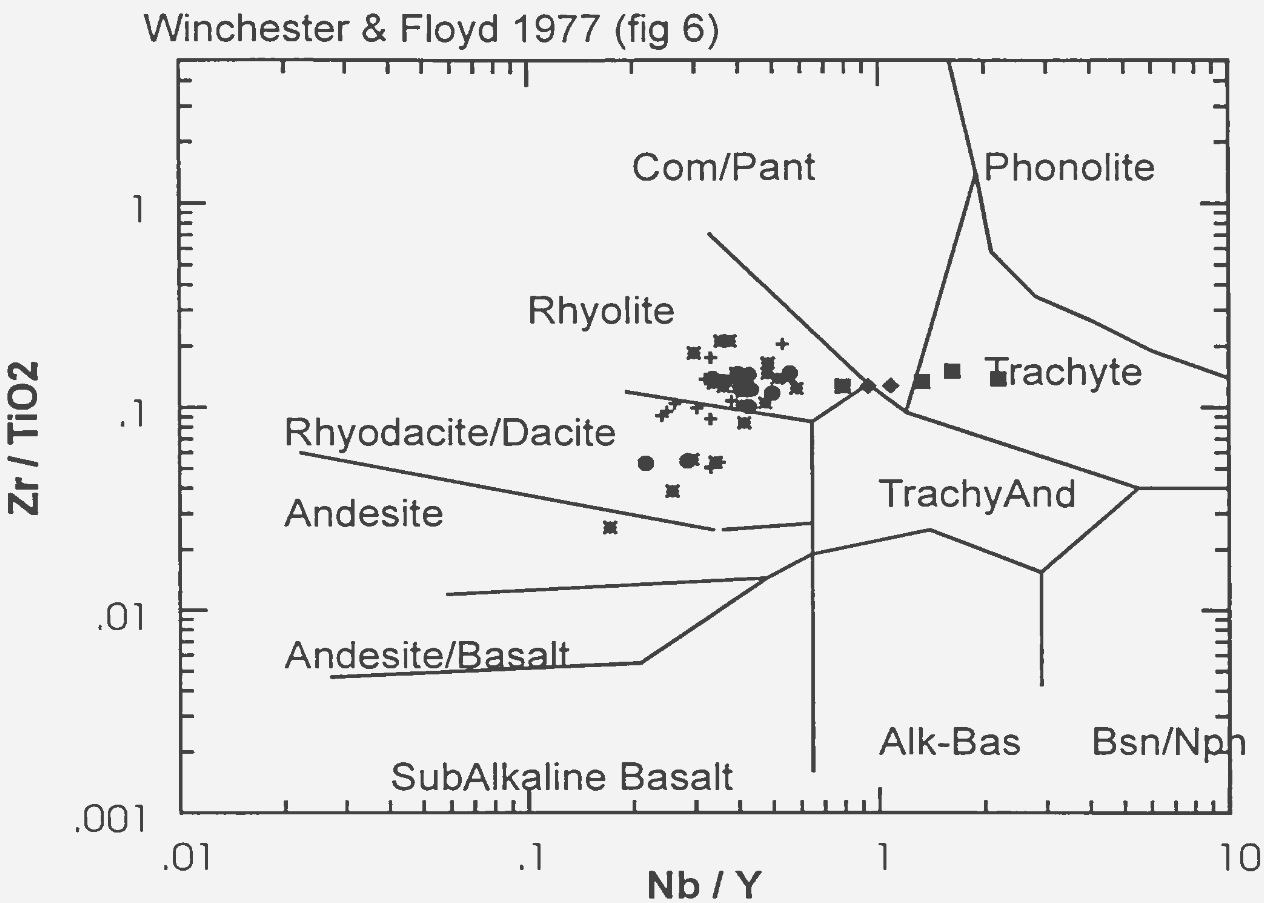
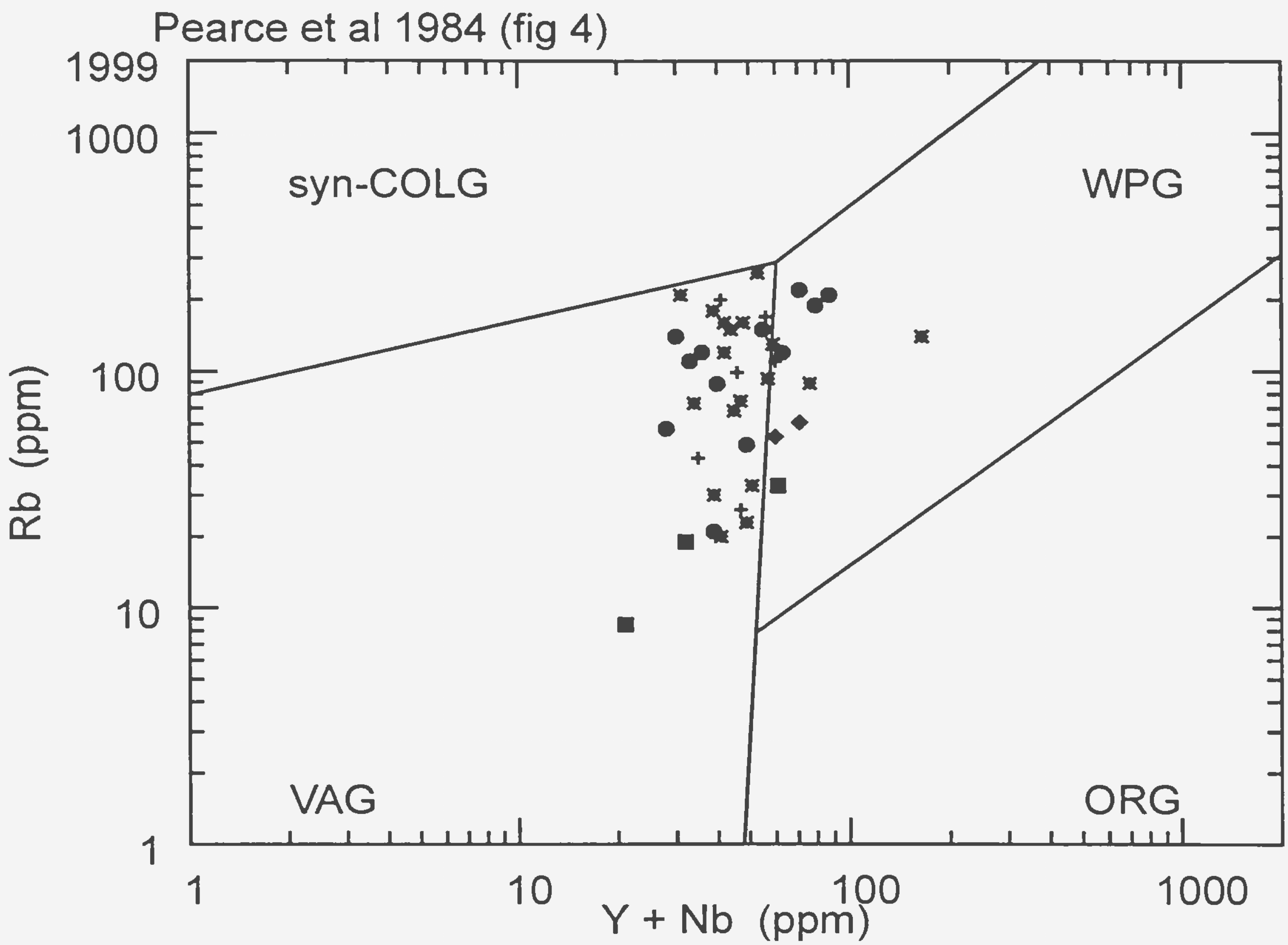

Winchester & Floyd 1977 (fig 6)
Com/Pant
Phonolite
Rhyolite
Trachyte
Rhyodacite/Dacite
TrachyAnd
Andesite
Andesite/Basalt
Alk-Bas
Bsn/Nph
SubAlkaline Basalt
Zr / TiO2
1
.1
.01
.001
.01
.1
1
10
Nb / Y

Figure 7.9 compares the composition of the AHAB rocks with the granite classification diagram of Pearce *et al.* (1984). The diagram is compares Rb, a large ion lithophile element that is chemically similar to K, to total Y+Nb. The diagram indicates that the bulk of the rhyolites are volcanic arc or I-type granites (compare Christianson and Keith, 1996). The most altered rocks containing pyrophyllite plot at low Rb values whereas the higher Rb values are associated with sericitized rocks (circles). This is consistent with covariation of Rb and K. The diagram appears to work despite the apparent dispersion of Rb and the dispersion of Y+Nb elements within the alteration for two simple reasons. Firstly, the range in Rb values are small compared to the overall range of Rb in granitoid rocks and similarily the variation due to losses and gains in other elements is of lesser importance when compared to the over all range in the concentration of these elements.

These two diagrams indicate that these classification diagrams provide first order information on the chemical affinity of the alteration system since the changes due to the alteration are small when compared to the overall ranges in values that characterize the different rocktypes or associations. Both diagrams are plagued by losses and gains that are due to other elements in the system and are not shown on the diagrams or considered when the diagrams are constructed. As it will be seen in the following section consideration of the gains and losses and diminishing their effect provides for a more consise analysis allowing for the detection of subtle patterns.

Figure 7.9. *AHAB rhyolitic rocks classified using the Rb vrs. Y+Nb diagram of Pearce et al. (1984).*



Pearce et al 1984 (fig 4)
1999
1000
100
10
1
Rb (ppm)
syn-COLG
WPG
VAG
ORG
1
10
100
1000
Y + Nb (ppm)

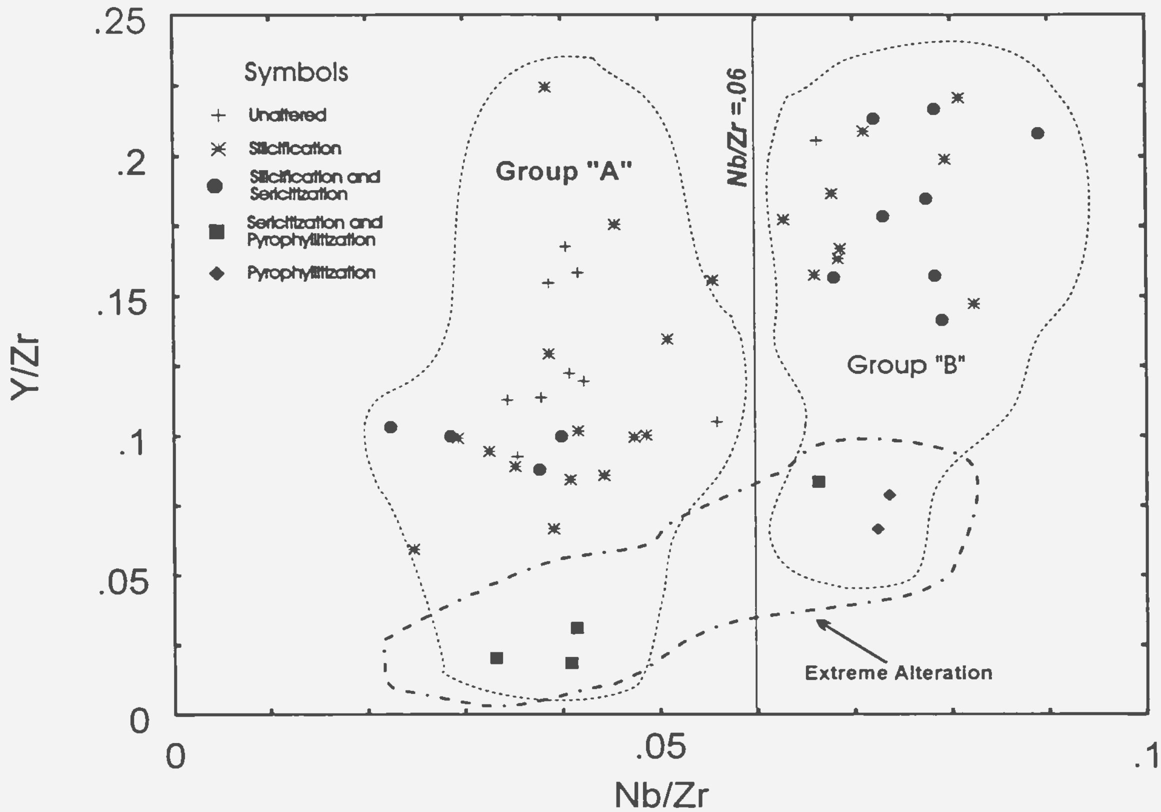
7.3.3 Pearce Element Ratios

Pearce element ratios employ a technique of comparing elements of interest by comparing them ratioed to a common denominator which is conserved during the alteration process. By comparing elements through ratios, the effect of losses or gains are diminished.

Figure 7.10 is a Pearce Element Ratio plot which compares Y and Nb, ratioed to Zr, which is immobile under most conditions. The distribution of points on the diagram reveals variation due to both variation in the original rock chemistry and variation due to alteration.

The variation due to original rock chemistry is most strongly expressed in the Nb/Zr ratios. Nb has a range in concentration in silicic magmas due to its initial variation in different source areas and its retention in the melt fraction of igneous systems since it is a high field strength element as is Zr (Christianson and Keith, 1996). The rhyolitic rocks of the Johnnies Pond Formation fall into two groups based upon Nb/Zr ratios however Y/Zr ratios fall into the same range in both groups. Within Group A and B the most altered rocks remain discrimated on the basis of NB/Zr ratios however the Y/Zr ratio in these rocks is noticibly lower. This might indicate the persistence of phases such as zircon even in highly altered rocks thereby lowering the Y/Zr ratio. It is significant however that these variations are only noted in rocks that are virtually completely altered to pyrophyllite.

Figure 7.10. *Discrimnation diagram using immobile elements demonstraing the use of Pearce Element Ratios to classify rhyolitic rocks of the Johnnies Pond Formation.*


Symbols
Unaltered
Silicification
Silicification and Sericitization
Sericitization and Pyrophyllitization
Pyrophyllitization
Group "A"
Group "B"
Nb/Zr =.06
Extreme Alteration
Y/Zr
Nb/Zr
.25
.2
.15
.1
.05
0
0
.05
.1

7.4 Discussion

The geochemical data from the AHAB reflect both changes due to alteration and the original bulk geochemical composition. Since the alteration is fracture controlled, a plausible explanation for this observation is that the alteration processes are not pervasive and only involve a portion of the rocks in the alteration system. This supports the field evidence that the alteration is characterized by high water:rock ratios and that the immobile elements are "conserved" within the fracture system. This latter point is especially clear when the fact that the alkali elements, typically mobile in alteration systems retain in part their original distribution as indicated by their covariance with TiO_2 which is cheifly an immobile element (*op. cit.*). The AHAB data contains significant information regarding alteration and classification using immobile elements. In the AHAB at least, alteration is a secondary influence on the distribution of many elements typically used in the classification of igneous rocks.

CHAPTER 8

ECONOMIC GEOLOGY

8.1 Introduction

After an exhaustive literature search it is clear that the AHAB has no clear analog among other examples of high-alumina alteration systems nor does it readily fall into existing classifications of alteration associated with auriferous hydrothermal systems. The most allied high-alumina altered rocks occur elsewhere within the Avalon zone and have features in common with the AHAB that extend beyond the morphology of the deposit to include the type and age of the host rocks. The AHAB, its host rocks, and their surrounding units are, however, well exposed compared to most of the high-alumina altered zones in the Avalon Zone. The low grade of metamorphism and good exposure permit clear observations with respect to distribution of mineral phases, structural and stratigraphic relationships. The AHAB in some respects appears to resemble epithermal alteration associated with the adularia–sericite style Au–Ag deposits, however the high-temperature and fracture-control distinguish it from these largely vein-style systems. The discovery of gold mineralization within the belt, in conjunction with the alteration history, provides insights into the mineralizing process in the AHAB-type system.

8.2 Overview of Epithermal Alteration Systems

8.2.1 Introduction

Two major classes of hydrothermal mineral deposits are recognized throughout the geological record, the acid-sulfate and adularia–sericite type alteration systems (Heald *et al.*, 1987). The terms "high-sulfidation" has also been applied to the acid-sulfate type alteration systems (e.g., Hedenquist *et al.*, 1994) and "low-sulfidation" type to adularia–sericite systems. The use of these terms and the range of deposits to which they are applied were discussed by White and Hendenequist (1990) who concluded that classifying an alteration system on the basis of the amount of sulphur in the hydrothermal system or mineral species is less appropriate than consideration of the redox state of sulphur in the hydrothermal fluid. Low sulfidation systems have sulphur as H_2S in the hydrothermal fluid, while high sulfidation systems have SO_4. A drawback to this approach is that the oxidation state of S will change as the hydrothermal fluid evolves. Some deposits are formed by different fluids at various stages in their evolution (such as the deposits of the Nansaku district of Japan, Hedenquist *et al.*, 1994). The purpose of reviewing the different deposit models is to isolate the fundamental controls of the morphology of the deposit they describe. Deposit morphology appears to be a robust indicator of deposit type. Mineralogy of the deposits is the most useful guide in this regard as the morphology of the deposit is represented by mineral zonation.

The Precambrian sequences of the Avalon Zone (Smith, 1986; Huard and O'Driscoll, 1985; Hayes and O'Driscoll, 1990) and other related Gondwanan terranes[7] in Newfoundland host a variety of alteration systems that can be broadly classed as epithermal. Some of these are clear examples of high-sulfidation systems such as the alteration system at the Hope Brook mine. Many of the deposits elsewhere in the Avalon zone are similar to the AHAB and have some broad characteristics that imply a relationship to the adualria–sericite type deposit. In the following section these two groups of alteration systems are discussed and comparisons made with the AHAB.

8.2.2 Acid-Sulfate

The pyrophyllite occurrences described in the literature are nearly exclusively associated with acid-sulfate type deposits (e.g., Heald *et al.*, 1987). Alunite is a characteristic alteration mineral in these deposits and serves to identify the acid nature of the hydrothermal fluid (Hemley *et al.*, 1969). The primary mechanism of pyrophyllite formation in acid systems is extreme acid leaching, usually of a volcanic host. The acid is produced by oxidation of H_2S bearing fluids in a shallow mixing zone (e.g., Schoen *et al.*, 1974) or by dispropriation of H_2S from a magmatic source (e.g., Hedenquist *et al.*, 1994). The acidic oxidized fluids in these systems promote extensive leaching which produces silica-rich

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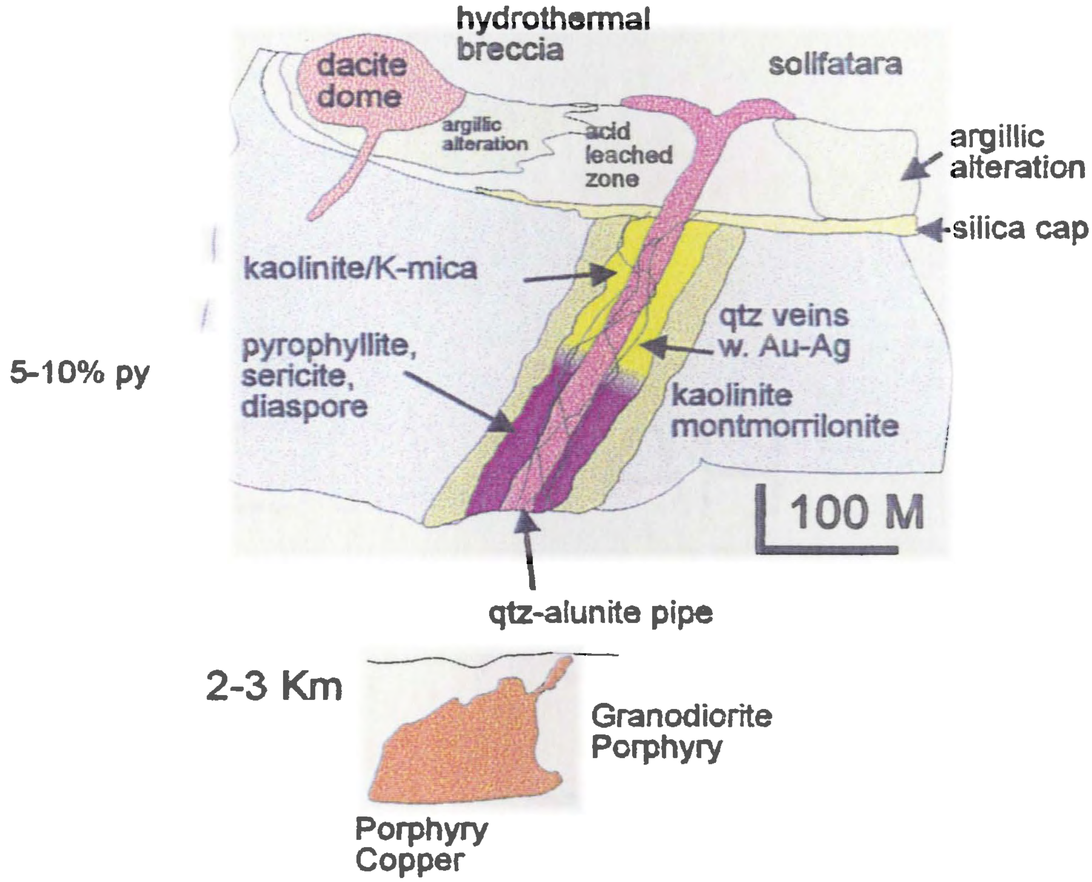
[7] The host rocks of the Hope Brook Mine have been interpreted to represent peri-Gondwanan crustal remnants within the Appalachian orogenic cycle (cf. O'Brien *et al.*, 1996).

residual pods enveloped by an advanced argillitic-type alteration aureole. These aureoles contain high-alumina minerals such as pyrophyllite and kaolinite. Steam Boat Springs (Schoen *et al.*, 1974) and the Kasuga Deposit (and other deposits) in the Nansatsu District (Hedenquist *et al.*, 1994) are type examples of these deposits. Pyrophyllite is also known to occur in association with massive sulfide ore bodies of the Kuroko type (Marumo, 1989). Figure 8.1 illustrates the main features of these types of deposits. Most acid-sulfate sulfidation systems contain copper in addition to gold.

The relative mobility of silica and alumina in high-sulfidation hydrothermal fluids as exposed in the morphology of the deposits is consistent with their acid conditions. Since silica has lower solubility than alumina under low pH conditions it readily explains why silicified vuggy residual zones form in the host rock following passage of a high-sulfidation fluid. The vuggy characteristics of the residual silica is a feature that persists in even ancient deposits such as the late Proterozoic Hope Brook in southern Newfoundland (Yule *et al.*, 1990). Alumina minerals tend to form along the outer margins of the silicified zones as alumina has increased mobility in acid systems. The reduction in alumina solubility, as indicated by precipitation of aluminous phases, results from neutralization of the acid fluid by either groundwater or wallrock reaction (Hedenquist *et al.*, 1994). The distinctive alteration zonation patterns of these types of deposits permitted recognition of an acid-sulfate origin for the Enåsen gold deposit (Sweden) despite overprinting sillimanite grade high temperature metamorphism (Hallberg and Fallick, 1994).

Figure 8.1. *Morphology of high-sulfidation or acid-sulfate type deposits (after Bonham, 1988).*

High sulpher-type deposit model Au-Cu (after Bonham, 1988)



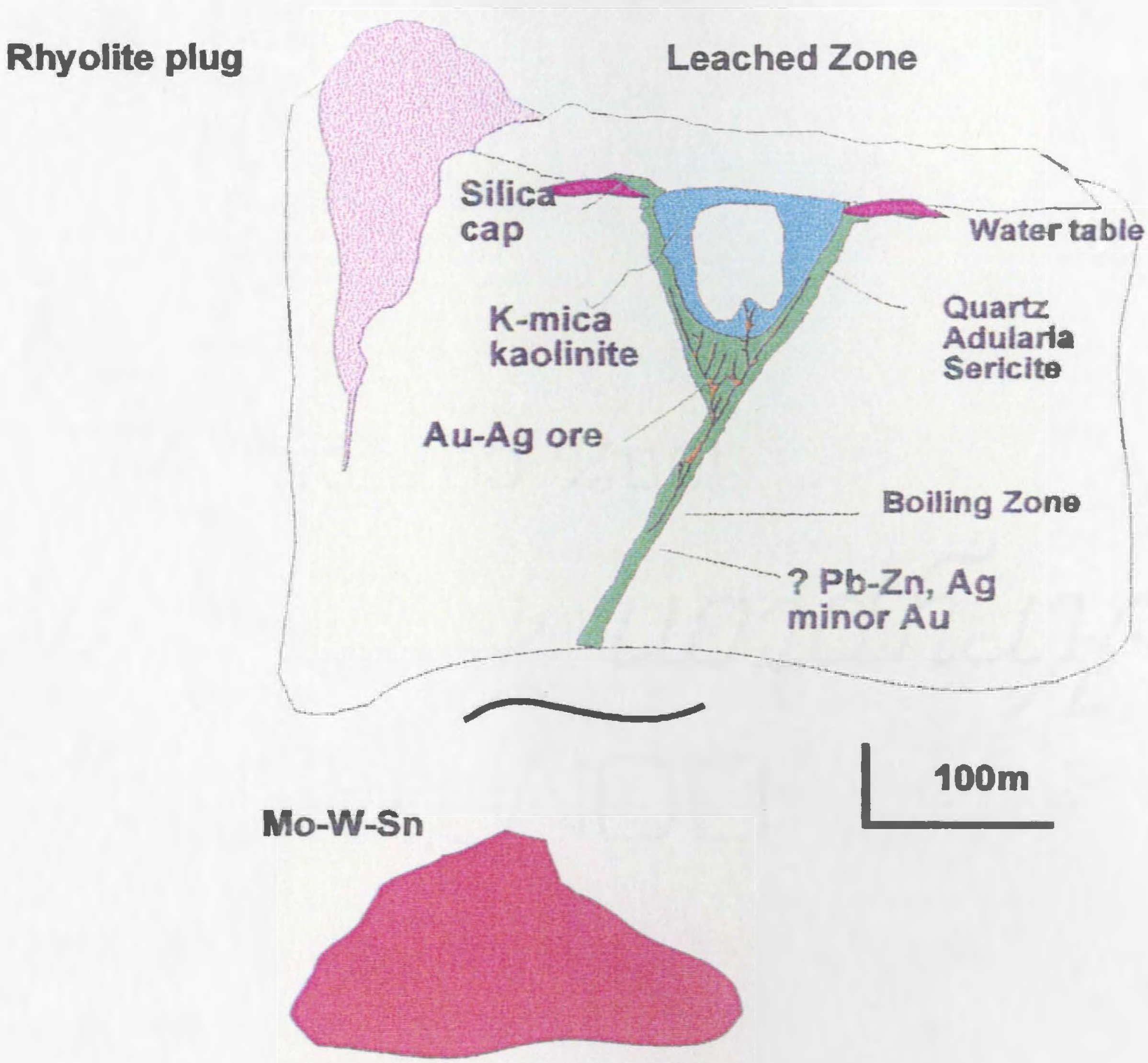
8.2.3 Adularia–Sericite Systems

Adularia–sericite systems form low-sulfidation conditions and, unlike the high-sulfidation systems, are not characterized by the development of extensive sulfate phases and extreme leaching. They are instead marked by the development of sericite, chlorite and adularia (Heald *et al.*, 1987). The typical form of this deposit type consists of a sericitic and chloritic alteration halo peripheral to a central vein system that contain adularia (Figure 8.2). There are a number of Paleozoic deposits within the US of this type including the Creede (Bonham, 1988). Adularia– sericite type alteration is also widespread within the recent island-arc sequences of Indonesia (Perelló, 1994). A particularly well developed example of this deposit type is Gunung Ponkor (Basuki *et al.*, 1994).

Whereas high-sulfidation systems are influenced heavily by magmatic fluids, adularia–sericite deposits form from the interaction of deeply circulating, essentially meteoric waters, with plume waters of magmatic or meteoric origin circulating upwards from greater depths (Heald *et al.*, 1987; Berger and Henley, 1988). Berger and Henley (1988) indicate that the presence of lakes at the paleosurface during the time some of these deposits formed signifying involvement with large-scale hydrological processes.

Figure 8.2. *Morphology of adularie–sericite deposits (after Bonham, 1988).*

Granite-rhyolite magmatism model (Bonham,1988)



8.3 Avalonian Deposits

A review of occurrences of high-alumina alteration throughout the Avalon Zone (Table 8.1) reveals that there are a range of characteristics within these systems. Examples of high and low sulfidation systems are present. High sulfidation type systems are the easiest to recognize given the presence of alunite and a Cu–Au metallogenic signature. Within the Avalon Zone this signature is found at the Hope Brook mine in Newfoundland and the Brewer Mine in the Carolina Slate Belt. Hickey's Pond and the Stewart Option have the alunite alteration characteristics of the high sulfidation style of system. Anomalous Au, Cu and Mo which are suggestive of high-sulfidation type processes at the Stewart Option. The remaining occurrences listed in Table 8.1 do not appear to fall into either high or low sulfidation categories.

8.4 Base Metals and Gold Systematics of the AHAB

Gold is deposited under different conditions in acid-sulfate and adularia-type hydrothermal systems (Heald *et al.* 1987). The metals associated with gold in acid-sulfate and adularia–sericite systems are also different. Acid-sulfate deposits often contain appreciable amounts of copper (i.e., Hope Brook, Yule *et al.*, 1990; Dubé *et al.*, 1994) and the presence of enargite is characteristic of acid-sulfate deposits (Bonham, 1988). Low-sulfidation systems are generally gold–silver systems (Heald *et al.*, 1987; Berger and Henley, 1988),

Table 8.1. *Overview of Avalonian volcanic-hosted hydrothermal alteration zones and deposits*

Deposit Name	Mineralogy	Commodity
Brewer[1,3]	Ser, Pyr, Alun, Ky, Ct, Di, To	Au–Cu*–Mo*
Haile[2]	Ser, Ka, To, Rt	Au–Ag–Mo*
Ridgeway		
Pilot Mountain[1]	Pyr, Ser, And, Ka, To	Au–Cu*–Mo*
Glendon[1]	Pyr, Ser	Pyr
Snow Camp[1]	Pyr, Ser, Par, Ct	Pyr
AHAB[8,9]	Pyr, Ser, Di, Rt, Hem	Pyr, Au*–Ag*
Hickey's Pond[7]	Pyr, Alun, Hem	Au*
Stewart Option[6]	Pyr, Ka, Ser, Chl, Alun	Au*–Cu*–Mo*
Hope Brook[4]	Pyr, Ser, And, Ka, Rt, Laz	Au–Cu
Headwaters Showing[7]	Pyr	—

References

1. Feiss, 1985
2. Hayward, 1992
3. Schmidt, 1985
4. Yule et al., 1990
5. Scheetz et al., 1991
6. Dimmell and MacGillivray, 1993
7. Huard, 1989
8. Papezick et al.
9. This study

Abbreviations

And – Andalusite
Pyr – Pyrophyllite
Ser – Sericite
Ka – Kaolinite
To – Topaz
Alun – Alunite
Hem – Hematite
Par – Paragonite
Ct – Chloritoid
Rt – Rutile
Di – Diaspore
Chl – Chlorite

Elements/commodities marked with asterisk occur in sub-economic concentrations.

however, Au–Ag deposits related to high-sulfidation systems have also been described (Muntean *et al.*, 1990).

Both Au and Ag anomalies occur in the AHAB and are most evidenced where the style of alteration is dominately intense sericite development accompanied by pyrite and chloritic zones. Figure 8.3 shows the range of high silver values associated with the AHAB and their distribution. The association of gold and silver in the most anomalous samples is consistent with a low-sulfidation origin for mineralization within the AHAB. A significant aspect of the alteration system is that gold and silver anomalies are not associated with pyrophyllite zones. The AHAB has a coincident period of alumina alteration and hematization which indicates that the hydrothermal fluids were oxidized. Sulfide complexes are inhibited under these conditions. Gold may only be carried in sufficient concentrations in an oxidizing fluid as a chloride complex.

Regional lithogeochemical and or surficial geochemical signatures for some gold deposits in the Avalon terrane includes elevated concentrations of Mo (Smith, 1986; Dimmel and MacGillivray, 1993) Mo mineralization is associated with the Holyrood Intrusive Suite (Rose, 1948), within quartz veins about 10 km southwest of the AHAB and locally in fractures within the granite (O'Driscoll, pers. comm.). The metallogeny of the Holyrood is also consistent with the high-level features described in the Holyrood from this study by Hughes (1971). Minor chalcopyrite is present in the roadcut showing and copper staining has been identified in the Oval Pit Mine (Max Dawe, 1989, pers. comm.). The relation of the copper minerals to the phases described here are unknown at present although these sulfide phases, in minor quantities, are not inconsistent with low sulfidation systems.

Figure 8.3. *Gold and silver occurrences in the AHAB.*

Bedrock Gold and Silver Anomalies Central Portion of the Eastern Avalon High-Alumina Belt

Gold in Rock Samples*
(ppb)

- ★ 210 to 580
- ● 44 to 210
- ● 24 to 44
- ● 17 to 24
- ● 12 to 17
- ● 10 to 12

X.X Silver in ppm

*less than 10 ppb not indicated

Legend

Precambrian

Conception Group

- CG — siltstone and sandstone

Harbour Main Group

- HMGv — basalt, ash to lapilli tuff, lesser agglomerate and greywacke
- HMGs — greywacke, lesser tuff and debris flows

Unconformity

Holyrood Granite

- HG — medium-grained equigranular biotite granite, lesser K-feldspar porphyritic granite

Johnnies Pond Formation

- JPF — rhyolitic ash-flow tuff including lithic and crystal tuff. Locally slightly to moderately silicified. Minor sericitization.

Eastern Avalon High-Alumina Belt

- AHAB — moderately to intensely silicified, extensive sericitization, local pyrophyllite zones

Foxtrap Diorite

- FD — medium-grained, foliated, granodiorite to diorite containing numerous amphibolite xenoliths

Symbols

Fault /

Geological boundary /

Mineral Occurrences

Pyrophyllite Occurrences

- ⊗ OPM - Oval Pit Mine
- ⊗ MH - Mine Hill Quarry
- X TP - Trout Pond Prospect
- X DP - Dog Pond Prospect
- X JG - Jakes Gully Prospect

8.5 Conclusion

The AHAB is a high-alumina alteration system. It was formed when low-fS fluids invaded the Johnnies Pond Formation along a fracture system. The fluids produce a residual high-alumina alteration zone and redistributed silica, alakais and iron oxides proximal to the high-alumina core. What is observed in outcrops is the distal silica alteration being overprinted by the high-alumina facies proximal to the alteration system. The earliest high-alumina products were a silica–alumina gel, perhaps allophane, which recrystallized to pyrophyllite and diaspore. Gold and silver mineralization in the belt is consistent with a low-sulfidation adularia–sericite type system. pH plays an important role in determining the morphology of epithermal systems in general and explaining the morphology differences between pyrophyllite occurrences associated with high-sulfidation deposits and the pyrophyllite of the AHAB.

The mineralization appears to be associated with a zone of silicification and sericitization. The fracture system hosting the AHAB is sited along a fundamental tectonic weakness that is reactivated throughout the geological history of the eastern Avalon Peninsula. The localization of hydrothermal alteration, granite magmatism and the presence of extensive basin controlling structures indicate that deposits of the AHAB type occur in areas of fundamental crustal weakness rather than, features of secondary consequence such as the volcano tectonic structures of high-alumina and ring calderas.

CHAPTER 9

CONCLUSIONS

9.1 Metallotectonics

The foregoing chapters have examined the main insights into the genesis and the regional setting of the AHAB. Future work is required to provide a better understanding of the relationship documented, since this thesis has exposed areas where further research is required. The data in this study, however, provide for an integrated model of structural evolution and alteration that in turn demonstrates that metallogenesis and tectonism were allied processes within the Precambrian rocks of the Avalonian terrane. A singular alteration or structural model would fail to explain much of the observed data and would similarily decouple these two processes which clearly interact on the regional scale. The basic question that remains to be addressed is the identification of the tectonic setting of the Johnnies Pond formation. Data presented in Chapter 7 indicate that the Johnnies Pond formation itself is akin to I-type granites although these appear highly evolved since these are chiefly high-silica rocks. It is probable that these rocks formed in a supra-subduction zone environment as envisioned by Christianson and Keith (1996) for many representatives of this group. The hypothesis that the Holyrood Granite and Johnnies Pond formation are comagmatic was not addressed geochemically in this study, however, their temporal and intrusive relationships support such a conclusion although the Holyrood Granite is younger than the volcanics and first alteration. The only statement that can be made about the tectonic setting of the AHAB is that it was probably situated in an active magmatic arc providing a high heatflow to support a prolonged period of hydrothermal activity. Gold mineralization and its association with Ag, is considered to be an important indication that the AHAB is related to the adularia–sericite–style alteration systems.

9.2 Alteration

The alteration processes in the AHAB have been demonstrated to involve near-neutral fluids, probably in large volumes given that the porosity in the system is directly related to the degree of fracturing. The AHAB is essentially a large scale flow-through reactor and is a natural example of some of the devices employed in laboratory studies. Unlike these studies the products of the reactions are produced in large quantity and the identification of mineral phases is made considerably easier. The indications of amorphous precursor phases to pyrophyllite indicates that further understanding of the formation of these phases is required to concretely define the conditions of alteration. The presence of this behaviour as demonstrated in this study requires that hydrothermal systems are far more complex than can be gained by a single phase diagram and full understanding of the reaction path can only be gained through the consideration of dissolution and precipitation kinetics of the mineral phases.

9.3 Regional Geology

The AHAB itself and the later structural history of the eastern Avalon Peninsula indicate that much of the geological evolution of the area has been controlled by the same fundamental structural zone. The influence of the structural zone can be traced through the evolution of the AHAB into the deposition of the Conception Group and development of the Holyrood Horst. The recognition of the role of this structure explains the northerly strike of much of the geology of the Avalon Peninsula and clearly demonstrates that the present distribution of units is the result of Precambrian rather than Paleozoic tectonics.

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