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STRUCTURAL SETTING OF THE ADAMANT PLUTON,
NORTHERN SELKIRK MOUNTAINS,
BRITISH COLUMBIA.

by

C

David Andrew Shaw

A thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfilment of the requirements for the degree of
Doctor of Philosophy

Department of Geology
Carleton University
Ottawa, Ontario
November, 1980

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Northern Selkirk Mountains,
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ABSTRACT

Rock types within the concentrically zoned Adamant pluton range from hypersthene-augite monzonite in the core to biotite-hornblende granodiorite and quartz diorite in the outermost zone. The core has maintained an igneous petrological and structural character whilst the outer zones contain secondary, hydrous minerals. Chemically the body is grossly homogenous petrological differences between the core and perimeter may be accounted for by the addition of water to the outer zones.

The Adamant pluton has been emplaced into rocks of the Horsethief Creek Group, of Proterozoic age, which is subdivided into the Lower Pelite member, the Middle Marble member and the Upper Pelite member. These members have been correlated with the Isaac, Cunningham and Yankee Belle Formations respectively in the Cariboo Mountains to the northwest of the Northern Selkirk Mountains.

The Northern Selkirk Mountains have experienced three main phases of deformation, the first of which probably occurred during the Paleozoic. During this phase at least one large-scale nappe was formed that inverted the stratigraphy to the west of the study area. A planar fabric (S_1) was produced that is generally parallel to primary layering (S_0) throughout the region. The second and third phases of deformation are thought to have occurred during the Middle Jurassic. The earlier phase formed tight to

isoclinal folds, the axial surfaces of which strike northwest-southeast and dip towards the northeast. The form of the third phase varies from a strong crenulation to large scale, tight folds with axial surfaces that also strike northwest - southeast but dip towards the southwest. Planar fabrics (S_2 and S_3) generally have similar attitudes but diverge sufficiently to allow phase two hinges to be deformed about phase three structures.

On the basis of petrological composition three planar fabrics are recognized within the pluton. In the core zone plagioclase crystals form a semi-circular pattern that bulges towards the east. In the outermost zones a planar fabric, defined by compositional layering and composed of hydrous mineral phases, is orientated parallel to the margin of the body. It is thought that both the core area fabric and the fabric of the outer zone were produced as a result of lateral, magmatic flow during the emplacement of the body. The present day differences in petrological composition of the fabrics are a secondary feature related to the hydration of the body, the hydrous minerals having grown during a period in which the outer part of the body was hydrated and the primary flow fabric mimetically recrystallized. Phase two folds deform the compositional layering in the outer part of the body and contain a biotite foliation that is orientated parallel to their axial surfaces.

An age of 169 Ma $\pm$ 4 Ma was derived from zircons collected from the hydrated part of the body. This age is interpreted to reflect the peak of regional metamorphism that achieved middle amphibolite facies and occurred after the second, but before the third, phase of deformation.

The emplacement of the pluton preceded at least the second and third phases of deformation and probably the first. The presence of a relatively rigid mass of igneous rock during the application of regional compressive stress influenced the orientation of fold axial surfaces adjacent to the body, a structural aureole being produced around the pluton.

Analogy with the results of finite element analysis and mathematical and laboratory models suggests that the pluton has experienced at least 9 degrees of rigid body rotation since its emplacement. The present discordant trend of the body, with respect to regional structural trends, is related to a combination of factors, the viscosity of the intruding magma and the nature and orientation of the intruded strata being foremost.

The Adamant pluton can be no younger than the Middle Jurassic but a much older age is highly probable.

ACKNOWLEDGEMENTS

During the course of this project I have benefitted from the advice and suggestions given by many. I am particularly indebted to Dick Brown for suggesting, supervising and showing a keen interest in this project.

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TABLE OF CONTENTS

	page
Abstract	III
Acknowledgements	VI
Table of contents	VII
List of Figures	VIII
List of Tables	XII
List of Plates	XIII
1. Introduction	
1a. Purpose	1
1b. Previous work	2
1c. Location and physiography	3
1d. Regional geology.	5
1e. Regional tectonic history	8
1f. Regional tectonic models	10
2. Stratigraphy	
2a. Introduction	15
2b. Lower Pelite member	16
2c. Middle Marble member	19
2d. Upper Pelite member	21
3. Structural geology of the rocks around the Adamant pluton.	
3a. Introduction	23
3b. Regional phases of deformation	26
3c. Deformation within Zone A.	29
3d. Deformation within Zone B	54
3e. Phase four deformation	57
3f. The Norman Wood Creek fault zone	57
3g. Discussion and Summary	58
4. The internal structure of the Adamant pluton	
4a. Introduction	64
4b. Internal structure	66
4c. Discussion	69
4d. Summary and Conclusions	72

5.	Metamorphic geology and textural relationships	
	5a. Metamorphic geology	77
	5b. Textural relationships	79
	5c. Minor Igneous rocks	82
6.	Geochronometry	
	6a. Introduction	84
	6b. Previous work	84
	6c. Recent work	89
7.	The behaviour of an elliptical body in a deforming matrix	
	7a. Introduction	105
	7b. Finite element analysis	106
	7c. Mathematical and physical models	122
8.	Mode of emplacement	
	8a. Introduction	151
	8b. Discussion	152
	8c. Emplacement mechanisms	154
9.	Comparison with Belchertown pluton	161
10.	Summary and Conclusions	164
	Bibliography	167
	Appendix tables	178
	Plates	

LIST OF FIGURES

	page
1. Columbia River Big Bend location within Canada.	4
2. Study location within Big Bend of Columbia River.	6
3. Northern Selkirks - project areas, Adamant pluton and its structural aureole.	i.f.
4. Structural features of the Omineca Crystalline Belt.	7
5. Major peaks within and adjacent to study area.	i.f.
6. Topography and drainage - Zone A.	i.f.
7. Station location map - Zone A.	i.f.
8. Lithological map - Zone A.	i.f.
9a. Structural domains around Adamant pluton.	24
9. Divergence zone locations.	31
10. Orientation of S_0 and S_1 - Zone A.	i.f.
11. Stereoplot of $D_{0/1}$, D_2 and D_3 fabric elements - Zone A.	i.f.
12. D_2 minor structures - Zone A.	i.f.
13. D_2 and D_3 fold axial surface traces, with structural cross-sections.	i.f.
14. D_3 minor structures - Zone A.	i.f.
15. Stereoplot of $D_{0/1}$ and D_2 fabric elements - Zone B.	i.f.
16. Stereoplot of D_3 and D_4 fabric elements - Zone B.	i.f.
17. Axial surface trace map - Zone B.	i.f.

18. Major folds adjacent to Adamant pluton.	35
19. Deflection of regional trends around Adamant pluton.	i.f.
20. Diagrams of Mount Enterprise structure.	38
21. Progressive tightening of Argonaut Mountain structure away from Adamant pluton.	i.f.
22. A. Modal classification diagram. B. Generalized mineralogical composition and modal variation in different rock units.	65
23. Fabric elements within Adamant pluton.	i.f.
24. Stereoplot of linear structures within Adamant pluton.	68
25. Structural core of Adamant pluton.	74
26. Metamorphic assemblages - Zone A.	i.f.
27. Sample location map - Isotopic analysis.	88
28. Rb/Sr values within Adamant pluton.	90
29a. Uranium - lead concordia plot of Adamant pluton zircons.	92
29. Distribution of zircon within Adamant pluton.	i.f.
30. Distribution of TiO_2 within pluton.	i.f.
31. Distribution of elements, layout 1.	i.f.
32. Key to nodes, layout 1.	i.f.
33. Principal stress components, layout 1.	i.f.
34. Trend of Principal stress 2, layout 1.	i.f.
35. Distribution of elements, layout 2.	i.f.
36. Key to nodes, layout 2.	i.f.
37. Principal stress components, layout 2.	i.f.
38. Trend of Principal stress 2, layout 2.	i.f.

39. Rotation direction with respect to initial orientation.	113
40. Finite element analysis results	118
41. Swerving of A-axes in the matrix around a rigid inclusion.	126
42. Relationship between schistosity and deformed pebbles.	129
43. Ranges of orientation for forward and backward rotation of inclusions.	132
44. Pure shear deformation paths.	136
45. Total strain in an elliptical cylinder v. total strain.	137
46. Notation for definition of drag.	139
47. Types of drag patterns of passive markers around rigid, elongate inclusions	143

i.f. - in folder

LIST OF TABLES

1. Potassium - argon analysis results, condensed from G.S.C. Reports 62-17 and 63-17. 85
2. Trace element analyses of Adamant pluton samples. 94

APPENDIX TABLES

1. Lake Sarah section (E-F), L.P.m.
2. Mount Stockmer section (D-C), L.P.m.
3. Top of Windy Creek section (I-J), M.M.m.
4. Palisade Massif (A-B), M.M.m. and U.P.m.
5. Alpina Dome and Redan Ridge (L-K), M.M.m. and U.P.m.

LIST OF PLATES

- A. Pluton - country rock contact.
- B. The Palisade Massif structure.
- C. Folds present in the Guardsman Peak Ridge.
- D. Major structures outlined by the Middle Marble member.
- E. Lithology and structure.
- F. Fold form.
- G. Fold form.
- H. Fold form and Mount Sir Sandford.
- I. Fold form.
- J. Igneous structure and petrology.
- K. Metamorphic petrology and microfabrics.
- L. Varieties of garnet form.
- M. Metamorphic petrology and microfabrics.

1. INTRODUCTION

1a. Purpose

On the map of the Adamant pluton by Fox (1969) a distinct change in the orientation of compositional layering and planar foliations within Horsethief Creek Group strata is apparent adjacent to the pluton. Especially noteworthy is the outcrop pattern of the Marble unit of the Horsethief Creek Group (Unit 2 on the map) around the eastern end of the pluton and along the northern margin of the body. The overall form of the pluton resembles that of a giant porphyroblast that is strongly discordant to a foliation that wraps around it.

An investigation of the factors controlling the re-orientation of the planar structures and outcrop pattern around the body was suggested to the author by R. L. Brown. In understanding the relationship of the regional phases of deformation to the pluton it was also hoped to determine a precise time of emplacement of the body. Fox (1969) believed the pluton to have been emplaced synkinematically, but given such a discordant orientation with respect to the regional structural trend, this hypothesis did not appear feasible.

The investigation was an integral part of a group project being carried out by graduate students at Carleton University under the supervision of R. L. Brown. In

studying the geology of the Adamant pluton and its environs a link was provided between the area to the south, studied by Tippet; and that to the north being studied by Perkins (Figure 3).

In order to understand the emplacement history of the pluton it was first necessary to establish the stratigraphic succession and the deformation and metamorphic histories of the surrounding country rocks.

1b. Previous Work

Brief descriptions of the Adamant pluton and its environs are presented in the Geological Survey of Canada reconnaissance maps and reports covering the Rogers Pass map area (Wheeler, 1963) and the Big Bend map area (Wheeler, 1965).

The only detailed geological study related to the Adamant pluton is that by Fox (1969), based on his M.Sc. and Ph.D theses. His study was primarily a petrological one, minor attention being given to the structural complexity of the rocks around the pluton.

The Selkirk Mountains, Dogtooth Range and Esplanade Range (Figure 2) have been extensively mapped by workers from the University of Calgary (Wind, 1967; Ellison, 1967; Jones, 1969; Ghent, Jones and Nicholls, 1970; Simony and Wind, 1970; Poulton, 1970; De Vries, 1971; De Vries, Ghent, Jones and Simony, 1971; Ghent and De Vries, 1972; Jones, 1972; Poulton, 1973; Ghent, 1975; Ghent and McKee, 1975;

O'Neill and Ghent, 1975; Simony, 1975). Their studies have emphasized the fields of metamorphic petrology, structural geology, stratigraphy and sedimentology.

Since 1973 students from Carleton University, Ottawa, under the supervision of R.L. Brown, have been working in the region enclosed by the Big Bend as far south as the Esplanade Range of Franzen, 1974; Van der Leeden, 1975; Tippet, 1976; Lane, 1977; Psutka, 1978; Perkins, in progress, Leatherbarrow, in progress). The work presented here is an integral part of Carleton University's Northern Selkirk project (Figure 3).

1c. Location and Physiography

The Selkirk Mountains are centrally located in the eastern Canadian Cordillera of southeast British Columbia and are enclosed on the west, north and east by the Big Bend of the Columbia River (Figures 1 and 2).

That part of the Northern Selkirk Mountains studied during the course of this project is outlined in Figures 2 and 3.

Elevations in the area reach a maximum of 3,666 m above sea level at the peak of Mount Sir Sandford (Plate H3), with valley floors descending to 1,000 m above sea level. Above 1,750 m the terrain is commonly ice- or snow-covered; below 1,250 m the valley slopes and lower reaches are densely vegetated (Figures 5 and 6).

July and August are the optimum months for mapping

although the field season was always extended into late June and early September. Mapping was undertaken in 1974, 1975, 1976 and 1977, the latter three years being spent exclusively on and around the Adamant pluton.

The study area lies within N.T.S. 1:50,000 map sheets 82N/12, 82N/13, 82M/9 and 82M/16.

1d. Regional Geology

The Selkirk Mountains are part of the Omineca Crystalline Belt (Douglas et al., 1976) which also includes the Kootenay Arc and Monashee Mountains (Figure 4).

Within the Monashee Mountains is a terrain of high grade metamorphic rocks termed the "Shuswap Metamorphic Complex" (Jones, 1959; Reesor, 1970). The various gneiss domes composing this complex have yielded isotopic ages ranging from 3 Ga (Duncan, 1978) to 1.9 Ga (Wanless and Reesor, 1975). These core gneisses appear to be continuous between individual domes (Read, 1980; Brown, 1980a) and form a basement terrain with a minimum age of 2 billion years.

Overlying this basement is a succession of shallow marine platform sediments which form an autochthonous cover of 1 to 3 km thickness (Brown and Psutka, 1979). Lithology is variable; a basal quartzite is overlain by carbonate, calc-silicate and pelitic rocks. These rocks have been variously assigned a Cambrian age (Wheeler et al., 1972; Reesor, 1970; Hoy and McMillan, 1979) or correlated with early Proterozoic (Belt-Purcell) sediments (Brown and

Figure 4 Structural and physiographic features of the Omineca Crystalline Belt.

from Brown, 1980.

Psutka, 1979; Brown and Read, 1979).

A thick succession of pelitic and amphibolitic rocks structurally overlies the autochthonous strata. Mylonitic fabric together with fault breccia and gouge occur along the length of this zone (Brown and Psutka, 1979; Brown, 1980a; Brown, 1980b in press). The rocks that crop out in the Northern Selkirk Mountains are contained within this allochthonous sequence. They consist of the Upper Proterozoic Horsethief Creek Group and the Lower Paleozoic Hamill, Badshot and Lardeau successions. The strata represent a westerly prograding cycle that culminates in the Lower Cambrian Badshot Formation, a carbonate bank deposit. The Lardeau Group consists primarily of a deep water sedimentary accumulation (Wheeler et al., 1972; Wheeler and Gabrielse, 1972).

Allochthonous cover rocks occur as fault slices along the eastern flank of the Columbia River fault zone (Figure 4) (Wheeler, 1965; Brown and Psutka, 1979; Read, 1979; Brown, 1980a). Selkirk Mountain and Kootenay Arc strata have been transported eastward relative to the Shuswap basement rocks and are located above the hanging wall of the Columbia River fault (Read, 1979; Brown, 1980b).

1e. Regional Tectonic History

In the Omineca Belt there is evidence of four major episodes of deformation. These occurred in the Proterozoic (Racklan - East Kootenay orogeny), Ordovician, Devonian to

Early Mississippian (Caribooan or Antler orogeny) and during the Middle Jurassic.

In the Northern Selkirk Mountains the earliest event recognized is the probable pre-Mississippian one (see Read 1975, 1976) where large nappes are developed along the western flank of the Selkirk-Kootenay terrain.

During the Middle Jurassic extensive deformation and metamorphism occurred in the Omineca terrain. Two, and locally three, phases of folding during this period are recognized in the Northern Selkirk Mountains. The first occurred before the regional metamorphism peaked at mid-upper amphibolite grade, and produced folds that were overturned towards the west. After the metamorphic peak, structures overturned towards the east were generated. Interference between these two successive phases produced the Selkirk Fan Structure (Brown and Tippet, 1978).

During this tectonic activity granitic plutons were emplaced. The beginning of the Late Jurassic is thought to mark the termination of regional ductile deformation, based on Rb/Sr dating of post-tectonic intrusive events (see Duncan et al., 1979).

Brown (1978) argued that late- to post-metamorphic folds located in the hanging wall of the Purcell Fault, adjacent to the Rocky Mountain Trench in the Northern Selkirk Mountains, are contemporaneous with the initiation of thrust faulting in the western margin of the Rocky Mountain

Foreland.

Uplift of the Omineca Belt from Late Jurassic to Eocene time is indicated by data from the Wolverine Complex of the Omineca Belt (Pigage, 1976), and by K/Ar ages on Late Jurassic plutonic rocks in the Omineca Belt (Duncan et al., 1979).

Some high angle normal faults in the Rocky Mountain Belt have been shown by Price (1965) to have been active in Upper Eocene and later times.

1f. Regional Tectonic Models

The traditional view concerning the evolution of the Rocky Mountain Foreland Thrust and Fold Belt has been that it is younger than the orogenic activity that gave rise to the metamorphic core complexes of the Omineca Belt.

Price and Mountjoy (1970) presented a new viewpoint when they proposed a cause and effect relationship between the emergence of the core complexes and the generation of the thrusts and folds to the east. An allochthonous origin is required for the metamorphic core complexes in the Price and Mountjoy model because they assume that cratonic rocks as far west as the Rocky Mountain Trench remained relatively stable whilst the cover rocks were contracted over a minimum distance of 320 km.

High angle faulting involving basement beneath the Main Ranges was invoked in the model proposed by Campbell (1973) although he accepted the presence of a passive basement

beneath the Front Ranges and Foothills. Westward underthrusting of the craton is cited by Campbell as a mechanism for producing such restricted decollement thrusting. Also contrary to the Price and Mountjoy model, Campbell viewed the Shuswap Metamorphic Core Complex essentially as an autochthon that experienced internal deformation and was vertically uplifted along with the basement.

The most recent tectonic model is that proposed by Brown and Tippet (1978) which was subsequently expanded by Brown (1980b) to include the Shuswap Metamorphic Complex as well as the Selkirk-Kootenay terrain. In this model there are three main elements present during the Proterozoic and part of the Paleozoic. In the west the Archean gneisses, that now crop out as domes in the Omineca Crystalline Belt, formed a platform upon which a shallow marine succession of probable Precambrian age was deposited. To the east lay the distal edge of the Rocky Mountain miogeocline, the Proterozoic cover forming a westerly thickening wedge. Overlying these distal shelf to slope sediments, which are recognized in the Selkirk Mountains, were Upper Proterozoic-Cambrian shallow marine clastics. In the model proposed by Brown (1980b) the eastern and western elements were separated by the Selkirk-Kootenay Basin, filled with over 10 km of Proterozoic sediments and volcanics, which was then overlapped by a westerly prograding wedge of Cambrian

shallow marine clastics (Wheeler, 1965; Wheeler and Gabrielse, 1972; Brown et al., 1978). Transitional or oceanic, rather than continental, basement is thought to have originally floored this basin (Brown, 1980b).

The pre-Middle Mississippian nappes in the Kootenay terrain (Read, 1975, 1976) were believed by Brown to be related to a Paleozoic period of plate convergence. Oceanic crust to the west was subducted below the Omineca terrain resulting in plutonism and the initiation of the collapse of the western margin of the Selkirk-Kootenay Basin (Brown, 1980b). Data initially presented by Brown and Tippet (1978) from the Northern Selkirk Mountains, and later amended by Brown and Read (1979), suggest nappe displacement from east to west, i.e. from the Basin westward across the Shuswap basement terrain.

Westerly-overtaken structures were generated in the Selkirk - Kootenay Basin as a result of deformation during the Middle Jurassic (Brown, 1980b). Brown and Tippet (1978) kinematically accounted for these structures by invoking an incipient underthrusting of the Shuswap basement below the strata of the Selkirk-Kootenay Basin.

Timing of uplift of the Omineca terrane is constrained by a pressure environment of at least five kb. during and immediately after this phase of deformation. The peak of metamorphism occurred between this deformation phase and the next.

Shuswap terrain encroached further upon the cratonic margin with continued collapse of the Selkirk-Kootenay Basin, "basement" material of the latter being consumed either beneath the Shuswap basement or below the cratonic margin to the east.

Easterly-overtaken folds were generated in the eastern part of the Basin as the tectonically thickened and buoyant Omineca terrain was underthrust initially by the basement of the collapsing Basin and then by the cratonic rocks of the continental margin (Brown and Tippet, 1978; Brown, 1980b).

Continued uplift of the Omineca terrain and progressive underthrusting of the basement initiated easterly-migrating decollement thrust faults in the Rocky Mountain Foreland (Brown, 1980b). Progressive thickening and uplift of the western end of the Foreland wedge would account for the eastward migration of the deformation (Chapple, 1978).

Eastward displacement, along the Columbia River fault zone, of detached Shuswap cover rocks occurred in conjunction with post metamorphic uplift (Brown, 1980b). This early movement was possibly a distal manifestation of thrust faulting in the Rocky Mountain Foreland.

Price and Mountjoy (1970) in their model showed that this decollement thrusting in the eastern part of the Rocky Mountains continued into the Paleocene.

From this brief review it appears that the Adamant pluton has been emplaced into what is now the Selkirk

allochthon. In this thesis the author will contend that the pluton was emplaced early in the evolution of the mountain belt before displacement of the Selkirk allochthon.

2. STRATIGRAPHY

2.a Introduction

Westward thickening and prograding wedges of sediment were characteristic of the initial deposition in the Cordilleran geosyncline, a structure initiated more than 1,300 Ma ago. The Belt-Purcell Supergroup, a continental terrace wedge deposited on the western flank of the North American craton, is the oldest sedimentary succession exposed in southeastern British Columbia and the northern United States. Overlying is the Windermere Supergroup, of Hadrynian age, represented in the Northern Selkirk Mountains by the Horsethief Creek Group. In parts of southeastern British Columbia the basal part of this Group includes a coarse diamictite and conglomerate, overlain by thick feldspathic grits and pelites. However in the Northern Selkirk Mountains the basal part is not recognized; instead the lowest member is one of transitional slate which in turn is overlain by a carbonate-rich member and a mixed carbonate and clastic member.

Crossbedded sandstones and orthoquartzites of the Hamill Group, with a probable age of Lower Cambrian, overlie the Windermere Supergroup. The Hadrynian clastic sedimentary wedge is covered by pelites and archaocyathid limestones deposited on a shallow marine platform.

The three members of the upper part of the Horsethief Creek Group, outlined above, are exposed in the study area,

each member recognized can be correlated with subdivisions recognized to the north and south. These formations have been tentatively correlated by Brown et al. (1978) with formations of the Cariboo Group in the Cariboo Mountains (Campbell et al., 1973).

Detailed lithological descriptions of the individual sub-units that compose the three members of the Horsethief Creek Group within the study area are presented in Appendix tables 1 to 5. The distribution of the rock types within the study area is shown in Figure 8; geographical locations referred to in the text are shown in Figure 5.

2b. The Lower Pelite member

The Lower Pelite member (L.P.m.) is exposed predominantly in the northwest quarter of the study area (Figure 8). It lies in the core of the Gold River anticline (Figures 12, 16) which is the northern extension of the large Cherub Mountain - Esplanade Range anticline (Tippett, 1976; Brown and Tippett, 1978). The axial surface trace of this structure strikes northwest, from the Esplanade Range, towards the southeast corner of the Adamant pluton. Here it diverges around the eastern end of the pluton and part-way along the northern margin before resuming a northwest strike in the Windy Range (Figure 12). Stratigraphic sections of the western limb are detailed in Appendix Tables 1 and 2; the eastern limb was not examined.

The base of this member is not exposed in the study

area. The top is defined by the first occurrence of major pure and impure carbonates which mark the base of the overlying Middle Marble member.

The Lower Pelite member is at least 1,300 m thick; in Tippet's section to the south (Tippet 1976, p. 24) a thickness of at least 900 metres is recorded. Poulton (1970) gave a thickness of 1,000 metres in the Dogtooth Range. Neither Poulton nor Tippet observed the base of the member.

Within this member there are five main units, detailed in Appendix Table 1. The lowest, Unit A, comprises interbedded pelites and psammities characterized by the presence of a thin marble horizon.

Sparsely scattered throughout this unit are thin, continuous amphibolite bands, both discordant and concordant on a local scale (Plate H2). Kyanite and garnet are extensively developed within the pelites.

Unit B consists mainly of pelite and semi-pelite. Amphibolite layers, with an average thickness of 15 cm, are more numerous than in Unit A. Because of their consistent concordancy with bedding and lateral persistence they are presumed to be para-amphobolites. In the Lake Sarah section (Appendix Table 1) a clean, light grey, medium grained, grit horizon overlies the amphibolite-rich section.

Unit C is transitional between the underlying and overlying units. It consists of thin (5 to 15 cm),

concordant and laterally persistent amphibolite layers with an aluminosilicate-poor pelite and semi-pelite host rock. Towards the top of this unit the pelite tends towards a rusty appearance and the amphibolites become thicker and more discordant.

The rusty yellow pelite and flaggy semi-pelite of Unit D are the most commonly outcropping rock types of the Lower Pelite member. Thick, massive and locally concordant amphibolite layers are a distinctive feature, the associated brown staining of adjacent strata making the unit easy to locate from a distance. Para-amphibolites similar to those described in Units A and B are also common. A deeply weathered and "crumbly" muscovite-rich pelite is usually associated with the massive amphibolites.

On the south side of the Mount Palmer - Mount Sir Sandford ridge a quartz-pebble conglomerate, with a calcareous pelite matrix, occurs in the upper part of this unit. This horizon has not been recognized elsewhere in the Lower Pelite member although there is a conspicuous quartz-pebble conglomerate in the Upper Pelite member.

The abundance of amphibolite decreases within Unit E, which is predominantly carbonate-rich pelite and rusty marble representing a transition into the overlying Middle Marble member (Plate G3).

In the Mount Stockmer section, (Appendix Table 2), Unit E is much thicker than elsewhere. At its base and top, there

is carbonate-rich pelite and rusty pelite, both with abundant tremolite and diopside. The lower carbonate-rich zone overlies a massive amphibolite layer with a thickness of at least 10 m. The upper and lower carbonate zones are separated by a considerable thickness of flaggy pelite. In the Lake Sarah section (Appendix Table 1), and on the south side of the Mount Sir Sandford - Mount Palmer ridge, Unit E has only a relatively minor thickness with sparse amphibolites underlying the Middle Marble member.

2c. Middle Marble member

The base of the Middle Marble member (M.M.m) is marked by the first occurrence of massive pure and impure calcitic and dolomitic marbles (Appendix Tables 1-5, Plate E4).

It crops out almost continuously around the pluton and forms the peaks of Mount Sir Sandford, Shaw Peak, Mount Stockmer, Ravelin Mountain, Palisade Mountain and Mount Enterprise, as well as numerous unnamed peaks that border the northern edge of the pluton.

The top of the member is exposed mainly along the southern perimeter of the body and is marked by a relatively rapid transition into pelites, psammites and grits, the basal strata of the conformably overlying Upper Pelite member (U.P.m). The Middle Marble member is wrapped around the eastern end of the pluton where it generally crops out as two layers of marble separated by interbedded pelite, carbonate-rich pelite, psammite, quartzite and rusty marble.

The basal main marble layer is commonly the thicker of the two and is the one that forms the massif of Mount Sir Sandford (Plates D1, H3).

A layer of quartzite is usually associated with the basal marble. At Mount Stockmer there is a layer of dirty grey quartzite directly below the lower main marble; in the Palisade massif there are quartzite layers directly below and above the lower main marble. Tippet (1976) also noted the presence of quartzite in close proximity to the lower marble in the area to the south. Such an association implies a rapid facies change, the nature of which is discussed by Tippet, before and after the marble was deposited.

A distinctive feature of the lower main marble unit (Unit 2a) in the Mount Stockmer section is the presence of pods and lenses of amphibolite (Plate E1). The amphibolite is often rimmed by a reaction zone of brown carbonate and diopside.

The M.M.m. exhibits a rapid variation in thickness along strike, a feature also described by Tippet (1976) and by Perkins (pers comm., March, 1978). In the Palisade massif (Appendix Table 4) it is at least 180 m thick, whereas in the Guardsman ridge it decreases to 40 m. In the south wall of Palmer Creek the member thins rapidly, in the lower part of the valley it is absent. The member reappears in the lower part of the north wall and thickens rapidly.

adjacent to and in the Mount Stockmer massif. Whilst some of this thickness variation may be primary it is thought that the main control is secondary and related to the mode of emplacement of the Adamant pluton, a topic discussed further in Chapter 8.

Towards the top of this member in the Goldstream massif there is a carbonate conglomerate horizon with elongate, carbonate clasts in a matrix of blue-grey marble (Plate G4). A distinctive feature of this clastic horizon is the lack of terrigenous material, possibly indicating an isolated carbonate bank source area (Tippett, 1976).

2d. Upper Pelite Member

The Upper Pelite member (U.P.m.) rests conformably upon the Middle Marble member and crops out along the southern margin of the pluton. The top of the U.P.m. was not recognized within the study area but it is overlain elsewhere by the Late Proterozoic-Cambrian Hamill Group.

The maximum thickness recorded in the study area is 3,175 m (Appendix table 5). To the south Tippett (1976) records a 2,900 m thick section from the top of the Middle Marble member to the base of the Hamill Group. Within the region to the south a northwestward thickening of the U.P.m. is observed (Tippett, 1976).

Within the U.P.m. there are 5 main units (Appendix Table 5). Unit A, at the base of the member, is transitional in the lower part from the underlying M.M.m.

Calc-rich pelites are succeeded by slaty pelites and these in turn are overlain by interbedded quartzite, psammite, pelite and semi-pelite 1,500 m thick.

Traces of copper mineralization are evident in the upper part of Unit A and in Unit B; this latter unit is predominantly composed of finely laminated pelite containing thin layers of green and brown, carbonate-rich rock. This unit can be traced eastwards along the southern margin of the pluton and southwards into the area of Sonata Mountain where it was recorded by Tippet (1976).

Overlying the striped pelite is a thin horizon of rusty yellow pelite that contains iron-stained, carbonate nodules.

Unit C is a massive quartzite-pebble conglomerate, the lower contact of which is sharp whilst the upper contact is transitional into the finer grained, grit sequence of Unit D (Plate E3). Within this unit grits are interbedded with psammite, quartzite and pelite.

Finely laminated pelites, rich in fuchsite (Brown, 1980, pers. comm.) and metamorphic index minerals, form Unit E. The rock is migmatitic, having pods of quartz and feldspar throughout.

3. STRUCTURAL GEOLOGY OF THE ROCKS SURROUNDING THE ADAMANT PLUTON

3a. Introduction

Peripheral to, and concentric with, the Adamant pluton is a belt of country rock within which the structural geometry has been influenced by the presence of the pluton. This area is termed the structural aureole (Figure 3). The study area includes the structural aureole in its entirety and a part of the Northern Selkirk Mountains that lies outside of it.

The study area has been divided for convenience of description into three parts: Zones A, B, and C (Figure 3).

Zone A is that part of the structural aureole that lies to the east of Norman Wood Creek (Figure 3), and was mapped by the author. This zone has been subdivided into nineteen domains (Figure 9a). A domain is defined as an area within which there is a similarity in the orientation of structures associated with individual phases of deformation. Domain boundaries are located where changes in structural orientation occur; each domain therefore contains a unique set of structural orientations.

Zone B is the remainder of the structural aureole and lies to the west of Norman Wood Creek (Figure 3). This zone was mapped and reported by Franzen (1974), and Van der Leeden (1975).

Zone C lies outside of the structural aureole (Figure

FIG. 9a Structural domains around Adamant pluton

3) and was mapped by Lane (1977), Perkins (in progress), Brown and Tippet (1978) and this author.

Three major phases of deformation have been recognized in the study area; each of these phases can be correlated with deformation events in adjacent areas and throughout the Northern Selkirk Mountains, (Franzen, 1974; Van der Leeden, 1975; Tippet, 1975; Lane, 1977; Perkins, pers. comm., 1978).

A description of the structures associated with each phase, generally applicable throughout the Northern Selkirk Mountains, is given below. A more detailed description of the deformation within the study area is presented later.

The reader is referred to the following figures for this chapter:

Figure 7 : Station location map - Zone A.

8 : Lithological map - Zone A.

9 : Divergence zone locations.

9a: Structural domains around Adamant pluton.

10 : Orientation of S_0 and S_1 - Zone A.

11 : Stereoplot of D_{0-1} , D_2 and D_3 fabric elements - Zone A.

12 : D_2 minor structures - Zone A.

13 : D_2 and D_3 fold axial surface traces with structural cross sections - Zone A.

14 : D_3 minor structures - Zone A.

15 : Stereoplot of D_{0-1} and D_2 fabric element -

Zone B.

- 16 : Stereoplot of D_3 and D_4 fabric elements - Zone B.
- 17 : Axial surface trace map - Zone B.
- 18 : Major folds adjacent to Adamant pluton.
- 19 : Deflection of regional trends around Adamant pluton.
- 20 : Diagrams of Mount Enterprise structure.
- 21 : Progressive tightening of Argonaut Mountain structure away from Adamant pluton.

3b. Regional phases of deformation

Phase One

The initial phase of deformation produced tight to isoclinal folds varying in size from minor folds, with limb lengths of 0.3 m (Plate F1), to nappes with limb lengths of at least 10 km.

Within Zone B, adjacent to the Goldstream River, phase two folds are superimposed upon inverted strata, thus indicating the presence of a pre-phase two nappe (Van der Leeden, 1975; Brown et al., 1978). This westward-facing structure (Brown and Read, 1979) has a limb length of at least 10 km.

Whereas the nappe described above appears to be an isolated, major phase one structure within the immediate periphery of the study area, it is only one of a number in the region between the Shuswap and Rocky Mountains terrains.

In the Kootenay Arc, nappes attributed to a first phase of deformation have been described by Fyles (1964), Ross (1970), Hoy (1974, 1975), Read and Wheeler (1975) and Read (1975, 1976). Thompson (1972) and Zwangig (1973) described nappes involving Paleozoic strata which overlie gneisses of the Clachnacudainn Salient. To the north of the Big Bend of the Columbia River, near Mica Creek, Simony (1975) and Robbins (1975) also reported evidence of nappe formation. The regional development of these nappes is believed to have occurred during the early Mississippian Caribboan or Antler orogeny (Wheeler et al., 1972).

Associated with the Goldstream nappe and other, but minor, phase one folds in the study area and adjacent areas is a foliation orientated parallel to the axial planes of those folds and parallel to bedding (S_0), except in hinge areas. This fabric is composed of biotite and muscovite plates, elongated grains of quartz and carbonate, being most commonly developed in pelites, semi-pelites and psammites. This fabric has been strongly transposed by later deformation phases.

Phase one folds, other than the nappe referred to above, are rare within the Northern Selkirk Mountains. They generally occur as isolated, isoclinal, minor closures with younger structures superimposed.

Phase Two

The second phase of deformation produced tight to open,

asymmetric folds along with a strongly developed cleavage orientated parallel to the axial surfaces (Plates, F1, F2, F3, G1, G2, G3, H1, H2, I1, I2, J1, J2). The planar fabric (S_2) is composed of muscovite and biotite plates, elongated grains of quartz and calcite, flattened pebbles of carbonate and quartzite, kyanite, fibrolite and rare epidote (Plates J1, J2, K1, L1, L2, M1). Second phase axial surfaces regionally trend northwest - southeast and are either horizontal or dip at a low to moderate angle towards the northeast.

To the south of the structural aureole associated with the Adamant pluton second phase fold hinges gently plunge predominantly towards the southeast. To the north of the structural aureole they plunge predominantly towards the northwest.

Phase Three

Large scale tight to open folds, which caused a strong crenulation of compositional layering (S_1 , S_2), were generated during the final major phase of deformation (Plates B1, C, D1, D2, F3, F4, G4, H2, I1, K2, K4).

Axial planes of phase three folds dip at steep to shallow angles to the southwest, fold hinges plunge at a moderate angle to the southeast. Major phase three structures can be traced along the length of the Northern Selkirk Mountains.

The type of axial planar cleavage (S_3) developed during

this phase varies with the host lithology. In pelitic rocks S_1 and more commonly S_2 (as S_1 is generally transposed into S_2) are strongly crenulated to produce a crenulation cleavage (Plates F3, F4, I3, K2, K4). The spacing and intensity of this cleavage are variable. In impure carbonate rocks scattered plates of muscovite are aligned with elongated grains of carbonate. Psammitic rocks developed a cleavage composed of aligned, elongated quartz grains and rare plates of mica.

3c. Deformation within Zone A

Phase one deformation

No major phase one structures were recognized within Zone A. There are occurrences of small, isoclinal folds, with axial surfaces parallel to compositional layering, that are assumed to have been formed during the initial phase of deformation. The limbs of one such phase one fold (Plate F1) are folded by second phase folds. A planar mineral fabric orientated parallel to the axial surface of the later fold, S_2 , is crenulated by phase three structures. A weakly defined S_1 is parallel to compositional layering except in the noses of the rare phase one folds.

Where S_1 is not deformed by phase two and/or phase three structures it is orientated parallel/sub-parallel to the margin of the pluton. However the very strongly developed S_2 appears to have been formed at the expense of S_1 , the latter fabric being much less apparent.

S_1 is not orientated parallel to the pluton in the zones of divergence adjacent to the northwest and southeast margins of the pluton. (See later in this section).

The similarity in orientation between the margin of the pluton and S_1 increases towards the pluton. Around the eastern end of the pluton and along the northern margin, the Middle Marble member rims the pluton (Figure 8), exactly reflecting the orientation of S_1 (Plate A).

Phase two and phase three deformation

During both phases tight to open folds were generated. Associated with phase three is a strong crenulation cleavage in the pelitic rocks. Planar mineral fabrics, orientated parallel to the axial surfaces of associated folds, were generated during both phases. However fabric formed during the earlier phase, S_2 , is much more commonly and intensely developed than the fabric generated during the later phase, S_3 , which is relatively rare.

A major feature of the deformation during both phases is that axial surfaces, when traced in either a northerly or southerly direction towards the pluton, exhibit a significant change in orientation adjacent to the northwest and southeast corners of the body. Each individual phase of deformation produced two zones of divergence, located adjacent to the southeastern and the northwestern parts of the pluton (Figure 9). A more detailed description of these divergence zones is given below.

The structural geology within Zone A is predominantly the result of interference between the second and third phases of deformation (Plate B), the latter phase being dominant, especially in the northeastern part of the study area. The descriptions of both phases within the individual domains are combined below in order to compare their respective geometries.

Domain A

No major folds of either phase were recognized within this domain but minor folds are common. Phase two folds are seen to go around the hinges of phase three folds producing numerous examples of Ramsay (1967) type 3 interference patterns (Plate H2).

S_2 , which strikes northwest-southeast and dips to the southwest at moderate to steep angles, is seen as either a mica foliation or it is outlined by ellipsoidal quartz-feldspar blebs, the two major axes of which lie in the plane of S_0 . These blebs may be crenulated by phase three folds.

The axial surfaces of phase three folds strike northwest-southeast and dip at a steep angle towards the southwest. Hinges plunge to the west/northwest.

Domain B

Phase two folds and fabric are strongly developed whereas those of phase three are rare (Plates F2, F3).

At the northern perimeter of domain B S_2 strikes

approximately 290-110 degrees and dips toward the south-southwest. Adjacent to the pluton S_2 strikes east-west and is either vertical or dips steeply to the north or to the south. This bend in strike and change in dip direction is exhibited by the major structural feature within the domain, a large phase two anticline-syncline pair. These two structures are outlined on the west bank of Windy Creek, station 378, by the Middle Marble member (Figures 8, 14). Two very apparent features of the outcrop pattern are the intense minor folding on the limbs of these structures and the extended noses of the folds (Plate F2). Adjacent to the pluton the axial surface traces of the structural pair are parallel to the margin with the southern limb of the syncline being in contact with it (Figure 13). S_2 is very strongly developed in most rock types; the strength of S_2 in the carbonates is a notable feature. Ellipsoidal migmatitic pods of quartz and feldspar in the pelites are orientated with the major and intermediate axes parallel to S_2 .

Evidence of phase three deformation is sparse and is only well documented at station 388 (Plate F3). Here phase two minor folds are wrapped around phase three hinge lines and S_2 is strongly crenulated. The sense of these folds indicates a structural position on the southern limb of the Gold River anticline (Figure 18), the culmination of which is located to the north.

Domain C

Figure 18 Major folds adjacent to the Adamant pluton

- 1 Sonata syncline axial surface trace
- 2 Palisade anticline
- 3 Sir Sandford anticline
- 4 Sir Sandford syncline
- 5 Guardsman Ridge folds
- 6 Gold River anticline
- 7 Argonaut Mountain folds
- 8 Goldstream nappe

This domain comprises a series of phase two and phase three minor folds of varying size that are structurally located on the southwestern limb of the Gold River anticline. The hinge zone of the major structure trends across the extreme north of the domain (Figure 13).

The axial surfaces of phase two and phase three folds are similarly orientated with a northwest-southeast strike and a southwesterly dip. Hinges of phase two folds plunge to the west/northwest whilst those of phase three folds plunge towards the southwest.

The dominant lithology in the domain is a rusty, semi-pelite with much amphibolite and pegmatite. The relative paucity of mica in the semi-pelite may account for the absence of a strongly developed S_2 , consequently there is little evidence of phase three crenulation.

Some phase two minor folds are seen to go around the hinges of phase three minor folds resulting in type 3 interference patterns.

Domain D

The strike orientations of phase two and phase three axial surfaces within this domain are transitional between the near regional attitudes described in domain C and the east-west striking axial surfaces described within domain B. Phase two deformation is dominant in domain D, axial surfaces strike at $110 - 290$ degrees. S_2 dips to the south-southwest and the hinges of phase two minor folds

plunge towards the west. A single phase three fold hinge was identified, the plunge direction was opposite to that of local phase two folds.

S_2 is recognized as an alignment of mica plates and migmatitic pods. The lithology is similar to, but more mica-rich than, that of domain C.

Domain E

Deformation within domain E is distinctive because of the intimate involvement of the outer zone of the pluton with phase two activity. A series of phase two folds, with axial surfaces striking grossly parallel to the margin of the pluton, but dipping steeply away from the interior of it, deform the outer granodioritic zone and the adjacent country-rock. Four major phase two folds, with associated minor folding strongly developed, are identified (Figure 14). Granodiorite can be successively traced around a synclinal and an anticlinal closure (Figure 13), the former being cored by Upper Pelite member quartzite. Immediately north of the anticline which deforms the extreme periphery of the pluton is another phase two syncline-anticline pair. The syncline is cored by grits of the Upper Pelite member whilst the anticline to the north is strongly outlined in the summit and slopes of Mount Enterprise by carbonate bands of the Middle Marble member (Plate D2, Figure 20).

Phase two axial surfaces and planar fabric in the eastern part of domain E strike east-west, as does the

FIG. 20 Diagrams of Mt. Enterprise structure (viewed from the south-west)

margin of the pluton (Plate A3). In the central and western part of the domain the margin of the pluton trends northwest-southwest, this change in trend is reflected by a similar change in the strike of phase two structures. Phase two fold hinges plunge towards the west except where phase three deformation has re-orientated them.

Phase three minor folds are common and varied in size, structurally they are located on the southern limb of the Gold River anticline. S_3 , seen as a crenulation cleavage in the mica-rich pelites, is essentially parallel to S_0 , and dips steeply away from the pluton towards the north. The margin of the pluton in domain E is either vertical or dips steeply towards the north.

Interference between phase two and phase three structures is well illustrated in the summit region of Mount Enterprise (Plate D2). Here the major phase two synclinal antiform, outlined by marble layers and referred to above, plunges very gently to the east or is horizontal as it is folded around a phase three structure to produce a type 3 interference pattern (Figure 13, 20). Within the outer zone of the pluton the effect of phase three deformation is not recognized, it is assumed that the phase two structures therein retain their original orientation.

S_2 is best developed in the migmatitic pelites in which both the mica plates and quartz feldspar blebs are aligned in a plane parallel to the axial surfaces of phase two

folds. A strong crenulation of this fabric is common and a crenulation cleavage, S_3 , parallel to the axial surface of phase three folds is often recognized. Phase two folds within the granodiorite deform a pre-existing, metamorphic, planar fabric. This fabric and other structural features within the pluton are discussed later (Chapter 4).

Domain F

Phase two and phase three structures are both strongly developed within this domain, the latter being dominant. A distinctive structural feature is the juxtaposition of a major phase three anticline and a major phase three syncline as a result of normal faulting (stations 311 and 312). The fault obviously post-dates the third phase of deformation and would appear to strike parallel to compositional layering. Strata of the Lower Pelite member outcrop on either side of the fault, the throw on the fault being equal to or less than the thickness of that member. The limbs of the major folds must have been sheared out to some extent in order for the hinge zones to be in such close proximity. To the immediate north of station 311 (Figure 7), interference between phase two and phase three structures is very apparent (Figure 13).

S_2 , in the locally common, migmatitic, silver-grey, kyanite pelite, is composed of aligned mica plates and quartz feldspar blebs. This fabric is often strongly crenulated. S_3 is seen as a well developed, crenulation

cleavage.

In the northern part of the domain both S_2 and S_3 strike northwest-southeast and dip towards the southwest. In the central and southern part of the domain the strike direction approaches east-west, the dip direction is southerly. Hinges of phase three minor folds generally plunge in an easterly direction, as do those of the more rare, phase two folds.

Domain G

Phase three minor folds throughout domain G are structurally located on the southerly limb of the Gold River anticline. Axial surfaces vary in strike direction from northwest-southeast to east-west, the dip direction is southwest and south respectively.

S_2 has a similar orientation to that of S_3 described above. Hinges of the much more rare second phase folds plunge towards the west whilst those of third phase structures plunge at moderate angles towards the east (Figures 11, 12, 13, 14).

Mica plates and ellipsoidal blébs of quartz and feldspar within the migmatitic pelites are usually orientated parallel to S_2 and crenulated by phase three deformation. S_3 is recognized as a crenulation cleavage.

Domain H

Deformation characteristics within the domain are dominated by a prolific occurrence of phase three minor

folds and an intense crenulation of S_2 (Plate F4).

In the central part of the domain a very micaceous, migmatitic pelite hosts a strongly developed and crenulated S_2 . In the north and northwest part of the domain rusty, amphibolitic pelite lacks such a pronounced fabric and accompanying crenulation. Phase three minor folds are common in the carbonate and rusty marble-carbonate rich pelite of the Middle Marble member that crops out adjacent to the pluton. Whilst the carbonate-rich strata develops only a weakly defined S_2 , composed of elongated grains of carbonate and dispersed mica plates, the associated pelite contains a strongly crenulated planar fabric.

The strike direction of phase three fold axial surfaces varies from northwest-southeast to east-west, dip directions being southwest and south respectively. The magnitude of dip increases towards the margin of the pluton as adjacent strata assume an orientation very similar to that of the east-west striking and steeply inward dipping margin of the body (Plate A2).

Phase three fold hinges plunge in an easterly direction and indicate a structural position on the southerly limb of the Gold River anticline.

In the outer zone of the pluton, a few metres in from the contact, there are a number of minor folds outlined by a gneissic layering and by quartz stringers that are parallel/sub-parallel to the layering. The layering is

poorly defined compared to that described in domain E and strikes parallel to the contact, dipping steeply inwards as does the contact itself.

The axial surfaces of the folds reflect the orientation of the margin. No axial surface mineral fabric was recognized in the field. Both in orientation and structural position the folds are very similar to those in the adjacent metasediments that have been identified as phase three structures.

Domain J

Whilst both phase two and phase three folds are very common there is very little interference recognized between the two. Axial surface orientations are similar, the strike direction being northwest-southeast and the dip direction is southwest. Hinges of minor folds plunge in opposite directions, those of phase two folds plunge towards the east whilst those of the later phase plunge towards the west.

In the carbonates and rusty carbonates of the Middle Marble member S_2 is developed as an alignment of ellipsoidal calcite grains and mica plates. In the pelites S_2 is crenulated by phase three deformation, L_3 being formed as a crenulation lineation.

The north trending ridge on the east side of Tabernacle Creek (Figure 6) contains a series of large phase two folds. Strata deformed by these folds are structurally located on the southwesterly limb of the Gold River anticline.

A northwest-southeast trending zone of structural discontinuity occurs in the western part of the domain. Second phase structures do not maintain continuity across the zone; strata on both sides of the break belong to the Lower Pelite member, the strata on the southwest side being stratigraphically higher than that on the northeast. A normal fault, postdating at least the second phase of deformation, and dipping towards the southwest is indicated, (section E-F of Figure 13). The throw on the fault is equal to, or more probably much less than, 1,350 m.

Domain K

A northeast-southwest trending ridge, due east of Mount Stockmer, is the locale for the majority of the data gathered in domain K.

Structurally the ridge consists of a series of phase two folds, the axial surfaces of which strike northwest-southeast and dip towards the southwest. Along the ridge phase two fold hinges plunge both to the northwest and southeast, the hinge zones passing through the horizontal.

Phase three deformation is occasionally recognized and consists usually of a crenulation of S_2 , L_3 is developed as a crenulation lineation. There are rare phase three minor folds recognized.

Towards the southern end of the ridge the phase two fold succession is discontinuous. The strata on both sides of the discontinuity belong to the Lower Pelite member. It

is assumed that this break is continuous with that described in domain J (section C-D, in Figure 13).

Domain L

This domain is dominated by Mount Stockmer, located at the southern end of a carbonate-cored massif adjacent to the extreme southeast corner of the pluton (Figure 5). Structurally the massif is located on the upper limb of the Gold River anticline.

Large scale phase three minor folds, limb lengths of 25 metres, outlined by grey carbonate, form a Z shape on the southern flanks of Mt. Stockmer. Tectonic thinning is very apparent in the carbonate, over a distance of 800 metres the thickness increases from a couple of metres to many tens of metres. Axial surfaces of the folds dip to the southwest, hinges vary in plunge direction from southwest at the south end of the massif, station 288, to northwest in the central part of the massif.

The phase three folds described above are superimposed on less spectacular phase two folds, the axial surfaces of which dip to the southwest whilst hinges trend to the west and southwest. Interference between the two fold sets, plus the variety of plunge trends associated with them, produces a complicated structural picture.

Whilst phase three deformation is very visible in the massif it is subordinate to phase two structures in the remainder of the domain. In the ridge trending northwest-

southeast at the south end of the massif, stations 268 and 269, rusty pelite hosts a well developed S_2 and associated minor folds. Where the pelite is mica rich the planar fabric is crenulated by the later deformation. Where the pelite is carbonate rich S_2 is composed of mica plates and elongated carbonate grains, this lithology does not host a phase three crenulation.

Phase two minor folds in the ridge are similar in form and style to those described in domains K and J, those in domain L occurring in the upper part of the Lower Pelite member. Axial surfaces dip at moderate angles to the southwest, hinges generally plunge towards the south.

Domain N

A pronounced change in strike direction of phase three axial surfaces is the dominant structural feature within this domain. In the southern part of the domain S_3 strikes northwest-southeast and dips steeply to the southwest. In the central part, about 1 km south of Palmer Creek, the strike direction is approaching north-south, the dip direction is west and the amount of dip has decreased to a moderate amount. On the banks of Palmer Creek the strike direction is northeast-southwest, the dip direction is northwest with the amount of dip being moderate to steep. A kilometre north of the creek, adjacent to the southern margin of the pluton, S_3 parallels the contact and dips steeply toward it.

In the southern part of the domain, hinges go through the horizontal, plunge directions being either to the northwest or to the southeast. Further north the plunge direction is consistently towards the north-northwest.

Phase three folding varies in size from a strong crenulation of pre-existing planar fabrics, S_2 being by far the more common, to large scale minor folds with limb lengths of up to 30 metres. These folds are structurally located on the westerly limb of the Gold River anticline. Examples of the latter are located in the ridge at station 428 where they are strongly defined by carbonate within the Middle Marble member. These folds and stratigraphy can be traced northwestwards where they crop out in the Guardsman ridge section, stations 121 and 122 (Figures 8, 13). Here an anticline-syncline pair form a large Z shaped minor fold, outlined by carbonate (Plate C). The folds plunge steeply towards the northwest and are structurally located on the lower limb of a major syncline (the Sir Sandford syncline) the hinge zone of which is within domain 0, and on the upper limb of a major anticline (the Gold River anticline), the hinge zone of which is to the east northeast.

Phase two deformation is much less apparent, folds of this phase being involved with phase three closures in type 3 interference patterns. S_2 is well developed in both the pelites and carbonates and exhibits a similar change in orientation to that described for S_3 , this latter fabric

being predominantly a crenulation cleavage formed from S_2 .
Domain D.

As with the previous domain a dominant feature of the structural geology is the pronounced change in the strike direction of S_3 within the domain. In the far southeast corner of the domain, S_3 strikes northwest-southeast and dips steeply towards the southwest. Immediately northwest of the confluence of the Palmer Creek tributaries (Figure 6) the strike direction is approaching east-west and the dip direction is to the north. This change of dip direction, coupled with the change in strike, is accomplished by S_3 passing through the vertical. An east-west strike and steep dip to the north is maintained in the northern part of the domain, adjacent to the margin of the pluton.

Hinges of phase three minor folds plunge moderately towards the northwest in the southern part of the domain. In the northern part of the domain the amount of plunge increases and the trend is towards the northwest.

Equally significant however is a complex interference pattern produced by the folding of major phase two folds over and/or around the hinges of major phase three folds. Such interference is well illustrated by the Palisade Hook (Figures 12, 13, Plate B).

Palisade Mountain is situated approximately 4 kms to the northwest of Mount Sir Sandford (Figure 5), at the southwestern end of a northeast-southwest trending ridge.

Structurally Palisade Mountain is located on the broad, crestal zone of a major phase three structure, the Palisade anticline, the axial surface of which strikes northwest-southeast and dips very steeply to either the northeast or southwest, or is vertical. The hinge of this major fold plunges at a moderate to steep angle towards the west/northwest.

On the northeast limb of this structure is the phase two Sir Sandford anticline, which is outlined by carbonate of the Middle Marble member. This structure was initially mapped to the south by Brown and Tippet (1978). The hinge zone of this major phase two fold has been tightly refolded by a large scale, overturned, S shaped fold (Plate B). The interference pattern produced is a type 3. The phase three minor folds that deform the Sir Sandford anticline have steeply dipping axial surfaces that strike northwest-southeast, hinges plunge steeply to the northwest. Phase two minor folds associated with the Sir Sandford anticline can be traced over the broad hinge zone of the Palisade anticline and onto its southwestern limb.

Paralleling the axial surface trace of the Palisade anticline and located 1.5 kms to the northeast is the axial surface trace of the Sir Sandford syncline, a major phase three structure first referred to by Brown and Tippet (1978). In the northeast-southwest trending ridge that connects Mount Sir Sandford with Guardsman Mountain, (Plate

D1) the syncline is outlined by the Middle Marble member. An upright and broad hinge zone is flanked on the west by the Palisade anticline and on the east by the anticline-syncline pair in Guardsman Mountain ridge (Plate C), described in domain N.

The axial surface of the Sir Sandford syncline can be traced northwestwards from the Mount Sir Sandford-Guardsman Mountain ridge to the confluence on Palmer Creek where the rivers flowing from Sir Sandford glacier and Howarth glacier meet (Figure 6). Immediately north of the confluence; in the vicinity of station 29 (Figure 7), a phase two anticline-syncline pair outlined by a distinctive layer of green, carbonate rich pelite within the Upper Pelite member, can be traced around the hinge zone of the Sir Sandford syncline (Figure 13). At this location the strike of the axial surface of the major phase three fold is approaching 110-290 degrees. When traced from this location towards the pluton it assumes an orientation sub-parallel/ parallel to that of the east-west trending, vertical to steeply inward dipping, pluton margin.

The orientation of S_0 within the domain, except where adjacent to the metasedimentary contact with the pluton, is strongly influenced by the major phase three folds described above. Adjacent to the pluton the orientation of S_0 reflects the form of the contact.

Domain P

The hinge zone of the Palisade anticline, described in domain O, strikes into domain P where it is well defined by the axial surface traces of phase two folds which are folded over/around it.

In the ridge to the south of Redan Mountain (Figure 5) a phase two anticline-syncline pair, stations 219 and 220 respectively, is structurally located on the Palisade anticline hinge zone. Axial surfaces of the paired phase two structures strike northeast-southwest and dip to the northwest. From the ridge they can be traced onto the western limb of the later structure where they strike northwest-southeast and dip towards the northeast. Hinges change from plunging towards the north to the northwest.

Phase three minor folds generally strike northwest southeast, they dip very steeply towards either the northeast or to the southwest. Phase three hinges plunge steeply towards the northwest.

Domain Q

At the head of the southeastern, subsidiary, tributary of Stitt Creek, stations 200 to 202 (Figure 7), phase two minor folds are strongly developed and are structurally located on the upper limb of an overturned phase two syncline. In the southern part of domain Q the axial surface of the major structure trends northwest-southeast and dips at a moderate angle to the northeast. Brown and Tippet (1978) describe this major fold in the area to the

south and refer to it as the Sonata syncline. The hinge zone of this fold can be traced adjacent to the southeastern bank of the southwestern tributary of Stitt Creek, at station 189. From this location the axial surface can be traced northwestwards across the tributary and into a ridge where it passes between stations 184 and 186. At this point the strike direction is approaching 290-110 degrees, the dip direction is north-northeast.

Along the ridge that parallels the west bank of the main southern tributary of Stitt Creek, stations 184 to 196, S_2 progressively changes in strike direction from northwest southeast to northeast southwest. Dip direction changes from northeast to northwest as S_2 passes through the vertical close to station 193. This behaviour may be explained by S_2 being folded over the hinge of the Palisade anticline, which at this location is striking east-west and dipping in a northerly direction. Concomitant with the change in orientation of S_2 , the Sonata syncline is gradually opened out and "unfolded" by the phase three deformation.

Phase three deformation within this domain is also recognized as a crenulation of S_2 , axial surfaces of crenulations strike northwest-southeast and dip steeply to either the northeast or southwest. Throughout domain Q wherever phase three crenulation is recognized the structural position is on the eastern limb of an anticline.

Domain R

Domain R is composed of a series of large scale, (limb lengths of up to 500m), phase three minor folds, the axial surfaces of which strike north northwest-south southeast and dip very steeply towards the west. Associated hinges plunge at a moderate angle towards the north. These folds are structurally located on the eastern and lower limb of a major phase three anticline, herein referred to as the Stitt Creek anticline.

Phase two planar fabric and folds are folded around the hinges of the later folds producing type 3 interference patterns. The dominant stratigraphy within this domain is that of the Middle Marble member and consequently S_2 is developed as an alignment of elongated grains of carbonate and also clasts of carbonate (Plate G4). In the overlying Upper Pelite member the more micaceous layers host a well developed fabric; in the grits S_2 is recognized as an alignment of ellipsoidal grains of quartz and quartzite.

The structural position of minor phase two folds with respect to major phase two folds was not resolved. However it is to be expected that any phase two folds within this domain are located on the lower limb of the Sonata syncline, previously discussed in domain Q.

Domain S

With respect to stratigraphy and structure there is a distinct similarity between this domain and domain R. The

dominant lithology is marble and carbonate rich pelite of the Middle Marble member, the structural geology is controlled by large scale, phase three minor folds. The strike direction of these folds varies from northeast-southwest to east-west with respective dip directions of northwest and north. Hinges plunge steeply towards the northwest. It is proposed that these folds are located on the same limb of the Stitt Creek anticline as are those folds in domain R.

S_2 strikes northwest-southeast and dips in a northeasterly direction, this orientation being similar to that of the adjacent margin of the pluton. A single phase two minor fold hinge was measured, it plunged steeply in a northeasterly direction towards the inward dipping margin of the pluton.

3d. Zone B

Zone B is that part of the structural aureole that lies to the west of Norman Wood Creek (Figures 3, 6). Parts of this zone were mapped by Franzen (1974) and parts by Van der Leeden (1975). At least four phases of deformation were recognized by Franzen and Van der Leeden, the first three of which in each case are analogous to those described within Zones A and C.

Phase One

The existence of a phase one nappe was first inferred by Van der Leeden (1975) on the basis of phase two folds

being superimposed on inverted stratigraphy. This structure is referred to as the Goldstream nappe (Brown et al., 1977) and in Zone C to the south is thought to have a limb length of 20 km, (Lane, 1977).

To the south of Zone B the axial surface trace of this nappe strikes northwest-southeast and dips to the southwest (Lane, 1977). Within Zone B the strike direction changes from northwest-southeast to north-south and in the vicinity of the headwaters of Norman Wood Creek it is striking northeast-southwest. Concomitant with this change in strike the dip direction changes from southwesterly to southeasterly within the phase one zone of divergence, located adjacent to the northwestern margin of the pluton. This is most easily explained if the axial surface goes through the vertical as it is traced northwards adjacent to the western end of the pluton where it assumes an orientation similar to that of the inward dipping margin.

In the southern part of the phase one divergence zone the axial surface strikes northeast-southwest and dips to the southeast; in the central part of the divergence zone the axial surface assumes a north-south strike and in the northern part it strikes northwest-southeast (Figure 17). At the northern perimeter of Zone B the axial surface strikes northwest-southeast and dips to the southwest.

Phase one planar surfaces are parallel to compositional layering except in the noses of rare phase one folds

(Franzen, 1975; Van der Leeden, 1975), consequently the orientation of bedding around the western end of the pluton is similar to that of the major phase one axial surface trace outlined above.

Phase two deformation

Franzen (1974) and Van der Leeden (1975) documented phase two folds that have similar axial surface orientations to those previously described for the phase one nappe. The phase two planar surfaces exhibit similar changes in orientation both around the western end of the pluton and also within the western half of the divergence zone produced during the second phase of deformation, that is located adjacent to the northwestern margin of the pluton.

Phase three deformation

Phase three folds dominate the structural geology of Zone B, the main feature being the Argonaut Mountain structure (Franzen, 1974; Brown and Tippet, 1978). Across this structure the dip direction of phase three axial surfaces and the culmination direction of phase three folds changes. The margin of this fanning structure occurs in domains 5 and 6, but the central part of the structure is located in domains 7, 8, 9 and 10 (Figure 16), where large scale folds with steep to vertical axial surfaces occur. In domains 7 to 10 inclusive, phase three folds tighten and steepen to become tight to isoclinal closures with very steeply plunging hinges (Figures 16, 17). The axis of the

fanning structure strikes northwest-southeast as do the other phase three structures within Zone B.

In the area mapped by Van der Leeden (1975) phase three axial surfaces dip to the northeast and hinge lines plunge to the southeast towards the margin of the pluton. Superposition of phase three folds upon phase two folds has produced type three interference patterns.

3e. Phase four deformation - Zone A

Structures associated with the fourth phase of deformation are recorded in domains O and N and are best developed in the Upper Pelite member.

Within these two domains second phase axial surfaces and planar fabrics are folded by tight crenulations and small scale folds (Plate I4). Axial surfaces strike northeast-southwest and dip to either the northwest or southeast at an average angle of 50 degrees. Such a strike direction differs significantly from the local strike direction of phase three structures; also the hinges of phase three folds plunge steeply to the southwest.

Tippett (1976) recognized post phase three crenulations and conjugate folds, with a similar orientation to those described above, in the region to the south.

3f. Norman Wood Creek Fault zone

At the southwestern end of the Windy Range, to the north of Norman Wood Creek (Figure 14, map reference 415185/5735387), a northwest - southeast striking,

southwesterly dipping fault juxtaposes Upper Pelite member strata of the Horsethief Creek Group against probable Cambrian Hamill Group rocks. The sense of asymmetry of minor folds changes across the fault zone.

The fault is thought to extend in a northwestward direction for a distance of at least 28.0 kms (M. Perkins, pers. comm, 1978). The extension of the fault in a southerly direction is unclear. Adjacent to the northwestern corner of the pluton this author has observed stratigraphic and structural continuity therefore the fault does not extend for any appreciable distance in a southeasterly direction. The most likely route for a southerly extension of the fault is down the valley of Norman Wood Creek; this would involve the fault undergoing a change in strike direction adjacent to the northwestern corner of the pluton similar to that described for the axial surface trace of the Goldstream nappe.

Using pressure and temperature estimates made on metamorphic mineral assemblages in Horsethief Creek Group rocks that crop out in the Argonaut Mountain area, Leatherbarrow (work in progress) proposes up to 7 km of vertical displacement across the fault, with the western side down.

3g. Summary and Discussion

Regional structural trends in the central part of the Northern Selkirk Mountains are strongly affected by the

presence of the Adamant pluton within a well-defined structural aureole. Folds and planar and linear fabrics all assume an orientation different from the regional in order to accommodate to the space problem produced by the discordant and rheologically rigid pluton.

Axial surfaces, when traced towards and around the body, diverge within specific zones to go around opposite ends of the pluton; each deformation should produce two such zones of divergence about the body. The best documented is that produced by the third phase of deformation adjacent to the southeastern end of the body in the vicinity of Azimuth Mountain. Phase three structures, when traced towards the pluton, diverge within the divergence zone either to the west, e.g. the Sir Sandford syncline, or to the east, e.g. the western limb of the Gold River anticline, which goes around the eastern end of the pluton. Within the central part of the divergence zone the stratigraphy and phase three structures and fabric are flattened against the east-west trending walls of the pluton.

It appears that the third phase of deformation was most intensely developed along the eastern side of the Northern Selkirk Mountains; a similar conclusion was first presented by Brown et al., (1977). Consequently the other deflection zone associated with the third phase of deformation, located at the northwestern end of the pluton and in the western part of the Northern Selkirk Mountains, is not as well

defined. It is interpreted to be centred around the Argonaut Mountain structure (Figures 18, 21), a very tight and steeply plunging fold that is progressively opened and flattened towards the not too distant walls of the pluton. Third phase structures to the northeast of this zone of divergence are traced around the eastern end of the pluton. The relative rarity of third phase folds to the southwest of the zone hinders the recognition of a similar pattern around the western end of the body.

Adjacent to the northwestern end of the body, and situated 0.8 km to the northeast of the phase three deflection zone, is one of the two zones of divergence associated with the second phase of deformation. Second phase folds that lie to the northeast of this zone diverge around the eastern end of the body, those that lie to the southwest diverge around the western end (Figures 13 and 17). The other zone of divergence associated with the second phase of deformation is almost certainly located at the southeastern end of the body near the third phase divergence zone at Azimuth Mountain. Due to the intense development of third phase structures in this particular area however it is thought that form of the second phase zone has been masked.

1.25 km to the northeast of the second phase zone of divergence, adjacent to the northwestern margin of the

pluton, is the zone in which the axial surface of the major phase one fold experiences a pronounced change in orientation. This change is interpreted to occur in the western part of a divergence zone associated with the first phase of deformation. Unfortunately there is insufficient phase one structural data in this particular area to provide an accurate outline of the zone.

The implications of the separate, yet close, locations of the three divergence zones adjacent to the northwestern margin, and of their assumed counterparts adjacent to the southeastern margin, are significant with respect to the interpretation of the behaviour of the body during events of regional compressive stress. If both the direction of regional compressive stress and the orientation of the pluton have remained constant during the successive phases of deformation then it is highly probable that the divergence zones associated with the deformation events would be superimposed. As this is not the case there has either been a change in the direction of the regional compression during the history of the pluton, or the orientation of the body itself has been altered, this being most probably accomplished by rotation during deformation.

Immediately adjacent to the pluton the orientation of the axial surfaces of both second and third phase folds reflects that of the walls of the body, being either vertical or steeply inward-dipping. The strike direction of

such axial surfaces is controlled by their particular location with respect to the adjacent walls. Those axial surfaces that are juxtaposed against the northern margin strike east-west, an exception being in domain E of Zone A where the margin of the pluton is folded. Those that lie adjacent to the eastern and western ends of the body have a general strike direction of north-south. Along the southern margin axial surfaces strike west northwest-east southeast.

Linear fabrics within the structural aureole assume a plunge direction towards the body, the amount of plunge generally increasing towards the usually inward-dipping margin.

The shape of the folds is either tightened or opened depending upon the angular relationship between the strike direction of the axial surface of the fold with the adjacent margin of the body. Where the two have a similar strike direction e.g. second phase folds in domain B of Zone A, the folds are progressively tightened against the walls of the body. However where there is a definite difference in the respective strike directions, e.g. the Sonata syncline in domain P, Zone A, the fold is progressively opened and flattened against the pluton. (It should be pointed out that part of the "unfolding" appears to be due to the third phase of deformation). The plunge direction and amount of plunge are important controls in the degree of flattening: those folds that plunge towards the inward-dipping walls of the

pluton with a similar amount of inclination are the most susceptible.

4. THE INTERNAL STRUCTURE OF THE ADAMANT PLUTON

4a. Introduction

The Adamant pluton has a grossly elliptical outline, the long axis of which is aligned east-west. The pluton is 27 kms in length and may be divided into two parts; a circular shaped eastern part joined to an elongated western part (Figure 23).

Within the eastern part an anhydrous core zone of hypersthene-augite monzonite is successively enclosed by a partially hydrated zone of monzonite with variable amounts of hypersthene, augite, hornblende and biotite; a hydrated zone of hornblende granodiorite with quartz monzonite and a hydrated zone of biotite-hornblende granodiorite with quartz diorite.

Two isolated, elliptical pods of partially hydrated monzonite grade into and are surrounded by hydrated quartz monzonite in the western part of the body (Figure 23).

For a detailed description of the petrology and geochemistry of the Adamant pluton the reader is referred to Fox (1969).

Modal analyses and petrological classification by Fox are presented in Figure 22. Fox noted that the pluton-country rock contact is sharp and straight or gently curving (Plate A). There is neither evidence of a chilled margin nor of any veins or apophyses of plutonic rock that cut the country rock.

The reader is referred to the following figures:-

Figure 12 : D_2 minor structures - Zone A.

13 : D_2 and D_3 fold axial surface traces, with structural cross-sections - Zone A.

23 : Fabric elements within the Adamant pluton.

24 : A stereo-plot of linear structures within Adamant pluton.

25 : Trace of planar fabric within central part of Adamant pluton.

4b. Internal Structure of the Adamant Pluton

The nature of the internal structure of the Adamant pluton has been investigated by Fox (1969) and this author.

Fox reported planar fabrics to be the most prominent structural feature; the degree of foliation varies but is generally best developed in the outer zones of the body (Figure 23). Fox described three main fabric groups:

1. A northwest striking fabric located in that part of the pluton to the west of the hypersthene-augite monzonite core. Fox relates this fabric, which he traced from the outer zone into the outer part of the transition zone (the zone of hornblende-quartz monzonite), to the regional northwest-southeast trend of structures in the country rock. This fabric is defined by hornblende.

2. A hornblende and biotite foliation was described in the peripheral rocks of the eastern part of the pluton. Fox believed this fabric to have been influenced by the walls of

the body as they have a similar orientation.

3. In the hypersthene-augite monzonite zone and transition zone Fox described a plagioclase foliation (Plate J3), that is replaced at the outer boundary of the transition zone by a mafic foliation. The plagioclase fabric is not oriented parallel to any petrological zone boundary but defines a semi-circular shape that bulges to the east.

As well as the three planar fabrics Fox also described two linear fabrics. The first is a "faint" structure defined by hornblende prisms and located in the peripheral zone. The second linear fabric, recorded at three stations only, is defined by trains of hornblende crystals that have grown as mantles around pyroxene grains. The first set are steep or vertical along the walls of the body but plunge from 40 to 60 degrees northwest in the interior of the quartz monzonite and granodiorite zones. The second set plunge at a moderate angle towards the east (Figure 24).

Fox related the two sets of linear structures to the northwest and northeast trending regional fold axes that he reported in the country rock. The formation of hornblende mantles around the trains of pyroxene crystals in the core zone was interpreted by Fox as mimetic after a pre-existing structure in the monzonite body.

The hornblende and biotite foliation that Fox reported only in the eastern part of the pluton was found by this

Figure 24 A stereo-plot of linear structures within the Adamant pluton (from Fox, 1969).

solid circles : lineation in monzonite core

open circles : .. peripheral rock

total number of points = 47

author to occur at various other localities within the peripheral zone of the body. This zone commonly contains a compositional layering formed of thin, (one centimetre or less), alternating mafic and quartzofeldspathic layers (Plate J1, J2). The orientation of the individual minerals within the separate layers is random and unrelated to the orientation of the layers themselves. Away from the perimeter of the body and towards the core zones this fabric decreases in strength. The orientation of this fabric is concordant with that of the margin of the body.

At certain localities, this fabric is deformed by folds that range in shape from open to tight. Hinge thickening is common in the minor folds, the silicic layers being much thinned on the limbs. A biotite foliation is oriented parallel to the axial surfaces of the folds, (Plates J1, J2).

4c. Discussion

The presence of planar fabrics is characteristic of the internal structure of many granitic bodies. A feature common to the outer, early-cooled shells of such granitic bodies is a planar fabric orientated parallel/sub-parallel to the pluton - country rock contact. In the Vrådal granite, Norway, such a planar fabric is composed of microcline megacrysts (Sylvester, 1964). In the Rogart granite, Scotland, hornblende and plagioclase crystals form the concordant fabric (Soper, 1963). Granitic bodies at Ardara,

Ireland (Arkaad, 1956), Flamanville, France (Holder, 1978), Ploumanac'h, France (Barrier, 1977), Birch Creek, California (Nelson and Sylvester, 1971), and numerous examples, as well as Ardara, within the Donegal granite complex, Ireland (Pitcher and Berger, 1972), all contain a planar fabric oriented parallel or sub-parallel to the margin of the body. A further feature common to many of these bodies is that the foliation becomes weaker with increasing distance away from the perimeter and towards the core. In the Enchanted Rock pluton, Texas (Hutchinson, 1960) a strong arcuate mineral foliation in the periphery gives way to a meandering mineral alignment in the core.

However internal fabrics are not restricted solely to the peripheral zones of granitic bodies; Soper (1963) describes a planar fabric within the central area of the Rogart granite. In this instance and also at other localities e.g. Ellicott City granite, Maryland (Cloos, 1933); the Loon Lake (Cloos, 1934) and Chandos lake granites (Saha, 1959), Ontario, a funnel shape is implied by planar fabric orientation.

There is general consensus that penetrative, planar mineral alignments form parallel with the plane containing the intermediate (Y) and long (X) axes of the deformation ellipsoid, that is parallel with the plane of flow (Berger and Pitcher, 1970). In the L-S fabric system (Flinn, 1965) the linear component of the mineral alignment forms parallel

with the direction (X) of maximum flow (Ramsay, 1967).

However, a general similarity between mineral alignment in granitic intrusions, resulting from magma flow under regional or diapiric stress, whether it be uniform or not (Balk, 1937; Maclin, 1947), and metamorphic fabrics complicates their interpretation.

Pitcher and Berger (1972) provide evidence that a strong structural grain can develop in granitic rocks below their liquidus temperature but before they have cooled completely. Whether or not the internal fabric in the peripheral part of a body is everywhere parallel to the margin of the body appears to be of prime importance in deciding which mechanism produced the fabric. The Fannad, Ardara and Thorr plutons of the Donegal complex (Pitcher and Berger, 1972) all contain a fabric that is generally concordant but locally oblique. Pitcher and Berger interpret these fabrics to be the result of forces applied to the bodies when they were in a near-solid state. They invoke a "reciprocal" mechanism for producing such a fabric; the country rocks, heaved aside by a forcefully emplaced pluton, driven by buoyancy differences in the crust (Ramsay, 1967), exert a stress on the pluton once it reaches a tectonic level at which further vertical or lateral movement is not possible. This model depends upon the ability of the country rocks away from the contact aureole to store up strain energy without experiencing more than a minimal

degree of deformation. Other important factors would be the rate of emplacement, the crustal level, the ductility contrast between pluton and country rocks.

Pitcher and Berger are of the opinion that it would be virtually impossible to distinguish between this model and one involving a regional stress system that is unrelated to the ascent of the pluton. It is however difficult to visualize how a regional stress system could produce a planar fabric within a pluton that is everywhere parallel to the contact of the body with adjacent country rocks.

Local discordancies of fabric alignment with the contact raise problems as to whether a fabric is solely related to laminar flow or to a stress system operating when the body is virtually solidified, or to a combination of both.

4d. Summary and Conclusions

A synthesis of the work by Fox (1969) and of this author establishes that there are two fabrics in the outer part of the pluton along with the plagioclase fabric in the inner part of the pluton.

On the basis of petrology and chemistry Fox believed that the core zone represents the original igneous state of the body; the plagioclase fabric can therefore be expected to have a primary igneous origin. The concordant compositional layering fabric in the outer part is composed of hydrous mineral phases which are thought to have

crystallized in a mimetic fashion after an original igneous fabric. An important character of the concordant fabric is the random orientation of the individual minerals in both the mafic and silicic layers. This implies that the mimetic crystallization occurred at a time when little or no stress was being applied to the Adamant pluton and its country rocks. Consequently the mimetic crystallization is unrelated to any tectonic event and probably occurred during a time of kinematic quiescence and thermal activity. As the fabric is deformed by phase two folds, it appears that this deformation post dated the secondary crystallization.

It is proposed that the fabric in the inner part and the fabric in the outer part of the body both formed as a result of laminar, magmatic flow during emplacement. The plagioclase fabric can be traced out of the anhydrous core zone and into the hydrated outer zone where it is composed of mafic minerals. This compositional difference is secondary, brought about by the hydration of the outer part of the pluton. When mineralogical differences are ignored the fabric pattern, in the western part of the hypersthene-augite monzonite zone and transition zone and the area to the immediate west, is concentric (Figure 25). This concentric, planar, fabric pattern in the interior of the pluton probably defines the structural core of the body whilst the concordant, planar, fabric that occurs in the outer part of the pluton defines the structural margin of

the body.

The second planar fabric recognized by the author in the outer part of the pluton is almost certainly related to a post-emplacement stress system. This biotite fabric is oriented parallel to the axial surfaces of folds that deform the concordant, planar fabric discussed above. These folds have axial surfaces that strike northeast-southwest and dip steeply towards the northwest. Hinges plunge towards the west. Phase two folds and fabric in the adjacent country rock can be traced into the perimeter zone of the pluton where they are correlated with the folds that deform the concordant fabric. The phase two age of these folds places a constraint upon the minimum age of the pluton, the folds and associated fabric being younger than the concentric and concordant fabric and also younger than the period of mimetic crystallization.

The structural history of the pluton may be summarized as follows:-

1. Emplacement, during which time a laminar flow fabric was formed. This fabric presumably was established initially in the outer part of the body where it was concordant with, and defined, the margin of, the body. Progressive crystallization towards the interior of the pluton followed; the centrally located, concentric planar fabric defines the structural core of the body and formed the final primary structural feature.

2. Hydration of the outer part of the body accompanied by mimetic recrystallization of the concordant fabric in the outer part of the pluton.

3. Deformation of the outer part of the pluton during the second phase of regional kinematic activity. This produced folds and fabric which are discordant to the margin of the body.

5. METAMORPHIC GEOLOGY AND TEXTURAL RELATIONSHIPS

5a. Metamorphic Geology

Barrovian regional metamorphism, ranging from chlorite to potassic feldspar-sillimanite grades, has affected the rocks of the Northern Selkirk Mountains. A metamorphic culmination, defined by the coexistence of sillimanite and potassic feldspar, is centrally located within the region and mineral zones on either side trend northwest-southeast (Leatherbarrow and Brown, 1978).

Four distinct mineral assemblages are recognized within the study area (Figure 26).

1. Staurolite-garnet-biotite-muscovite-quartz

This zone occurs in the southwestern and south-central part of the study area (Figure 26, Plate M2).

Staurolite is very common and the grains are typically poikiloblastic in habit, inclusions invariably being composed of quartz. Grain outlines are euhedral to subhedral.

Garnets vary in outline from euhedral to anhedral; adjacent to staurolite grains they may have embayed boundaries. The garnet grains are commonly poikiloblastic with quartz, mica and opaques forming the inclusions. Some of the garnet grains are surrounded by rims of retrograde chlorite.

Biotite occurs as either coarse or fine grains, the former usually contain inclusions of quartz and opaque

minerals. Muscovite is fine grained in form.

2a. Kyanite-staurolite-garnet-biotite-muscovite-quartz

This assemblage marks the first appearance of kyanite and is located to the north of zone 1 and to the south of the pluton (Figure 26). It occurs associated with assemblage 2b.

Kyanite varies in outline from anhedral to subhedral, often poikiloblastic with quartz and opaques enclosed; grain outlines are usually embayed.

2b. Kyanite-garnet-biotite

The difference between this assemblage and the previous one is the absence of staurolite and muscovite (Plate K2).

Kyanite tends to be more common than in the previously mentioned assemblage and it has a lath-like form with better defined grain boundaries.

3. Sillimanite-garnet-biotite

This assemblage occurs adjacent to the southern perimeter of the pluton and in the area to the north of it. (Figure 26).

Sillimanite occurs as fibrolitic intergrowths associated with biotite and muscovite. It may form in randomly orientated sheaves or be aligned parallel to S_0 .

Discussion

The mineralogical changes between assemblages detailed within the study area are controlled by two reactions. The first involves the breakdown of staurolite and the

introduction of kyanite. This reaction occurs between assemblage 1 and 2b; assemblage 2a is presumably transitional:

(Leatherbarrow, 1980, unpublished)

The second reaction is the one involving the introduction of sillimanite at the expense of kyanite. Kyanite and sillimanite are seen to coexist at certain localities (Figure 26 and Plate K2).

The assemblage of sillimanite + potassic feldspar, detailed by Leatherbarrow and Brown (1978), that is located to the northwest of the pluton, was not recognized within the study area, perhaps due to rather restricted sampling.

Textural Relationships

The earliest foliation recognized within the country rock (S_1) is that associated with the first phase of deformation. This foliation is variously defined by laths of hornblende, elongated grains of quartz, plates of muscovite, epidote grains and elongated grains of opaque minerals.

S_1 appears to have been strongly transposed by later fabrics and is not as apparent in thin section as it is in the area to the south studied by Tippet (1976). The planar foliation is usually parallel to compositional layering, except in the noses of rare, first phase folds.

A planar fabric associated with the second phase of deformation (S_2) is extensively developed and variously defined by plates of biotite and muscovite, phlogopite, laths of hornblende, elongated grains of quartz, quartzite, calcite and dolomite. This fabric is developed in a variety of rock types ranging from marble and quartzite to mica schist and amphibolite. It is seen as alignment of laths, plates and elongated grains rather than as a crenulation of a pre-existing fabric (Plates J1, J2, K2, L1, L2, M1 and M2).

Some of the garnets, contained within amphibolites bearing second phase planar fabric, have equant, poikiloblastic core zones surrounded by inclusion-free rims which are elongated in a direction parallel to that of the second phase linear fabric, L_2 . These cores are believed to have grown before the onset of the second phase of deformation. The rims grew synkinematically and were either flattened as a result of applied stress, or, more likely, grew by a process of diffusion flow in a preferred orientation. Elongated grain outlines are also observed in the quartzites, grits and conglomerates (Plates E2, E3, G4), the grains and the clasts in the latter two being composed of quartzite. The major and mean axes of the ellipsoidal grains and clasts lie within S_2 , the direction of elongation being parallel to L_2 .

The most prolific period of mineral growth occurred between the waning stages of the second phase and the onset

of the third phase of deformation. Phase two planar fabrics were overgrown by plates of biotite and muscovite, staurolite, kyanite, sillimanite and garnet grains, all of which contain straight inclusion trails composed of elongated grains of quartz (Plates K1, L1, L2, M4). The highest grade of metamorphic minerals grew during this period, culminating in the breakdown of staurolite and muscovite to produce fibrolite. The metamorphic peak is bracketed between the second and third phases of deformation; Franzen (1974), Van der Leeden (1975), Tippet (1976), Ghent et al (1977), Lane (1977), Leatherbarrow and Brown (1978) and Perkins (pers.comm.1979) all reached a similar conclusion in their respective study areas. Kyanite overgrew S_2 and some kyanite laths grew parallel to L_2 (Plate K1). Sillimanite occurs as fibrolite and forms either randomly orientated clusters or has overgrown and assumed a similar orientation to that of L_2 (Plate K2).

Many of the garnets with straight inclusion trails, having overgrown the pre-existing second phase fabric, have inclusion-free rims that show no preferential elongation, indicating further growth after the second phase of deformation but before the third phase.

With the advent of the third phase pre-existing porphyroblasts were rotated, consequently the internal fabrics of these porphyroblasts are not continuous with the

fabric of the groundmass (Plate L2). In rocks where the porphyroblasts are of a similar size, outline and species, the degree of rotation is remarkably similar. Rare garnet and staurolite grains are seen to have overgrown a weakly curved S_2 indicating that growth occurred in the initial stage of the third phase. (Plates L3, M2). Such grains were rotated as the deformation intensified and the surrounding matrix was strongly crenulated. Porphyroblast growth diminished rapidly during the third phase of deformation; only biotite is a persistent phase.

S_2 was strongly crenulated during the third phase and a widely spaced crenulation cleavage was formed in the mica-rich rocks (Plates K3, K4). Where this fabric is well developed it transposes all previous fabrics. Layers rich in mica alternate with those rich in quartz, the mica plates being generally aligned obliquely to the foliation. A rare third phase fabric composed of biotite laths and orientated parallel to the axial surfaces of third phase folds is recognized.

Some biotite growth continued after the third phase of deformation; rare and large plates of biotite are seen to have overgrown a very strongly crenulated S_2 .

5c. Minor Igneous Rocks

The only igneous rock type recognized outside of those associated with the pluton was a mass of amygdaloidal diabase having a circular outline with a diameter of

the body has had a multiple intrusive history. This author agrees with the original interpretation of Fox (1969), that the pluton was formed during a single intrusive event.

Any primary distribution pattern of a major, or trace, element that exhibits a variation in abundance within the body should reflect the primary structure of the body. An example of this is the distribution pattern of TiO (Figure 30) which appears to show a definite relationship to the ~~inferred internal structure of the body~~. The highest values of TiO_2 content are in the perimeter zones; presumably this was the first part of the body to crystallize. Its content decreases progressively until the lowest values are encountered, in the inferred structural core of the body, these rocks presumably being the final ones to crystallize. A distribution pattern such as this is thought to be a primary feature associated with intrusion of the body.

Any comparison between the distribution patterns of TiO_2 and zirconium is seriously hindered by the limited number of zirconium analyses available. Whilst both species increase in abundance away from the central part of the pluton they do so in a distinctly different manner. TiO_2 does not exhibit the pronounced perimeter enrichment shown in zirconium (Table 2 and Figure 27).

From the trace element analyses (Table 2) it appears that the threshold level of zirconium content required to form zircon lies between 51.58 and 91.79 p.p.m.

2

approximately 15 m. The amygdales are predominantly filled with calcite (Plate J4). The rock does not contain any tectonic fabric, nor does it appear to have been deformed, although it is surrounded by meta-sediments that contain a strongly crenulated S_2 . This indicates that the intrusive event was no older than the Middle Jurassic.

6. GEOCHRONOMETRY

6a. Introduction

The Adamant pluton, on the basis of field data, is as old as the second phase of deformation. Comparing field data with the results of finite element analysis indicates that the pluton may be as old, or older, than the first phase of deformation.

It was hoped that a more precise age of emplacement would be given by an isotopic study.

6b. Previous Work

Potassium-argon isotope analyses.

Six Adamant pluton samples were analyzed for potassium-argon at the Geological Survey of Canada laboratory, Ottawa. These samples were collected by Fox; the results were published in Geological Survey of Canada Papers 62-17 and 63-17. A compilation of the results is presented in Table 1; sample locations are shown in Figure 27.

Four of the six analyses were carried out on granodiorite samples, these gave a spread in apparent ages from 281 Ma to 92 Ma. Of these four analyses two were done on biotite grains (analyses 61-21 and 61-23) collected at separate localities but situated at similar distances from the margin of the pluton. These two biotites differ in apparent age by 81 Ma, a fact that Fox (in G.S.C. Report 62-17, 1962) found inexplicable. The remaining two of the

G. S. C. analysis #	61-21	61-22	61-23	61-24	61-24	61-25
Mineral analysed	biotite	biotite	biotite	biotite	k'spar	hornblende
K-Ar age	281 m.y.	131 m.y.	200 m.y.	90 m.y.	92 m.y.	116 m.y.
K content %	8.08	8.19	7.45	8.14	9.8	1.7
$\frac{^{40}\text{Ar}}{^{40}\text{K}}$	.0177	.00792	.0123	.00538	.00550	.00700
Radiogenic Ar %	89	100	48	87	100	61
Host rock type	granodiorite	pegmatite	granodiorite	quartz vein	granodiorite	granodiorite
Fox's sample #	FK-A-1	FK-A-2	FK-A-3	FK-A-4	5FK-7-2	FK-A-3
Fox's map unit	B	B	B	B	B	B
G. S. C. report	62-17	62-17	62-17	62-17	63-17	63-17

Table 1. Potassium-argon isotope analysis results, condensed from G. S. C. Reports 62-17 (Lowdon et al) and 63-17 (Leech et al).

four granodiorite analyses were of potassium feldspar and hornblende crystals (analyses 62-24 and 62-25). They produced apparent ages of 92 Ma and 116 Ma respectively. The hornblende was separated from the sample that yielded biotite (analysis 61-23), which gave a much older apparent age. As hornblende is more retentive with respect to radiogenic argon (Faure, 1977) the older age would be expected from the hornblende and not as in this case from the biotite. Reesor (in Leech et al., 1963) attributes the young apparent ages of the feldspar and hornblende to a late thermal event in the history of the Adamant pluton.

Analyses 61-22 and 61-24 are of biotites from a pegmatite vein and from a quartz vein respectively, both veins occurring within the granodiorite zone. Apparent ages of the vein rocks differ by a minimum of 70 Ma from the host rock, granodiorite, a rather excessive disparity to be attributed solely to a period of crystallization.

Discussion

In the results for analyses 61-22 and 61-24 the radiogenic argon content is given as 100%; for analyses 61-21 and 61-24 the amounts of radiogenic argon are 89% and 87% respectively. These analyses were performed in 1961 and 1962 respectively during a period when the G.S.C. laboratory was experiencing problems in determining correct radiogenic argon levels. This problem is well illustrated by the results from successive studies of the Guichon batholith,

British Columbia.

The initial study of this batholith was done by the G.S.C. (G.S.C. Reports 63-17 and 64-17). Eleven samples were analyzed; the mineral employed in each case was biotite. Results from the first report gave apparent ages ranging from 224 Ma to 245 Ma, the latter report gave apparent ages ranging from 240 Ma to 260 Ma. The arithmetic mean of the two groups is 240 Ma. In each analysis the radiogenic argon level given was 100%.

These results contrast with those presented by White et al., (1967), derived from twenty-four samples analyzed at the University of British Columbia. Their samples gave an arithmetic mean apparent age of 200 Ma with standard error of ± 5 Ma, error limits for each sample being 2%, or 4 Ma, this being the limit of analytical precision in their laboratory. All but one of the samples fell within the 200 Ma ± 5 Ma bracket, the single exception to this being suspect due to its low potassium content. None of the twenty-four samples were listed with radiogenic argon levels of 100%, the highest recorded being 93%, the lowest 27%, and the average 74%.

The above comparison highlights the questionable nature of the Adamant pluton analyses, (Table 1). . . Internal inconsistencies e.g. the difference in age of 81 Ma between biotites in adjacent samples, analyses 61-21 and 61-23, of the same rock type, add further to the doubt.

Rubidium-strontium isotope analyses

Samples collected by Fox were analyzed at the Geological Survey of Canada's laboratory, Ottawa. The variation in the Rb/Sr values was insufficient to derive an isochron.

6c. Present Work

Rubidium-strontium isotopic analyses

During the summer of 1975 six samples were collected by the author along a traverse (Figure 27) that included the four petrographic zones of the pluton. These samples varied by only 0.08 in their Rb/Sr values, indicating that the pluton is grossly homogeneous with respect to Rb/Sr values (Figure 28). Consequently it was not possible to derive an isochron.

Uranium-lead isotope analyses

In view of the inconclusive results obtained from the potassium-argon analyses and the lack of results from both the rubidium-strontium study made by Fox and that done by this author, a uranium-lead study was undertaken. Samples were collected by the author from both the hydrous and anhydrous parts of the pluton.

Three groups of samples were collected and analyzed for zircon content.

U-Pb zircon study

Group A: This group was assembled from samples collected by Fox. Each sample within this group was

collected from a locality in the hydrous outer zones of the pluton (Figure 23).

Group B: The samples in this group were collected by the author in the southern part of the hypersthene-augite monzonite core zone (Figure 27).

Group C: The samples in this group were collected by the author from a single locality in the biotite-hornblende granodiorite zone at the western end of the pluton (Figure 27).

Zircons were abundant in sample groups A and C; sample group B was devoid of zircons.

Analytical technique and results

For a detailed account of the analytical technique and results the reader is referred to Shaw (1980).

An average age of 169 ± 4 Ma (Figure 29a) was derived from nine isotopic ages, determined from three size fractions of sample group C.

The distribution of zircon and zirconium

The distribution of zircon within the Adamant pluton is limited to the hydrated part of the body only (Figure 29).

With respect to the major elements the body is essentially homogeneous, the only differences between core and perimeter being a variation in the SiO_2 and MgO content (Fox, 1969). Petrological differences between core and perimeter may be simply explained by the addition of water

Fig. 29a Uranium lead Concordia plot for Adamant Pluton zircons

and oxygen to the outer zones of the body. The transition from the hydrated outer zone inwards to the anhydrous core is a gradual one. Fox (1969) believed that the pluton crystallized initially as a pyroxene monzonite body, the present petrological variation being secondary.

The hydration of the body probably occurred during its intrusion to present levels. This event precedes the second phase of deformation because the fabric in the outer zone of the body, composed of hydrous mineral phases, has been deformed by second phase folds.

Whilst zircon is absent from the anhydrous core zone of the body, zirconium is present in very small amounts (Figure 27 and Table 2). Samples C17 and C18 yielded 23.12 p.p.m. and 51.58 p.p.m. respectively. Samples C4 and C12, located in the hydrated part of the body, have zirconium contents of 91.79 and 106.10 p.p.m. respectively. These rocks contain zircon, although most zircon bearing rocks have Zr contents of at least 200 p.p.m. This apparent anomaly may be due in part to the low alkali content of the rocks. A high alkali content in the presence of such low Zr values would probably inhibit the formation of zircon (M.Gorton, pers. comm., July, 1980). Towards the outer part of the body the amount of zirconium increases rapidly; samples C5 and C6 contain 199.80 and 377.85 p.p.m. respectively.

Table 2. Trace Element Analyses of Adamant Pluton Samples

Element	Sample					
	C6	C5	C12	C4	C18	C17
Zr	377.85	199.80	106.10	91.79	51.58	23.12
Y	83.9	29.05	16.59	12.17	14.13	13.56

Amounts given in parts per million (p.p.m.)

Analyses carried out at University of Toronto by M. Gorton.

The abundance of zirconium between the anhydrous core zone and the hydrated perimeter zones differs by a factor of 20, an unusually large variation for a single intrusive event. Variations of up to a factor of 5 are considered normal (M. Gorton, pers. comm., July 1980).

Such a large and unusual variation may be explained by the following possibilities:-

1. The body is composed of series of injection phases, i.e. it is a multiple intrusion.
2. There is an unusual primary distribution pattern of zirconium.
3. The distribution of zirconium has been strongly influenced by secondary activity.

Both structurally and chemically (other than with respect to zirconium) there is no evidence to suggest that

the body has had a multiple intrusive history. This author agrees with the original interpretation of Fox (1969), that the pluton was formed during a single intrusive event.

Any primary distribution pattern of a major, or trace, element that exhibits a variation in abundance within the body should reflect the primary structure of the body. An example of this is the distribution pattern of TiO (Figure 30) which appears to show a definite relationship to the ~~inferred internal structure of the body~~. The highest values of TiO_2 content are in the perimeter zones; presumably this was the first part of the body to crystallize. Its content decreases progressively until the lowest values are encountered, in the inferred structural core of the body, these rocks presumably being the final ones to crystallize. A distribution pattern such as this is thought to be a primary feature associated with intrusion of the body.

Any comparison between the distribution patterns of TiO_2 and zirconium is seriously hindered by the limited number of zirconium analyses available. Whilst both species increase in abundance away from the central part of the pluton they do so in a distinctly different manner. TiO_2 does not exhibit the pronounced perimeter enrichment shown in zirconium (Table 2 and Figure 27).

From the trace element analyses (Table 2) it appears that the threshold level of zirconium content required to form zircon lies between 51.58 and 91.79 p.p.m.

Consequently the presence of zircon within the hydrated rocks immediately adjacent to the western edge of the structural core implies that the zirconium content is greater than at localities 2 km to the east, within the anhydrous core zone. Thus the distribution pattern is one of an increase away from the anhydrous core zone and does not appear to relate to the primary structure of the body. In the western part of the pluton there is another anhydrous core area (Figure 29), a sample from which was found to be devoid of zircon. Yet this anhydrous area, as with the larger anhydrous area in the eastern part of the body, is surrounded by hydrous, zircon-bearing rock. It is assumed that the zirconium content of the unaltered, anhydrous rock is at a primary level associated with the initial intrusion of the body. The pronounced enrichment of the outer part of the pluton, especially the perimeter area, with zirconium is interpreted to be due to some secondary activity, the nature of which is puzzling as zirconium is regarded as a very immobile element (M. Gorton, pers. comm., July 1980).

The most probable time for the introduction of the zirconium would have been during the hydration of the body, there being some type of relationship between the hydration and the influx of the element. This would explain why the zirconium is more abundant in the hydrated parts of the body, and why the anhydrous parts of the body contain only the low, primary amounts of zirconium

It appears that zircon will only be produced within rocks that have a zirconium content equal or greater than a certain amount. The primary content level of the body, as evidenced by the hypersthene-augite monzonite, anhydrous core, is insufficient and consequently there is a lack of zircon within this zone. Outside of the anhydrous core area the hydrated zones, with their increased zirconium content, are able to host zircons. The capacity to do this would presumably increase towards the perimeter where the zirconium content is the highest.

Discussion

The origin of zircon and its resistance to regional and contact metamorphic activity has long been debated. The opinions are polarised into two main groups; on the one side are those who believe that the growth of zircon is restricted to environments of magmatic consolidation. Alternatively there are those who believe that zircon growth is not restricted solely to magmatic domains and may also be grown as a result of metamorphic or even authigenic activity.

Poldervaart (1956) and Larsen and Poldervaart (1957) contended that zircons crystallize early in a magmatic consolidation cycle whereas Gottfried et al. (1959), Silver and Deutsch (1963) and Silver (1963b) noted that certain grains of zircon were zoned, indicating progressive growth during magmatic consolidation.

Taubeneck (1957), Mertie (1958), Karlsbeek (1962) and Silver (1963a) all were of the opinion that the character of zircons remained unaltered in sediments and metamorphics, the morphological distinctions surviving selective melting and metasomatism. Any zircon grains found in sedimentary or metamorphic rocks were assumed to be detrital, in spite of the fact that overgrowths on zircons within metamorphic rocks had long been recognized.

Such overgrowths usually alter the outline of the grains from round to euhedral. Taubeneck (1957) reported that zircons within argillaceous rocks that had experienced pyroxene hornfels facies metamorphism had this form of overgrowth. Eckelman and Poldervaart (1957) reported similar findings. Poldervaart (1950) noted that during the ultra-metamorphism of sediments the zircons tend to acquire an almost "magmatic" character, whilst Berthelsen (1950) found that in amphibolite facies metamorphism a new generation of zircons was produced. The basic assumption of these authors however was that the zircons examined were of a detrital origin with respect to their presence in metamorphic rocks.

As Saxena (1968) pointed out, it is easy to recognize overgrowths but difficult to recognize new grains. The fact that material may be added to existing grains was interpreted by him to indicate that it may also be possible to form new grains in a variety of pressure and temperature

conditions.

Saxena (1966) listed 3 genetic types of zircons, along with another 2 types:

1. Crystallized from a magma.
2. Formed authigenically in sediments.
3. Formed under metamorphic conditions.
4. Of authigenic origin, transformed during metamorphism.
5. Zircons of all types completely recrystallized under a high grade of metamorphism.

The authigenic growth of zircons indicates that they may be formed in low temperature and pressure environments; metamorphism would accelerate such a process. From hydrothermal experiments Saxena (1966) concluded that any zircons present in a decayed state during a high grade of metamorphism should be completely recrystallized.

Armstrong (1922) was of a similar opinion to Saxena, and various other authors related zircon growth to authigenic and metamorphic activity. Gillson (1925) reported abundant euhedral zircon as a contact metamorphic mineral in Idaho. Hutton and Turner (1936) described elongated euhedral zircons in the greenschists of eastern Otago, New Zealand. Smithson (1937) and Butterfield (1936) noted authigenic outgrowths on detrital zircons in non-metamorphosed rocks; they believed that the growth was in situ.

The work of Krogh and Davis (1972, 1973, 1974 and 1975)

at the Geophysical laboratory of the Carnegie Institute provided a considerable insight into the behaviour of zircons during metamorphism and the interpretation of U-Pb ages. Krogh and Davis found that during events of minor metamorphism some zircons were almost completely unaffected, the zircon U-Pb systems being extremely resistant to metamorphism and apparently supporting the concept that they can withstand the effects of regional metamorphism. It was also noted that a loss of radiogenic lead may occur in the absence of any metamorphism. Tilton (1960) attributed such a loss to continuous diffusion, whereas Goldich, Hedge and Stern (1970) invoked the effect of uplift and erosion. Episodic activity was thought by some to account for the disparity (e.g. Wetherill, 1956; Silver, 1963a). Krogh and Davis noted that both the continuous diffusion model of Tilton and the episodic loss theory were supported by data from various areas.

To test the effects of regional metamorphism on zircons Krogh and Davis (1972) performed a detailed study on samples from the French River granite and adjacent paragneiss south of Sudbury, Ontario. It was found that the zircons had been strongly affected by a period of metamorphism 1320 to 1025 Ma. ago. The primary effect was a loss of lead, a lesser effect being the production of new zircons. The formation of the new zircons displaced the U-Pb data points towards the time of the event; the smaller the grains the larger the

displacement. Also for a given grain size the degree of displacement is proportional to uranium content, an effect similar to that noted by Silver (1963a).

Krogh and Davis (1973) pointed out, with respect to the formation of overgrowths, that the smaller grains are more susceptible to producing an age similar to that of the event because of their larger surface-to-volume ratio which will result in their having a greater abundance of overgrowth generated during the event. Such grains are clearly composed of material of two ages.

In their conclusions Krogh and Davis (1973, p. 610) make an illuminating statement: "The extent of the metamorphism is indicated by the production of zircons in the mobilizates, the overgrowths on the zircons in the paragneiss,.... Each of these products is able to withstand minor reheating (unlike micas) and the determination of a time of intense metamorphism rather than cooling can be made."

Krogh and Davis (1974) found that the migration of lead and possibly uranium, such activity giving rise to discordant ages, is enhanced during, and perhaps after, the zircon grain has experienced alteration. This alteration is of a specific type and has a botryoidal form, similar in appearance to hydration diffusion fronts in volcanic glass. The mechanism of loss of lead, or gain in uranium, at this time was still a controversial issue, the two main theories

being those of diffusive loss as opposed to episodic loss. The observations of Krogh and Davis have shown that chemical reaction is a major contributing factor to this loss and resulting discordance in U-Pb systems.

The exact nature of the chemical change that occurs during botryoidal alteration was not determined by Krogh and Davis, however a slight decrease in both Si and Zr were observed. This supports an assumption made by B.O. Mysen (personal communication to Krogh and Davis, 1974) that hydration may be the major chemical change. An observation by Gruenfelder et al. (1966) that the H₂O - OH ratio decreases with the amount of lead loss further supports the possibility of hydration. Medenbach and El Goresy (in Krogh and Davis, 1975) found that the sum of the oxides in the botryoidal zones of alteration was low by 5% to 12%.

The apparent age of the Adamant pluton zircons - an interpretation.

Observations:-

1. The emplacement and hydration of the Adamant pluton is known to have occurred before the second phase of deformation.

2. The peak of regional metamorphism occurred after the second but before the third phase of deformation.

3. Sample group C of zircons collected from the outer zone of the Adamant pluton produced a very concordant $^{206}\text{Pb}/^{238}\text{U}$ - $^{207}\text{Pb}/^{235}\text{U}$ plot. This suggests that the zircons have not experienced any hydration, such a reaction being thought to affect the ratios and consequently negate the possibility of producing a concordant plot.

4. There are no overgrowths on any of the grains. The temperature and pressure conditions that are thought to have prevailed during the peak of regional metamorphism would probably have been conducive to the formation of overgrowths on existing zircon grains along with the generation of new grains. Okulitch (pers. comm., June 1980) reports the presence of overgrowths on zircons collected in the Cordillera of southeastern British Columbia. An apparent Devonian age was yielded by the cores of the grains; the formation of the overgrowths is attributed by Okulitch to the same thermal peak that affected the Northern Selkirk Mountains in Middle Jurassic time. The fact that overgrowths are absent from the Adamant pluton zircons suggests that there were no zircon grains before the thermal event.

Interpretation:-

The Adamant pluton zircons are believed to have been formed during the peak of regional metamorphism, consequently the apparent age derived from them determines a time of intense metamorphism, corresponding to the peak of regional metamorphism, and it does not indicate a time of plutonic emplacement.

7. THE BEHAVIOUR OF AN ELLIPTICAL BODY IN A DEFORMING MATRIX

7a. Introduction

In plan view the long axis of the elliptical Adamant pluton trends east-west, while regional trends of fold axial planes and associated fabrics are northwest-southeast.

The following discussion attempts to resolve the question of whether or not this oblique attitude dates from the original emplacement of the pluton or is due to deformation induced rotation after emplacement.

Two methods are used in an attempt to answer this question. In the first, finite element analysis is employed to produce the strain pattern around an elliptical body during uniaxial compression. Two separate orientations of the body are modelled, for each orientation the body has the properties of a fixed, rheologically rigid mass. Each orientation produces a unique strain pattern, these patterns are then compared to strain fabric data collected in the field.

The second method involves physical and mathematical models of non-rooted, elliptical inclusions in a deformable matrix. The parameters pertaining to each model are precisely known and/or controlled. Results derived provide constraints upon the rotation of elliptical bodies in a variety of situations. Also illustrated is the manner in which the strain ellipses in the matrix adapt to the

presence of a rotating, rigid inclusion.

7b. Finite Element Modelling of the Stress Field Around the Adamant Pluton

7bI. Purpose

The purpose of this study is to derive the stress field produced around a rigid body when the material surrounding the body is compressed. Such a model is applicable to that of a pre-tectonic pluton during regional deformation.

For a general background into the finite element method of stress analysis the reader is referred to the following texts:

BOWES, William H., and RUSSELL, Leslie T., Stress analysis by the finite element method for practicing engineers. (Toronto: Lexington Books, 1975).

ZIENKIEWICZ, O.C., The finite element method in engineering science (New York: McGraw-Hill, 1971).

The following are an integral part of this section:-

Figure 9: Divergence zone locations

31: Distribution of elements, Layout 1

32: Key to Nodes, Layout 1

33: Principal stress components, Layout 1

34: Trend of principal stress 2, Layout 1

35: Distribution of elements, Layout 2

36: Key to Nodes, Layout 2

- 37: Principal stress components, Layout 2
- 38: Trend of principal stress 2, Layout 2
- 39: Adamant pluton potential rotation directions.
- 40: Finite element analysis results

7bII. Definition of Terms

- Element - 2 dimensional, triangular shaped body.
The outline is defined by 3 nodes.
- Nodes - point at which 2 converging sides of a triangular element meet. Each element has 3 nodes.
- Centroid - point located in the centre of an element.
- Model - rectangular outline, 2 dimensional shape which contains all of the elements.
- Principal Stress 1 - the larger stress produced within the model when a specific set of nodes are displaced a specific distance in a specific direction.
abbreviated to PS1.
- Principal Stress 2 - the smaller stress produced at the same time as PS1. Principal stress 2 is orientated in the same plane as PS1 but trends at 90 degrees to it. Principal stress 2 is always less than PS1, abbreviated to PS2.

7bIII. Deformation.

The matrix in both models is strained when those nodes that lie on both of the sides of the rectangular model that are parallel to the Y axis are displaced 0.75 units inwards in a direction parallel to the X axis. This displacement and resulting strain occur as one instantaneous action, i.e. there is no incremental accumulation of strain.

The cumulative shortening in the X direction is 0.75 units plus 0.75 units for a total of 1.5 units, a percentage shortening of 10.

Deformation is two dimensional and occurs as plane strain, any displacement in the third dimension being zero.

7b IV. The Models

Models I and 2 are enclosed in rectangles with initial length dimensions of $Y = 10$ units and $X = 15$ units. Within each rectangle a rigid body is located with its central point superimposed upon the centre of the rectangular frame (Figures 31 and 35).

The matrix in each model is divided into a number of triangular elements. Precision of results is improved by the use of three techniques. Firstly, for each model there is an optimum number of elements. This number can be arrived at by either calculation or by trial and error graphics. Secondly, each element should be as equilateral as possible. Results for each individual element are arrived at by an averaging equation based on an equilateral element

shape. Finally, where there is a need for a concentration of results and a relatively greater degree of precision the areal extent of the element is important. The smaller the element the greater the degree of precision. However this latter technique is limited by the capabilities of the computer programme. Within each model the critical area is the zone bordering each rigid body, a concentration of small elements is located therein (Figures 31 and 35).

The rigid body in each model is a straight edged approximation of the outline of the Adamant pluton, modelled at a scale of $0.46\text{cm} = 1\text{ km}$.

In model 1 the long axis of the rigid body is aligned at $046-246$ degrees and is defined by 20 nodes (Figure 28). In the second model the east-west aligned rigid body is defined by 21 nodes (Figure 36).

Nodes that are located around the rigid body, except for those on the perimeter of each model, are free to move an unlimited distance in either the X or Y directions.

7b V. Boundary Conditions

1. Those nodes that lie on the rectangle sides parallel to the Y axis, excluding the nodes at each of the 4 corners, are free to move an unlimited distance in the Y direction but can only move a pre-determined distance in the X direction.

2. Those nodes that lie on the sides of the rectangle parallel to the X axis, excluding the nodes at each of the 4

corners, are free to move an unlimited distance in the X direction but are fixed with respect to movement in the Y direction.

3. Those nodes at each of the four corners can only move a pre-determined distance in the X direction and are fixed with respect to movement in the Y direction.

4. Those nodes that lie on the outline of the Adamant pluton, centrally located within each model, are fixed and cannot move in either the X or Y direction.

7b VI. Assumptions made in the modelling

No major phase of deformation has been recognized in the study area, or elsewhere in the Northern Selkirk Mountains, that postdates the third phase of deformation. It is assumed that the present day orientation of the long axis of the Adamant pluton, with respect to the structural trends in the surrounding metasediments, was also the orientation prevailing in the final stages, if not earlier, of the third deformation phase.

The present day orientation of the long axis of the pluton is east-west. Planar fabrics that were formed during the third phase of deformation strike northwest-southeast. Assuming that there were no components of rotation or shearing such a fabric orientation implies that the principal compressive stress was aligned northeast-southwest.

Model 2 is based on the probable east-west orientation

of the Adamant pluton during the third phase of deformation and the northeast - southwest trend of the principal compressive stress axis.

The planar fabrics produced in the Northern Selkirk Mountains during the second and first phases of deformation also strike northwest-southeast where they are not visibly reorientated by later phases of deformation. If it is again assumed that there were no components of rotation or shearing involved in either of these phases of deformation then the principal compressive stress axis during each of them was orientated northeast-southwest.

Any rotation of the pluton in the horizontal plane during one or all of the three major phases of deformation will have occurred in either a clockwise or counter-clockwise direction. Speculation concerning possible rotation of the pluton is limited by the present day orientation of the body being known and the regional principal stress orientation for all three major deformation phases being assumed.

With these two constraints it is very improbable that the pluton rotated in a counter-clockwise direction. It would have had to pass through, or away from, the plane of maximum elongation, aligned northwest-southeast, in order to arrive at its present day east-west orientation.

The maximum amount of clockwise rotation that the pluton could have accomplished is restricted to an amount

that can be calculated. The direction of maximum shortening, parallel to the principal stress direction, is aligned northeast-southwest. If the pluton were initially aligned in this orientation compression of the body, as opposed to rotation, would have occurred.

The direction of maximum shortening is northeast-southwest, the direction of maximum elongation is northwest-southeast, the two lines being mutually perpendicular to one another (Figure 39). An initial long axis orientation that lies within the northern and southern quadrant formed by the two lines would rotate in a counter-clockwise direction during compression. Such a rotation direction has already been discounted. An initial orientation within the eastern and the western quadrants would place the body in the field of clockwise rotation and enable it to achieve the present day east-west orientation

Model one is based on the latter orientation and a principal stress direction of northeast-southwest. The long axis of the body is aligned within the eastern and western quadrants and has the coordinates 046 - 226 degrees, this allows the maximum possible rotation of 44 degrees in order for the body to be aligned in its present day east-west trend.

7b VII. Approximations Used in the Modelling.

In order to model the stress environment of the Adamant pluton the following approximations were necessary. It is

Rotation direction with respect to initial orientation.

figure 39

realized that these approximations over-simplify the real case and the results derived can only have a qualitative significance.

1. The physical character of the Adamant pluton is approximated to be that of a rigid body; it can neither be deformed nor rotated, any strain applied to it being abruptly terminated at its perimeter.

This approximation contrasts with the field evidence of both folds and a tectonically induced, axial planar, mineral fabric in the outer zones of the body. The presence of such features imply that when the pluton was subjected to the high temperatures and pressures associated with middle amphibolite grade metamorphism, it behaved as a ductile rather than rigid medium in the perimeter zones. Whilst the folds and planar fabric are recognized in the outer zones they are absent from the inner zones. This change from ductile to apparently rigid behaviour is transitional. However the areal extent of the region where folding is recognized is small in comparison to the total area of the pluton.

Both the ductile and rigid zones were presumably affected by the same temperature and pressure conditions during regional metamorphism. Whilst the rocks in the outer zone are hydrous, those in the inner zone are anhydrous. This difference in water content probably influenced the rheological behaviour of the rocks during regional

deformation.

2. The rheological contrast between the Adamant pluton and the surrounding metasediments is simplified in the modelling. The matrix of the rigid body is assigned a uniform rheological character, that of a linear elastic medium. A wide range of rheologies is present in the various rock types that constitute the country rock of the Adamant pluton. Rheologically the country rocks are inhomogeneous and anisotropic. Such a complex geometry cannot be accurately detailed, therefore, assigning the mass a uniform rheological property is no more, or less, inaccurate than attempting to represent only a portion of the inhomogeneities.

It is realized however that the country rocks adjacent to the Adamant pluton will not behave in a linear elastic manner during deformation, a non-linear plastic rheology is more probable.

3. Nodal displacements that are applied to each model produce a total shortening of 10%, this is approximately one fifth of the regional shortening estimated in the Northern Selkirk Mountains as a result of successive phases of deformation.

Strain patterns generated by a shortening of 10% will obviously differ from those generated by a shortening of 50%. However, the general trends will be grossly similar.

Even a percentage shortening as small as 10 generates

very large stresses within the matrix of each model. This is because imposed boundary conditions constrain the matrix within the rectangular frame and prevent it merely bulging around the rigid body during compression. The stresses are large also because the body is considered purely elastic - i.e. there is no stress relaxation.

Stresses in the actual deformation were probably low, in the order of hundreds of bars.

7bVIII. Results.

When the nodes are displaced and internal deformation ensues the presence of a rigid body modifies the internal stress components. This modification is manifested as a zone of influence or structural aureole (Figures 34 and 38). The amount of influence exerted by the rigid body decreases as the distance from it increases.

A structural aureole is generated in each model, within both aureoles there are two zones at which the trend of PS2 diverges to go around opposite ends of the rigid body (Figures 34 and 38). These areas are referred to as zones of divergence.

In both models the mode of deformation and percentage shortening are the same, as are the rheologies of the respective components. Consequently, the trend of PS2 outside of the structural aureoles is similar.

In Model 1 the structural aureole is grossly elliptical in outline with its long axis parallel to that of the rigid

body. The areal ratio between the structural aureole and rigid body is approximately 15.5 : 1 (Figure 34).

In model 2 the bulge at the northeastern corner of the rigid body is apparent in the outline of the structural aureole. The long axis of the aureole is sub-parallel to that of the rigid body, the former being orientated approximately 15 degrees counter-clockwise of the latter (Figure 38). The areal ratio between the structural aureole and rigid body is approximately 13 : 1.

In model 1 the zones of divergence are located at approximately equidistant positions from the perimeter of the rigid body, on either side of it, one to the north and one to the south (Figure 34).

In model 2 the zones of divergence are located adjacent to the northwest and southeast corners of the rigid body (Figure 38).

As the pluton is rotated in a clockwise direction from its northeast - southwest orientation in model 1 to an east-west alignment in model 2 the zones of divergence migrate from their central location to a position adjacent to the ends of the body. Thus a 44 degree rotation of the rigid body induces the zones of divergence to migrate a distance equivalent to 12 kms parallel to the perimeter of the rigid body (Figure 40).

7bVIII. Discussion.

The trends of PS2 around the rigid body produced in

FIG. 40 Finite Element Analysis Results

model 1 do not correspond to the pattern of any planar fabrics mapped in the field. There are two obvious explanations for this disparity. Firstly the Adamant pluton may never have had a northeast-southwest orientation, hence a strain fabric relating to such an orientation would never have been produced. Secondly if the pluton was previously in such an orientation any fabric generated around it at that time may have been completely transposed by the action of later deformation(s).

In model 2 the rigid body has been rotated clockwise 44 degrees, the major axis aligned east-west corresponding to the present day orientation of the Adamant pluton. The trend map of PS2 is very similar to the axial surface trace maps of zones A and B (Figures 13 and 17). Computer derived zones of divergence are located in the same general area as the zones of divergence recorded in the field, or inferred on the basis of field data (Figure 9). The major change in the location of the zones of divergence, with respect to the perimeter of the rigid body, between models 1 and 2 is achieved by rotating the rigid body through an angle of 44 degrees. The zones of divergence recorded in the field, or inferred, whilst having separate positions are in fact quite closely located, thus indicating that the amount of rotation involved is substantially less than 44 degrees.

Using the theoretical results as a control, the total amount of pluton rotation required to change a divergence

zone position from that formed during the final part of the first phase of deformation to that formed during the final part of the third phase is approximately 9 degrees. In order to produce such a change in positions, the pluton has to rotate 5.5 degrees during the second phase and 3.5 degrees during the third phase.

The areal ratio between structural aureole and rigid body in model 2 is 13.0 : 1, the areal ratio between the structural aureole as mapped in the field and the pluton is approximately 13.75 : 1. The areal ratio between aureole and rigid body in model 1 is higher than both of these, 15.5 : 1. This is to be expected as in model 1 the rigid body is aligned more discordantly than in model 2 and in the field situation. The smallest ratio would be achieved when the rigid body, or pluton, was aligned parallel to either PS2 or to the regional structural grain.

The areal ratios listed above are large when compared with deformation aureoles attributed to post tectonic emplacement of igneous bodies. Pitcher (1979) noted that such aureoles usually extend almost as far as the thermal recrystallization aureoles associated with such bodies. The areal ratio between a thermal aureole and the igneous body is usually quite low when compared to the Adamant pluton structural aureole ratio eg.

1. thermal aureole : Tono (Japan) granodiorite,

0.15 : 1

2. thermal aureole : Santa Rosa (Nevada) granodiorite

0.7 : 1

3. thermal aureole : Suian (Korea) granodiorite

0.8 : 1

4. thermal aureole : Granite Peak (Montana) granite

0.5 : 1

(The above ratios are approximations, data derived from Turner, 1968).

The major disparity between the Adamant pluton ratio, both that derived from model 2 and the ratio derived from field data, with those derived from the post tectonic igneous bodies is a further indication of the pre-tectonic origin of the Adamant body.

7bx. Summary and Conclusions

The very strong similarities between the PS2 trend map of layout 2 (Figure 38) and the axial surface trace map of Zones A and B (Figures 13 and 17) indicate the presence of the Adamant pluton prior to the third, second, and possibly the first, phases of deformation.

Comparison of calculations with field data suggests that during the second and third phases of deformation the pluton rotated approximately 9 degrees.

The areal extent of the structural aureole associated with the body is many times larger than deformation aureoles associated with post tectonic bodies. It is however comparable to experimentally produced structural aureoles

which are formed around pre-tectonic inclusions.

7c. Mathematical and Physical Models

7cI. Introduction

The second approach that attempts to resolve the problem involving the discordant trend of the Adamant pluton is a literature review in which the results of published theoretical studies, dealing with the behaviour of an elliptical inclusion in a less viscous matrix, are compared to field observational data. Any comparisons made are solely qualitative as the models assume that the groundmass has the properties of a linear, homogenous, isotropic medium. Such an assumption, discussed in the previous section, limits the extent to which comparisons may be drawn.

The figures pertinent to this section are as follows:-

- Figure 41 : Swerving of A-axes in the matrix around a rigid inclusion.
- 42 : Relationship between schistosity and deformed pebbles.
- 43 : Ranges of orientation for forward and backward rotation of inclusions.
- 44 : Pure shear deformation paths.
- 45 : Total strain in an elliptical cylinder v. applied total strain.
- 46 : Notation for definition of drag.
- 47 : Types of drag patterns of passive

markers around rigid, elongate inclusions.

7cII. Rigid inclusions in a viscous matrix

The motion of a rigid ellipsoid in a viscous matrix has been detailed in various publications - Gay (1968a, 1973), Ghosh and Sengupta (1973), Ghosh and Ramberg (1976).

Gay (1968a) takes a quantitative approach and has developed two formulae which describe the motion of an elliptical particle in a viscous matrix deforming by pure shear. The motion of the particle in the matrix is of primary importance here, the stresses in the matrix are only considered indirectly.

The long axis of the particle is projected onto a plane containing the axis of compression and the axis of maximum extension. The amount of rotation of the long axis is given by:-

$$\ln \cot \phi_f = \ln \cot \phi_i + (a^2 - b^2 / a^2 + b^2) \ln \sqrt{\lambda_1 / \lambda_2} \quad \text{Eqn. 1}$$

where ϕ_i - the initial angle between the projection of the long axis onto the plane mentioned above, and the axis of compression.

ϕ_f - the final angle analogous to ϕ_i

a, b - the long and short axes of the ellipsoid of rotation.

λ_1, λ_2 - the quadratic elongation of the strain in the matrix i.e. $\sqrt{\lambda_1}$, and $\sqrt{\lambda_2}$ are the major and

minor semi-axes of the strain ellipse in the matrix where there is no perturbation from the inclusion.

To apply this equation to the Adamant pluton two basic assumptions are required.

1. The apparent long axis of the pluton is parallel to the maximum dimension of the outline of the pluton and is therefore aligned at 90-270 degrees.

2. The regional compressive stress trends at 45-225 degrees i.e. at ninety degrees to the plane of maximum shortening associated with the youngest phase of deformation which strikes at 135-315 degrees, this is similar to that inferred for the first and second phases of deformation.

ϕ_f is 90 minus 45 degrees, or 270 minus 225 degrees

$$\phi_f = 45 \text{ degrees}$$

$$a = 4$$

$$b = 1$$

$$\sqrt{\lambda_2/\lambda_1} = .48 \text{ (50\% shortening assumed)}$$

substituting these values into equation 1

$$\phi_1 = 28 \text{ degrees}$$

$$\phi_f - \phi_1 = 17 \text{ degrees}$$

Consequently, the formula derived by Gay (1968) predicts that the Adamant pluton would experience a rotation of 17 degrees in a clockwise direction, in the horizontal plane, if the matrix has been shortened by 50%.

Ghosh and Sengupta (1973) constructed laboratory models

to investigate the motion of a rigid ellipsoid in a viscous matrix. The models involved a rigid body composed of modelling clay embedded in a viscous matrix of painters putty. Compression of the model was achieved by moving two plates towards each other.

It was found that away from the inclusion the major axes of strain ellipses were essentially perpendicular to the direction of compression. Close to the inclusion the swerving of the major axes is apparent, this is accentuated with increased deformation and with closer proximity to the inclusion (Figure 41).

The major axis of the inclusion rotates in a direction away from the direction of compression. The closer the alignment of the major axis of the inclusion with the direction of compression then the larger the angle is between the major axes of the strain ellipses and the major axis of the inclusion. With further deformation this latter angle decreases whilst the former increases.

The larger the axial ratio of the inclusion the greater the degree of rotation for the same amount of total compression.

A naturally occurring counterpart to the experiments of Ghosh and Sengupta is the occurrence of pebbles in a schistose matrix. Gay (1973) studied pebble deformation based on the work of various authors (Strand, 1945; Oftedahl, 1948; Brace, 1955; Flinn, 1956; Hossack, 1968;

Figure 41 Swerving of A-axes in the matrix around a rigid inclusion.

A Partial swerving around a rigid elliptical inclusion when deformation is small.

B Swerving when deformation is moderately large.

from Ghosh and Sengupta, 1973.

Gay, 1969) and concluded that the plane containing the major and mean axes of pebbles is roughly parallel to the schistosity in the matrix. However Gay's use of "roughly parallel" covers a range from strictly parallel to concordant with respect to schistosity and pebble axis (Figure 42).

With a small amount of deformation A-axes in matrix strain ellipses will not in general be parallel to the X-axes of elliptical inclusions. This contrasts with the common observation referred to above of rough parallelism between schistosity and pebble elongation. This discrepancy is explained by Gay as being related to the amount of deformation that the matrix has experienced. Where deformed conglomerates within a schistose matrix have been described in the field they have commonly undergone moderately strong to extreme deformation. Progressive deformation diminishes the angle between the A-axes of inclusions and the X-axes of matrix strain ellipses (Ghosh and Sengupta, 1973).

A further aid to reducing the angular discrepancy is the viscosity contrast, the greater it is the larger the angle for the same amount of deformation. Any bowing out of schistosity around pebbles has been shown by experimental and theoretical work to be related to a difference in competency between inclusion and matrix.

Gay cites a number of factors that control the final orientation of the deformed pebbles.

Figure 42 Relationship between schistosity and deformed pebbles.

- A strict parallelism between X-axis and schistosity.
- B Bowing out of schistosity ("concordant relation") around a pebble.
- C Partial swerving of schistosity around a pebble.

fig. 42

1. Degree of deformation..
2. Viscosity contrast between pebble and matrix.
3. Initial orientation of pebble with respect to deforming forces.
4. Axial ratio of pebble.
5. Closeness of spacing of pebbles.

Ghosh and Ramberg (1976) combine a mathematical approach with physical modelling in their comprehensive study of the reorientation of inclusions by a combination of pure shear and simple shear.

Their study highlights the importance of the relationship between the axial ratio of the inclusion and the ratio of the rates of pure shear to simple shear. Also an important factor is the initial orientation of the inclusion.

According to Ghosh and Ramberg (1976) unlimited rotation of an inclusion will occur during progressive deformation if:-

$$R < 1 + \sqrt{1 + 4S_r^2} / 2S_r \quad \text{Eqn.2}$$

R - axial ratio

S_r - ratio of the rates of pure shear to simple shear

The sense of rotation of the simple shear component of the bulk deformation controls the sense of rotation of the inclusion.

When $R > 1 + \sqrt{1 + 4S_r^2} / 2S_r$ (Eqn.3) there is an orientation at which the inclusion will be stable, this will not change

with further deformation. In Figure 43 this orientation is labelled ϕ_1 .

An inclusion with an initial orientation (ϕ_0) between $\phi_0=0$ and ϕ_1 will rotate in a positive sense until it reaches ϕ_1 (Figure 43).

Inclusions initially orientated between $\phi_0=\phi_1$ and $\phi_0=\phi_2$ will rotate backwards (Figure 43), until stabilized at ϕ_1 .

Inclusions initially orientated parallel to ϕ_2 will be stabilized in that orientation, the rate of rotation at ϕ_2 being zero. However, ϕ_1 is the only orientation at which rotating inclusions arrive at a stable position.

When ϕ_0 is slightly more than ϕ_2 the inclusion will undergo forward rotation until stabilized at ϕ_1 .

If ϕ_0 is less than ϕ_2 backward rotation occurs until a position at ϕ_1 is achieved. Consequently ϕ_2 is considered to be a metastable position.

Ghosh and Ramberg (1967) performed a series of experiments in which rigid blocks of differing axial ratios were placed in a viscous matrix, composed of silicone putty ($\mu = 10^5$ poise), which was then deformed by simple shear. Some of their results are summarized below

1. When the long axis of the inclusion is at a high angle to the direction of simple shear, inclusions with higher axial ratios rotate faster.

2. When the long axis of the inclusion is at a low angle to the direction of simple shear, inclusions with

Figure 43 Ranges of orientation for forward and backward rotation of inclusions

from Ghosh and Sengupta, 1976.

lower axial ratios rotate faster.

3. An elongate inclusion has a maximum rate of rotation when it is aligned at right angles to the direction of simple shear and a minimum rate when parallel. An equant inclusion has a constant rate.

7cIII. Viscous ellipsoid, rigid core, in a viscous medium

Initially the presence of a rigid nucleus, within a viscous body, will affect the finite strain ellipses in adjacent, less viscous material. An analysis based on the premise was developed by Tan (1974) to examine strain in oolites and other similar objects that have nucleated on a rigid core.

As the outer part of the Adamant pluton has been deformed, whilst the inner part appears not to have experienced any deformation, such an analysis may be applicable. However the technique developed by Tan is still in a formative stage and cannot be applied to initially elliptical bodies that are not parallel to stress axes.

7cIV. Viscous ellipsoid in a viscous medium

Theoretical analyses were developed by Gay (1968b) for two specific occurrences of a viscous ellipsoid in a viscous medium.

1. Pure shear deformation of a single, elliptical particle with its axes parallel to the strain axes.

Pure shear is the mode of deformation, consequently the shape of the final ellipse indicates the strain in the

particle, if the initial shape is known.

Gay arrives at the following equation to determine the change in particle axial ratio during deformation.

$$\ln(a/b) = \ln(a_i/b_i) + (5/2R+3)\ln\sqrt{\lambda_1/\lambda_2} \quad \text{Eqn. 4}$$

a, b - long and short axes after deformation

a_i, b_i - long and short axes before deformation

R - (viscosity of ellipsoid)/(viscosity of matrix)
ratio.

λ_1, λ_2 - quadratic elongation of strain in matrix

The term $5/2R + 3$ is the viscosity factor controlling the change in particle shape during the deformation. For R values greater than 10 the particle-matrix system has to experience very large strains to achieve a significant increase in particle axial ratio.

2. Pure shear deformation of an elliptical particle with its axes not parallel to the strain axes.

Deformation in this case results in both a change of particle shape and a rotation of the particle itself.

Where $R = 1$, i.e. no difference in competence between the particle and matrix, the change in orientation is purely geometrical, one ellipse being superimposed upon another.

Where R is greater than 1, i.e. the particle has a greater competency than the matrix, a component of rigid body rotation is introduced when the matrix is deformed. Gay solves this more complex numerical problem by summing infinitesimal strains to obtain a finite pure shear.

Equation 4 is rewritten in an exponential form and solved by use of a computer.

There are a few problems with the mathematical procedure used by Gay, consequently the results are in error (Bilby et al., 1975). Gay combines a method of spherical harmonic analysis, developed by Lamb (1932), with a mathematical procedure developed by Taylor (1932) which determines the deformation of small drops of one liquid in another. Both of these procedures are 3-dimensional. To find the corresponding 2-dimensional solution Gay puts $Z = 0$ in the formulae developed by Lamb. To obtain the harmonic functions to insert in the formulae Gay again gives Z a zero value. Bilby et al., (1975) re-calculated certain sections of Gay's analyses and noted that by making $Z = 0$ incorrect numerical coefficients are generated. Furthermore, merely by making $Z = 0$ a 3-dimensional harmonic function does not become a 2-dimensional one.

However the qualitative conclusions arrived at by Bilby et al. (1975) regarding the deformation of an elliptical body by pure strain concur with those of Gay. Results from both researches outline the controlling influence of the viscosity contrast when considering deformation (Figures 44 and 45).

7cV. Viscous inclusions in a less viscous matrix

Ghosh and Ramberg (1976) experimented with some scale models involving elongate, deformable inclusions in a

Figure 44 Pure shear deformation paths for initially 2:1 ellipses aligned at $\phi = 45^\circ$ to the Y' strain axis. Each point on the curves represents an interval of 0.1 in the pure shear natural strain.

from Gay, 1968.

Figure 45 Total strain, S , in an elliptic cylinder versus applied total strain, S_H .

curves labelled with viscosity ratio

from Bilby, Eshelby and Kundu, 1975.

viscous matrix, deformed by a combination of pure shear and simple shear.

The rate of rotation of the inclusions was found to vary with:-

1. the axial ratio of the inclusion
2. the orientation of the inclusion
3. viscosity contrast.

At $\phi < 45$ degrees, long inclusions rotated faster than short inclusions and soft inclusions rotated faster than hard ones.

At $\phi > 45$ degrees, the reverse of the above occurred.

- ϕ - angle between Y coordinate axis and a axis
- y - parallel to direction of compression of pure shear and normal to planes of simple shear.
- a - major axis of elongate inclusion.

7cVI. Drag patterns around rigid, elongate inclusions

During rotation of an inclusion with a matrix containing a planar fabric, there occurs at the surface of the inclusion an apparent dragging of the matrix fabric along the interface of the inclusion.

The following definitions of normal and reverse drag are amended versions of those presented by Ghosh (1975) and refer to Figure 46.

The point A is located at the edge of a circular body, centred at point O, the line AE is an marker line in the groundmass. Without the presence of a rigid, circular

Figure 46 Notation for definition of drag.

Adapted from Ghosh, 1978.

inclusion the line AE, or its extension FE, would change its orientation to FD by simple shear along the X axis. The presence of the inclusion means that the deformed line is in fact only essentially parallel to FD at a sufficient distance from the inclusion. Point A moves to point B assuming rigid body rotation. The angle AOB is the angle of rigid body rotation (ω).

When B coincides with C there has been no drag effect on the marker line, C being the point of intersection of the circle and the line FB.

To define drag the angular distance between points B and C is measured.)

The drag of the marker line is defined as:-

$$D = \omega - (\phi_0 - \phi) \quad = \text{angle BOC in Figure 46}$$

$$\phi_0 - \text{angle XOA}$$

$$\phi - \text{angle XOC}$$

Normal drag occurs when the marker line is dragged in the same direction as the sense of rotation of the rigid inclusion i.e. when ω is greater than $(\phi_0 - \phi)$.

In reverse drag the point B lags behind point C, the marker line having been dragged in a reverse direction to the sense of rigid body rotation of the rigid inclusion i.e. ω is smaller than $(\phi_0 - \phi)$.

Ghosh (1975) and Ghosh and Ramberg (1976), examine a variety of experimental cases in which drag effects are

produced at the perimeter of elliptical inclusions. They categorize the patterns produced into four main groups (Figure 47), these patterns being generated if the deformation is small and if the bulk deformation is in the form of simple shear.

In type A (Figure 47) the direction of shear is parallel to the initial marker line. The amount of drag in the periphery varies in all types, except for the first.

The pattern of drag gives an approximate idea of the nature of the bulk deformation, if that deformation is known to be rotational or irrotational.

The patterns produced vary with the initial orientation of the inclusion; the axial ratio of the inclusion; the ratio of the rate of natural strain in the X direction to the strain rate of simple shear; and the amount of simple shear.

The direction of drag can be opposite to the sense of rigid rotation of the body. Also irrotational bulk deformation may produce an asymmetrical drag pattern whereas simple shear may produce a symmetrical one. Consequently the rotational, or irrotational, character of the bulk deformation is not specified by the drag pattern produced.

7cVII. Discussion

The results of Ghosh and Sengupta (1973) which show the swerving of strain ellipse A-axes around the rigid body (figure 41) are similar to those produced by the finite

Figure 47 Types of drag patterns of passive markers
around rigid, elongate inclusions.

- A symmetrical bowing out of marker lines
- B asymmetrical bowing in of marker lines
- C asymmetrical pattern with same amount of
normal drag everywhere.
- D asymmetrical pattern with both normal and
reverse drag patterns.

from Ghosh and Ramberg, 1976.

fig. 47

element analysis which in turn are similar to data gathered in the field. In the models of Ghosh and Sengupta the rheologically rigid body is free to rotate, each set of A-axis orientations will correspond to a particular orientation of the body. As the body rotates so do the A-axes immediately adjacent to it, trying to accommodate to the constantly changing orientations of the rotating body. Both the finite element analysis and the models of Ghosh and Sengupta, in imitating the strain data gathered from the field, assume a pre-tectonic presence of a rigid body. As the orientation of the A-axes are constantly changing, an "old" orientation being replaced with a "new" one as it were, the patterns produced around the body give no indication of the rotational or irrotational nature of the deformation, unless the "old" patterns are preserved in the matrix with the "new" ones superimposed.

In the field the "new" patterns correspond to the phase three fabric whilst the "old" patterns are those related to the first and second phases of deformation. Adjacent to the northwestern margin of the pluton strain fabric associated with all three phases is preserved. The difference in orientation between the individual fabric patterns is small, indicating that only a minor change in the orientation of the pluton occurred between each deformation event (Figure 9).

The pattern produced during each individual phase of

deformation is presumably related to the final position of the pluton during that particular phase. Thus the amount of rotation that occurred during the second and third phases of deformation can be calculated; using the results from the finite element analysis as a control an amount of 9 degrees is arrived at. However the amount of rotation that occurred during the first phase of deformation is unknown, only the position of the body at the end of that phase is known. The 9 degrees of rotation is therefore a minimum estimation with respect to the total amount of rotation that the body may have experienced.

Whether the deformation mode is simple and/or pure shear or compressive, rotation of a body within a less viscous matrix that hosts a planar fabric would be expected to produce drag effects at the surface of the body as outlined by Ghosh (1975) and Ghosh and Ramberg (1976) (Figure 47).

No such patterns were recognized in the field adjacent to the pluton or anywhere else. The planar fabric in the matrix i.e. the surrounding metasediments, is generally concordant with the outline of the pluton, except in the area of the divergence zones, the geometry of which are outlined in Chapter 3, parts c and d.

The absence of any recognizable form of a drag pattern(s) at the margin of the body may be due to the relatively minor amount of rotation that the pluton appears

to have experienced. The cumulative amount of rotation recognized is only 9 degrees whereas the maximum amount achieved during an individual phase is 5.5 degrees, this having occurred during the second phase of deformation.

An unknown quantity is the amount of rotation that occurred during the first phase of deformation, however, as presumably there were no planar fabrics existing in the country rock prior to the first phase, a drag pattern would not have been produced.

It would appear from the results of the various mathematical and physical models presented that the main controls concerning the behaviour of an ellipsoidal body embedded in a less viscous matrix are the following:-

1. The viscosity contrast.
2. The axial ratio of the ellipsoid.
3. The degree of deformation.
4. The initial orientation of the ellipsoid.

However, before proceeding to compare experimental results with field data it should be pointed out that the mode of deformation in the models is different to that visualized in the field situation. Although the Northern Selkirk Mountains are bounded by fault zones on all sides there is no evidence of any simple shearing motion along the discontinuities. Instead regional compression appears to have been the controlling mode of deformation. The only experimental work to rely solely on compression as its

deformation mechanism is that of Ghosh and Sengupta (1973).

Despite this difference in deformation mode it is the opinion of the author that the only controlling factor affected in a comparison between experimental and field data would be number 3, the degree of deformation. The extent to which it is affected is not apparent. The other three controlling factors will remain as important parameters whatever the deformation mode.

1. The viscosity contrast of the Adamant pluton with its matrix during deformation cannot be accurately determined. However, it is quite probable that the temperature and pressure conditions prevalent during regional dynamothermal metamorphism served to reduce the contrast in viscosities across the margin. Both the outer zones of the pluton and the adjacent metasediments were deformed in a similar manner during the second phase of deformation. At this time the rheological character of the outer zones of the pluton must have approached that of the matrix. However, with an increasing distance from the perimeter and towards the core of the body fold and fabric evidence suggests that there was a gradual transition from a ductile character to a rigid one. It seems most likely that the greatest viscosity contrast occurred not at the margin of the body but at some point within it. Berger and Pitcher (1970) noted that there is often as great, or greater, ductility contrast between limestone and adjacent quartzite

than there is between intruding granite and its country rock.

The peak of regional thermal activity passed prior to the onset of the third phase of deformation, however the outer zone of the pluton was still sufficiently ductile during the third phase to be compressed with the adjacent metasediments. The third phase folds in the outer zone of the body are more open than those developed during the second phase of deformation and they do not penetrate as far into the body as the earlier structures. This suggests that either the body was less ductile during the later phase or that the applied stress was lower.

The effect of the outer zone being ductile, along with the surrounding metasediments, would be to reduce the viscosity contrast across the margin. This would reduce the potential of the body to rotate during the application of either compressive or shear stress. If the greatest viscosity contrast was located within the body itself then it is possible that internal rotation, rather than rotation of the entire body, would be more likely in the event of there being any rotation at all. This prospect is somewhat unlikely though as the change in the viscosity within the body is one of gradual transition and is not seen as a distinct and rapid change across a narrow zone.

2. The axial ratio of the pluton is 4 : 1, with respect to experimental modelling this is a relatively high ratio and as such would be a positive contribution towards

any potential rotation.

3. The percentage shortening in the Northern Selkirk Mountains is in the region of 50%, this degree of deformation would be expected to contribute in a positive way to any potential rotation.

4. The initial orientation of the pluton is constrained by field data, an aspect that is discussed in the finite element analysis section. To briefly reiterate, the pluton can only have rotated in a clockwise direction if it has rotated at all. Furthermore, the amount of rotation that it may have experienced is approximately 44 degrees or less. If in fact it did rotate the full 44 degrees then it would have had an initial orientation of 46 - 246 degrees. If it is assumed that the principal axis of compression was aligned northeast southwest during the regional phases of deformation then both the present day orientation of the body and the possible initial orientation are discordant with respect to the direction of elongation. Such discordant trends would make the body highly susceptible to rotation during regional, compressive deformation.

7cVIII. Summary and Conclusions

Experimental and theoretical results imply that preservation of major angular discordance such as that observed for the Adamant pluton would not be expected.

Field observations clearly demonstrate that the pluton

was emplaced at least prior to the second phase of deformation. Field observations coupled with the results from modelling indicate that the pluton was emplaced prior to the first phase of deformation. A clockwise rotation of 9 degrees during the second and third phases of deformation has been interpreted, this being a minimum value for the total amount of rotation experienced, the amount of rotation accomplished during the first phase being unknown.

A cumulative rotation of 9 degrees during two major, regional events of compressive stress does not initially appear to be of much consequence. This somewhat restricted movement may be explained by the following factors:-

1. It is quite probable that the Adamant pluton is a keeled body, such a structure will be inherently more stable than a body with a flat base, such as those used in the experimental models. The presence of a keel will impart a stabilizing force to the body that will oppose any rotational couple acting upon it.

2. The outline of the Adamant pluton is ellipsoidal only in an approximation. Unlike the experimental bodies it does not possess a smooth outline, rather it has embayments along its perimeter. This lack of a smooth profile may increase the frictional resistance of the body to rotation.

8. MODE OF EMPLACEMENT

8a. Introduction

According to Pitcher (1979) the average areal extent of intermediate, granitic bodies is 150 km ; the Adamant pluton is approximately 120 km . The most common outline of such bodies is circular, there sometimes being a certain degree of elongation parallel to the structural grain of the country rock. The shape of the body is probably an expression of the contrast in ductility between the intrusion and its envelope. As the viscosity of the body increases so does the potential for it to be discordant.

There are two aspects concerning the present-day orientation of the Adamant pluton that constrain any interpretation of the mode of emplacement. The first is the discordant alignment which probably indicates that the body was emplaced as a viscous mass. The relative lack of veining and reaction at the contact further suggest that the outer part of the body at least was a semi-solid crystal mush, a skin of viscous monzonite being visualized.

The second constraint is the orientation of the metasediments around the body. They dip towards and below the body and increase in age away from it. To accommodate such an orientation the form of the pluton has to be that of a body with some lateral extent, similar to that of a sill or laccolith. At a certain tectonic level further vertical movement of the magma must have been halted, to be replaced

by extension of the body in a horizontal/sub-horizontal direction.

Consequently during emplacement the magma must have been sufficiently viscous to account for its discordant trend but sufficiently mobile to be able to flow laterally.

8b. Discussion

It is quite probable that the majority of magmas ascend through the crust at sub-liquidus temperatures and are therefore likely to be crystal-bearing to some degree. This crystal proportion will increase by precipitation until the magma evolves to a crystal mush. As such they may behave as Bingham bodies (Shaw et al., 1968; Shaw, 1965, 1969, 1972; Bottinga and Weill, 1972; Murase and McBirney, 1973) having well defined yield strengths and much higher apparent viscosities. This non-Newtonian character is in accord with the conclusions of Nickel et al. (1967), and others who found that flow layers were not produced in viscous media containing crystal-like particles until high rates of flow were achieved. Such high rates are not considered to be likely in granitic plutons and indicate that the observed fabrics in granitic plutons have been formed outside of the Newtonian flow domain when crystallization was near completion.

A high degree of crystallization does not necessarily mean that the granite is immobilized; various chemical and physical factors that are present may serve to induce and/or

lengthen the period of mobility. Tectonic squeezing (cf. Rast, 1970), which commonly enhances buoyancy as the driving mechanism, is viewed by Pitcher (1975) as the most effective of these factors. Where the intrusion of magma is via a pre-determined lineament, heat will be conserved by successive intrusions, and the country rocks may also act as an insulating medium with the "magmas being fluxed by the water sucked back into the pluton", (Pitcher, 1975). However reaction with the country rocks can also increase the viscosity of the magma quite drastically (cf. Nelson and Sylvester, 1971).

In order to spread laterally, once vertical ascent has ceased, the magma has to exert a force upon the enclosing rocks. This force is a combination of doming the overlying strata upwards, shouldering aside the strata in front of the advancing magma and compressing to a minor degree the material below.

In association with the shouldering aside mechanism of emplacement a deformation fabric is commonly superimposed upon the country rocks eg. the Ardara and Main Donegal granites (Pitcher and Berger, 1972), the Rogart Granite Complex (Soper, 1963), the Vradal granite (Sylvester, 1964).

The strain imposed on the country rocks during the expansion of these bodies is recognized as a set of folds and fabric that increase in intensity towards the body and are not recognized beyond a certain distance from it. Pitcher (1979)

noted that with respect to expanding diapirs in Donegal, "the superimposed deformation aureoles extend almost as far as the thermal recrystallization aureoles indicating that plastic deformation depended upon the pre-heating of the envelope".

All of the above examples presumably occur where the magma, having ascended in a narrow pipe, is halted in the relatively ductile crust and then expands outward by continuous, or a series of, injection(s) of magma into the hot core. The resulting pluton not only has a deformed periphery but also has a deformed envelope. Pitcher (1979) explains the lack of a deformed envelope around some plutonic bodies eg. Ploumonac'h (northern France), as being due to the magma remaining sufficiently mobile to enter the brittle upper crust where it possibly deforms its own periphery but not the rigid envelope.

8c. Inferred Emplacement Mechanisms

An obvious mechanism of emplacement to produce an east-west alignment of the Adamant pluton is to have a linear conduit aligned east-west (due to the chemical homogeneity and inferred internal structure of the body it is assumed that there is only one conduit).

Brown (1980b) shows that the Columbia River fault zone dips to the east below the Northern Selkirk Mountains and he contends that easterly directed movement along it has emplaced strata of the area as an allochthon from an

original location to the west. Consequently, it is to the west that one should look for pre-phase two, east-west trends. East-west trends characterize the Shuswap terrain, these trends probably originated during or before the onset of regional metamorphism. The relative timing of events in the Shuswaps and Selkirks is still not clearly understood.

It is possible therefore that east-west trends were present in the source terrain of the Adamant pluton and that these trends could have controlled the orientation of the pipe. However, the inferred elliptical outline of the conduit does not support this possibility.

The preceding hypothesis presupposes that the elongated outline and present day alignment of the body are primary features. They may however be secondary, the original outline and alignment having been quite different. In order for the body to be elongated and aligned parallel to an east west trend a similarly orientated structural grain, that is presumably related to a north-south compressive stress direction, must be invoked. Nowhere in the Northern Selkirk Mountains has such a structural grain, or evidence of such a stress direction, been recognized. Furthermore whilst the outer zone of the pluton was ductile during at least the second and third phases of deformation, the actual area that appears to have been sufficiently mobile to enable a distinct change in shape to occur was somewhat restricted, and probably insufficient to accommodate anything other than

minor changes in the outline of the body.

The two hypotheses outlined above both assume that the present day shape and position of the body were controlled by either pre- or post- emplacement kinematic stresses. In the following hypothesis a controlling factor is the nature of the sediments into which the body was emplaced. The paleo-slope during Hadrynian times was towards the west; it is assumed that the sediments dipped towards the west and had a strike direction that was closer to north-south than east-west. Such an orientation of planar anisotropies would induce an easterly inclination of the conduit, should it be inclined at all.

A distinctive feature of the outcrop pattern around the Adamant pluton is the manner in which the Middle Marble member is wrapped around the eastern end and along the northern margin of the body. Whilst the second and third phases of deformation undoubtedly have exerted some influence upon this outcrop pattern it is possible that they have merely amplified a feature that was formed during the emplacement of the body.

At certain localities within the outer zone of the body, in close proximity to the margin, inclusions of various shapes and sizes are present. These inclusions are invariably composed of marble and/or quartzite. In the central area of the body, 0.75 km to the west of the western edge of the hypersthene-augite monzonite core zone, Fox

(1969) reported the presence of a large xenolith of marble with quartzite. This author interprets the xenolith to be a roof pendant associated with the emplacement of the body. Inclusions of marble within the outer zone, which only occur where marble of the Middle Marble member is in close proximity, are also interpreted as being derived during the emplacement of the body.

The trace of the Middle Marble member around the eastern end and along the northern margin is not everywhere continuous, also there is a distinct variation in thickness along strike. At the southeastern corner of the pluton the summit areas of Guardsman Peak and Mount Stockmer are underlain by carbonate of the Middle Marble member (Figures 5 and 8), the intervening valley of Palmer Creek however is devoid of carbonate. On both the northern and southern valley sides the competent carbonate can be seen to thin gradually until it has zero thickness in the lower part of the valley.

It is suggested that the Middle Marble member exerted a controlling influence upon the manner in which the Adamant pluton was emplaced, in the form of the body, and in its resulting orientation. The tectonic level at which magmatic ascent ceased was above the stratigraphic level of the Middle Marble member. Where the latter is in contact with the body, or adjacent to it, it can be seen to dip towards and beneath it. It is expected that in passing through the

Middle Marble member the hot magma would have precipitated decarbonation of the carbonate rich strata (cf. Nelson and Sylvester, 1971). Liberated CO_2 would have been introduced into the magma causing isothermal crystallization, a viscous skin of magma being formed over and around the body. The possibility of magma ascending further would be greatly reduced; it would probably spread laterally. Overlying the Middle Marble member is a thick, interbedded succession of quartzite, grit and conglomerate. This competent succession overlying the crystallizing magma may have acted as a further obstacle with respect to vertical magmatic ascent. The position of the conduit through which the magma was emplaced is inferred to be adjacent to the hypersthene-augite monzonite core zone (Chapter 4 and Figure 25). As the magma spread laterally to the east from this aperture it would have been partially rimmed by the Middle Marble member. The spreading magmatic front would have exerted a tensional force upon the carbonate strata resulting in thinning and then rupture of the layers, hence the discontinuous trace across the valley of Palmer Creek.

Lateral spreading to the west and southwest does not appear to have been hindered by the presence of the Middle Marble member carbonate strata, consequently there is a distinct bulge in the southwestern part of the body (Figure 8). Lateral spreading to the northwest was controlled by the carbonate strata, the northwestern margin of the body

being defined by a linear contact adjacent to the trace of the Middle Marble member (Figure 8).

Whilst the perimeter of the pluton has been folded and the alignment of the body has been altered slightly, due to an element of rigid body rotation, it is envisioned that the present-day form and orientation of the body are grossly similar to those at the time of emplacement.

Neither Fox (1969) nor this author recognized any folds or fabric in the country rock adjacent to the Adamant pluton that may be primarily related to the emplacement of the body. Both the periphery and the envelope are deformed but only by the folds that can be definitely related to regional kinematic events. Phase two folds in the country rock become progressively tighter adjacent to the body; rather than this resulting from forceful action by the magma during emplacement of the body it is interpreted to be an accommodation feature related to the presence of a pre-existing rigid body. This aspect is discussed more fully in Chapter 3, section f.

As it is unlikely that the pluton was emplaced by a passive stoping action, the production of a structural aureole associated with the forceful emplacement of the body would be expected. The present day absence of such an aureole may be explained in various ways.

1. The tectonic level to which the pluton was emplaced was sufficiently high that the country rocks were brittle,

as at Ploumonac'h (Pitcher, 1979). Whilst the periphery of the body may, or may not, have been deformed during the emplacement, the country rocks were not.

2. The lateral extent of the spreading during the emplacement of the body may be much less than is envisioned, the conduit having a larger cross-sectional area that has been inferred. Consequently doming of the overlying strata, since eroded, rather than the pushing aside of laterally adjacent strata, would have been the dominant deformation mechanism during emplacement.

3. A fabric associated with the emplacement of the body was generated by a pushing aside action. This fabric has since been transposed and/or recrystallized by later thermal and kinematic activity associated with regional events, in much the same manner that S_0 is interpreted to have been transposed by the action of the second and third phases of regional deformation.

The last explanation is the most appealing to this author.

9. COMPARISON WITH BELCHERTOWN PLUTON

The composition and zoning of the pluton are quite unusual, similar bodies within the Cordillera are rare. The Belchertown pluton in the Appalachians of Massachusetts however is strikingly similar to the Adamant pluton in many respects, a fact first noted by Ashwal et al. (1979) in a comprehensive description of the syn-tectonic Acadian intrusion.

The comparable features between the two bodies include:-

1. Chemistry and mineralogy; with respect to the major elements the body is essentially homogenous.

2. Zoning of the body; the core zone is composed of two pyroxene-monzodiorite which grades outward into pyroxene-free, hornblende-biotite-epidote gneiss. Mineralogical changes were isochemical except for water, and reflect progressive hydration.

3. Internal structure; the core zone contains a foliation composed of plagioclase crystals, the outer zone contains a foliation composed of hydrous mineral phases that is orientated parallel to the contact and to a foliation in the country rock.

4. Ashwal et al. (1979), interpret the pluton to have been emplaced with a brittle core zone that did not undergo plastic deformation during regional metamorphism.

5. Initial crystallization temperature of the magma

was 950 to 900 degrees C.

6. The interpreted (Ashwal et al., 1979) form of the body is that of a semi-concordant sill with a pipe like feeder vent.

There are certain physical and interpreted features presented in the work of Ashwal et al. (1979) that differ from the corresponding aspects of the Adamant pluton and the interpretations of this author.

1. The oxidation ratios $(2\text{Fe}_2\text{O}_3 \times 100) / (2\text{Fe}_2\text{O}_3 + \text{FeO})$ decrease progressively outward in the Adamant pluton whereas in the Belchertown pluton no such regularity has been recognized.

2. In the outer zone of the Belchertown pluton the foliation strikes parallel to a foliation in the adjacent bedded rocks, such a trend being generally parallel to the contact. This foliation is interpreted as a syntectonic fabric related to the late stage of the Acadian orogeny. In the Adamant pluton the fabric in the outer zone that is generally parallel to the contact is interpreted as being related to flow of the body during emplacement whereas the fabric that is parallel to fabric in the adjacent metasediments is interpreted to be related to a post intrusive, regional deformation event.

3. In an earlier paper Ashwal and Hargraves (1977) postulate that the Belchertown pluton has experienced 30 to 60 degrees of rotation towards the northwest about a

horizontal axis that trends northeast southwest. From data presented earlier it is the opinion of this author that the Adamant pluton has experienced only a limited amount of rotation during successive phases of regional deformation.

10. SUMMARY AND CONCLUSIONS

The Adamant pluton is a club-shaped mass aligned east-west. The broader part of the body, at the eastern end, is composed of a series of concentric, petrological zones. Hypersthene-augite monzonite forms the core and is successively enclosed by zones of monzonite with variable amounts of hypersthene, augite, biotite and hornblende; hornblende granodiorite and quartz monzonite; biotite-hornblende granodiorite and quartz diorite. The western part of the body is composed of two pod-shaped, isolated zones of monzonite surrounded by quartz monzonite.

The pluton has been emplaced into the strata of the Horsethief Creek Group, part of the Windermere Supergroup of Hadrynian age. Middle amphibolite facies metamorphism affected these rocks during the Middle Jurassic. Adjacent to the pluton the meta-sediments generally dip towards and below the predominantly inward dipping or vertical margin of the body.

Whilst the body is chemically homogenous with respect to the major elements, the distribution of zirconium is anomalous and shows a strongly pronounced trend of perimeter zone enrichment. Such a distribution pattern is thought to be secondary and related to syn/post emplacement activity that occurred during the hydration of the body.

Zircon is limited to the hydrated parts of the body, the anhydrous core zone and transition zone being devoid of

zircon. The distribution of zircon appears to be controlled by the distribution of zirconium in the presence of a low alkali content. The zircons are thought to have formed during the regional metamorphic peak that occurred in the Middle Jurassic.

The three-dimensional form of the body is interpreted to be similar to that of a sill or laccolith, the conduit being centrally located.

On the basis of data collected in the field the pluton is at least as old as the second phase of deformation.

The highly discordant alignment of the body, with respect to the regional phase two structural trend, suggests that rather than being emplaced synkinematically it was intruded prior to that deformation phase.

Finite element analysis indicates that the pattern of the strain fabric produced by the first, second and third phases of deformation around the pluton is consistent with the pluton being pre-tectonic to each deformation phase. Furthermore the orientation of the zones of divergence about the pluton, when compared to the results derived from finite element analysis, indicate that the body has experienced a limited amount of rigid body rotation. This consists of approximately 5.5 degrees of movement in a clockwise direction during the second phase of deformation and approximately 3.5 degrees of movement, also in a clockwise direction, during the third phase. The behaviour of the

body during the first phase of deformation is unknown.

Mathematical modelling predicts that the pluton should have experienced 17 degrees of rotation in a clockwise direction, giving the body an original long axis alignment in the horizontal plane of 73 - 253 degrees.

The Adamant pluton may be as young as the Middle Jurassic but an older age is equally possible. If the first phase of deformation in the Northern Selkirk Mountains is contemporaneous with the earliest phase of deformation recognized to the south then the pluton was emplaced prior to, or during, the Middle Paleozoic.

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APPENDIX TABLES

Key to Appendix Tables 1 to 5.

The format presented here is similar to that of Tippet (1976).

1. Stratigraphic unit letter.

2. Stratigraphic distance of the base of the unit from the base of the member, except where the base of the member is not exposed, in which case the column is left blank.

3. Thickness of the unit. With respect to thick units the measurements are derived from cross-sections; for the thinner units the measurements are those recorded in the field. In neither case has any correction been made to allow for the effects of structural repetition, tectonic thickening or thinning. Consequently the accuracy of the thicknesses given is sometimes questionable.

4. Stations at which the relevant data was collected.

5. General description of the unit based on field data.

The data in each individual table reads in an ascending stratigraphic order. Refer to Figure 8 for the location of each section.

Appendix Table 1 - Lake Sarah Section
Lower Pelite Member

	1	2	3	4	5
1a	Base not seen	200	316		Silver-grey, migmatitic pelite, rich in kyanite, garnet, biotite. Thin layers of psammite
		2	317		Coarse, graphitic, cream marble with rusty marble zones at upper and lower contacts
		200	318		Silver-grey, migmatitic pelite, rich in kyanite, garnet, biotite. Interbedded with semi-pelite and psammite. Thin amphibolite layers scattered sparsely throughout unit.
1b		275	319		Pelite interbedded with psammite and semi-pelite. Kyanite and garnet less abundant than in underlying pelite. Concordant and discordant amphibolite bands.
		1	315		Feldspathic grit, elongated quartzite pebbles up to 3 cm in length.
		225	313		Semi-pelite with thin pelitic layers.
1c		225	314		Pelitic strata with thin (5 cm to 15 cm thickness), concordant and laterally persistent amphibolite layers.
1d		650	324		Rusty yellow, migmatitic pelite interbedded with semi-pelite and occasional psammitic layers. Semi-pelite very flaggy, gives a dull ring when struck with a hammer.
					Amphibolite occurs in two forms: a: thick, massive, locally discordant lenses.
					b: laterally persistent, thin layers, with garnet common. The massive form may contain small pods of carbonate with green reaction rims composed of diopside and tremolite
					Gap in outcrop.
		350			
1e		150			Interbedded sequence of carbonate rich, dirty, crumbly pelite and rusty marble.
					Sequence becomes more carbonate rich towards top. One 2 cm thick band of garnet amphibolite (projected into section).
2		18	147		Approximately six metres of medium grained, buff grey marble with borders of rusty marble

PLATE M

3

Appendix Table 2 - Mount Stockmer Section (D-C)
Lower Pelite Member, Upper Section

1	2	3	4	5
1d	Base not seen			
		12	280	Rusty marble with thin quartzite layers
			280	Light brown pelite with thin quartzite layers
			280	Thick, massive, discordant locally, amphibolite. Weathers to a shale. Some garnet and carbonate inclusions.
			279	Interbedded sequence of pelite and rusty marble. Some green carbonate bands rich in tremolite.
			278	Rusty yellow, kyanite rich pelite. Thin amphibolite bands
			277	Quartzite, distinctly layered, interbedded with rusty marble containing green, tremolite rich layers.
			258	Rusty pelite, semi-pelite and psammite interbedded. Concordant amphibolite bands, some with abundant garnet.
			257	Psammite with pelitic interbeds. Rusty appearance.
			274	Grey pelite and semi-pelite. Slabby, have characteristic ring when struck with a hammer.
1e		800	268	Tremolite rich, heavily weathered carbonate. Dirty grey-brown, crumbly.
			269	Tremolite rich carbonate, thin interbeds of pelite, semi-pelite, psammite and quartzite.
			269	Rusty marble with layers of kyanite rich pelite.
			270	Interbedded sequence, rusty marble predominant with pelite and quartzite.
		350	270	Grey quartzite
2a		10+	270	Blue-grey, massive coarse grained marble.

Appendix Table 3 - Top of Windy Creek (I-J)
Middle Marble member

I	2	3	4	5
1e?			162	Rusty weathered, interbedded, carbonate rich pelite
2a	0	150	385	Coarse grained, massive, clean, blue-grey marble. Flakes of graphitic and phlogopite.
2b	500	350	385	Rapid transition into a rusty marble with numerous rusty pelite layers, average thickness 5 cm, interbedded.
			161 161/ 153	Medium grained, grey marble Interbedded rusty pelite, grey pelite and semi-pelite. The pelite is locally migmatitic, the semi-pelite is garnet rich. Layers that are very migmatitic resemble grits due to the pod-like form of the quartz feldspar migmatitic lenses. Sub-unit is more quartz rich upwards with interbedded grey semi-pelite and light grey quartzite.
			159	Pelite/semi-pelite with thin, green carbonate rich layers forms a distinctive unit.
2c	530	30	154	Dirty brown semi-pelite
3a		8	154	Clear, blue-grey marble with numerous thin layers of rusty pelite. Marble bands, average thickness 30 cm, are separated by pelite layers, average thickness 3 cm. Rusty pelite with rusty marble.

Appendix Table 4 - Pelisade Massif Section (A-B) Middle Marble member
and Lower Section of Upper Pelite member

1	2	3	4	5
1e	Base not seen	40	001	Interbedded calc rich pelite, marble and calc-silicate layers, psammite
2b	0	200	002	Yellow, buff dolomitic marble
2c	208	8	002	Yellow, calc rich pelite
3a	0	50	009	Grey marble, massively bedded.
3a			010	Rusty pelite, calc rich
3a			012	Well layered quartzite, interbedded with semi-pelite and pelite. Pelite contains kyanite, staurolite, garnet, biotite.
3a	550	500	014	Silver grey kyanite rich pelite
			027	Quartzite dominant, occasional layers of pelite
			028	Interbedded semi-pelite and pelite.
3b	590	40	029	Grey pelite with brown or green carbonate bands. Traces of copper mineralization

Appendix Table 5 - Alpaga Dome and Redan Ridge (K-L) Upper Part of Middle Marble member and Upper Pelite member

1	2	3	4	5
2a	Base not seen	10	60	Calclitic and dolomitic buff marble, pelitic lenses
2b		50	62	Pink quartzite
2c		30	66	Interbedded sequence of rusty marble, calc' rich pelite, rusty semi-pelite, buff dolomitic marble.
3a	0	30	65	Clean, grey, massively bedded calcitic marble.
3a'	65	35	59	Calc' rich crumbly pelite interbedded with slaty pelite and dirty grey, thinly bedded pelite.
3a''	1565	1500	69	Quartzite with thin layers of pelite and semi-pelite interbedded.
			73	Interbedded sequence of quartzite, psammite, pelite and semi-pelite. Pelite contains kyanite, garnet, biotite, + staurolite and fuchsite. Thin layers of biotite and/or hornblende schist are scattered throughout the sub-unit. Towards the top of this sub-unit there are traces of copper mineralization
3b	2060	35	74	Distinctive grey, finely laminated pelite with regularly spaced green and brown carbonate layers, up to 7 cm thickness. Traces of bornite and malachite.
		2	245	Rusty yellow pelite, contains iron stained carbonate nodules, fresh surface is grey and fine grained. Nodules have an ellipsoidal outline, long axis length up to 30 cm.
3c	2025	25	201	Quartzite pebble conglomerate. Large clasts of white quartzite comprise about 60% of this rock, the other clasts are variously composed of medium grained buff marble dark quartzite plus finer grained grit fraction. The matrix, which comprises about 25% of the rock, is a mixture of fine grained quartz, micas, carbonate. Clast range in size up to 0.5 m length, 0.25 m wide and 0.20 m thick.
3d	2375	350	200	The lower contact is sharp, the upper is transitional. Psammite, massively bedded, fine grained groundmass with gritty layers scattered throughout.

Appendix Table 5 - continued

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
3d 2525	150		171		Thick grit unit with psammitic and pelitic lenses. The grits are feldspathic with lensoidal clasts predominantly composed of polycrystalline quartz, up to 5 cm long and 3 cm wide. Within the grits are very fine grained pelitic and graphitic lenses which outline small cross-beds. A transitional contact upwards.
3d 3035	500		169		Interbedded sequence of pelite, semi-pelite, psammite and quartzite. A less quartz rich assembly than underlying 3d member. Psammites contain garnet, eplites host kyanite, staurolite, garnet and biotite.
3e 3175	150		164		Fuchsite rich pelite with abundant staurolite and biotite plus kyanite and garnet. Finely laminated pelites contain two phases of biotite growth - plates and laths. Some migmatitic pods of quartz and feldspar. Sparsely scattered psammite and semi-pelite layers.

PLATE A

1. Looking northwesterly at the pluton-country rock contact along the eastern end of the pluton. (The slopes on the right are those of the western bank of Tabernacle Creek.

M.M.m. and L.P.m. strata dip towards, and under the pluton and are structurally located on the western limb of the phase three Gold River anticline.

2. Looking westerly at the pluton-country rock contact on the western edge of Granite Glacier (map reference 432378/5735354).

M.M.m. and L.P.m. strata are vertically stacked against the margin of the body and structurally lie on upper limb of the phase three Gold River anticline.

3. Looking at the M.M.m. and L.P.m. strata dipping away from the pluton margin between Mount Enterprise (to the left) and Mount Golassal (left of centre).

4. M.M.m. strata vertically stacked against the pluton margin, approximately 3 kms west of Austerity Pass. Viewed looking northwesterly.

PLATE A

PLATE B

1. The Palisade massif with the Palisade Hook structure outlined by Unit 2a of the M.M.m. The structure is viewed from the southeast, the grey marble peak in the lower right is Ravelin Mountain.

On the northeastern limb of the Palisade anticline (P.a.), the hinge zone of which is shown by a solid line, the Sir Sandford anticline is refolded. The dashed line marked S.S.a. indicates the hinge zone of the phase two Sir Sandford anticline.

One of a series of flat-lying phase two minor folds (dotted line) is shown on the crest of the Palisade antiform.

2. A close-up of the Palisade Hook structure viewed from the south.
3. The easterly facing aspect of the Palisade massif (Ravelin Mountain lower slopes are at the lower left).

PLATE B

PLATE B

PLATE C

A panorama view of the east-southeast facing slopes of the Guardsman Peak ridge, total length of ridge shown is approximately 1.0 km. The phase three folds are structurally located on the eastern limb of the Sir Sandford syncline and on the western limb of the Gold River anticline.

PLATE C

PLATE C

PLATE D

1. Looking southeasterly at the Mount Sir Sandford syncline, outlined by the M.M.m. with the U.P.m. in the core.
2. Station 132 viewed from the west. The summit area of Mount Enterprise is composed of the M.M.m. which outlines a type 3 interference pattern.

Trace of S_0 within M.M.m. shown by dotted line.

PLATE D

PLATE D

PLATE E

1. Amphibolitic lenses within Unit 2a of M.M.m. Adjacent to station 223.
2. Boulder of coarse, quartzite pebble conglomerate, Unit 3a' of U.P.m. (lens cap diameter - 54 mm).
3. Quartzite grits, clasts of quartz, quartzite, and carbonate. Unit 3a" of U.P.m.
4. Looking southeast towards core-zone of phase two Mount Sir Sandford anticline. M.M.m. strata folded over L.P.m. strata. Station 008.

PLATE E

PLATE F.

1. Looking southeasterly at a flat lying, first phase fold with second phase folds superimposed upon the upper limb. Strata of L.P.m. Station 293.
2. Second phase minor fold in thinly interbedded marble with calc-rich pelite. Fold shows characteristic necked hinge. Station 337.
3. Second phase fold, outlined by a semi-pelite layer, within migmatitic pelite that is strongly crenulated by phase three deformation. Strata of the U.P.m. Station 386.
4. Third phase crenulations in migmatitic pelite, S_2 strongly folded by D_3 activity. Strata of L.P.m. Station 330.

PLATE F

PLATE G

1. Phase two folds showing characteristic necking in hinge zone; a strongly developed mica planar fabric orientated parallel to the axial surfaces of the phase two folds. Some phase three crenulation visible. U.P.m. strata. Station 115.
2. Close-up of above.
3. Shearing parallel to S_2 seen in more competent layer within interbedded rusty marble, pure marble and dolomitic marble sequence. Sequence at top of the L.P.m., 1m below lower contact of Unit 2a of the M.M.m. Station 063.
4. Phase three fold outlined by carbonate conglomerate horizon within Unit 2b of M.M.m. Elongated carbonate clasts orientated parallel to S_2 and are folded over hinge zone of the phase three fold. Station 354.

PLATE G

PLATE H

1. Second phase folds on the limb of a phase three anticline. Unit 2b of the M.M.m. Station 358.
2. Type 3 interference pattern outlined by a concordant amphibolite layer in the U.P.m. Station 395
3. Unit 2a of the M.M.m. veneering the Mount Sir Sandford massif. Viewed from the northwest, Sir Sandford glacier in the middle ground.

PLATE H

PLATE I

1. Phase two minor folds developed, in thinly layered alternating bands of marble and "dirty" marble, upper part of Unit 2b of the M.M.m. Adjacent to Station 068.
2. Type 3 interference pattern developed in pelites of the U.P.m. Station 047.
3. A strongly developed phase three crenulation lineation at a high angle to S_2 .
4. Phase four crenulation lineation developed in very mica-rich pelite, U.P.m. Adjacent Station 111.

PLATE I

PLATE J

1. Second phase fold, outlined by gneissic layering in biotite-hornblende granodiorite. Two phases of biotite growth, first phase has a large platy form and does not exhibit a preferential orientation. The second phase of growth is smaller, the grains are orientated parallel to the axial surfaces of second phase folds. (Such orientated biotite grains are identified by arrows). Station 133.
2. As above.
3. Aligned feldspar laths in hypersthene-augite, monzonite, (core zone of pluton). Crude planar fabric parallel to striped line. Station 32 (Fox, 1967).
4. Calcite filled amygdale in diabase. Station 435.

PLATE J

PLATE K.

1. Kyanite (some grains identified by arrows) parallel to S_2 ; post- D_2 and pre- D_3 growth. Station 430.
2. Sillimanite (fibrolite), kyanite, garnet, biotite and quartz. Station 288.
3. D_3 crenulation cleavage (S_3 parallel to striped line) produced by deformation of S_2 . Station 194.
4. Hinge zone of D_3 crenulation showing formation of alternating quartz-rich and mica-rich layers (S_3 parallel to striped line). Station 194.

3

PLATE L

1. Garnet, with straight inclusion trails of quartz, overgrew a straight S_2 prior to onset of D_3 . $S_1 = S_e$. Station 424.
2. Garnet, with straight inclusion trails of quartz, overgrew a straight S_2 prior to onset of D_3 . During D_3 the porphyroblast was rotated as the fabric in the matrix was crenulated. $S_1 \neq S_e$. Station 424.
3. Garnet porphyroblast with curved inclusion trails of quartz. Growth occurred during initial part of D_3 , a mildly crenulated S_2 was overgrown by the garnet. After cessation of garnet growth S_2 in the groundmass was strongly crenulated. Station 429.

PLATE L

PLATE .M

1. Biotite orientated parallel to S_2 (striped line) marking a high angle with S_0 , defined by contact between quartz-rich layer and amphibole-rich layer. Station 429.
2. Faintly curved inclusion trail in staurolite grain, S_2 strongly deflected around porphyroblast. Staurolite growth occurred at a very early stage of D3, overgrew a very weakly crenulated S_2 (S_2 parallel to striped line). Station 99.
3. Muscovite, orientated parallel to S_2 , crenulated by F3. Garnet, with straight inclusion trails, overgrew S_2 prior to onset of D3. Station 191.
4. Large porphyroblast of biotite, overgrew a straight S_2 prior to onset of D3. S_2 in groundmass strongly crenulated around porphyroblast. Station 191.

PLATE M

20F

..... approximate boundary of area

----- " " " proje

--- " " " struc

0

km's

Approximate boundary of area mapped
" " project areas
" " structural aureole

km's 30

fig. 3

NORTHERN SELKIRKS — F

KIRKS — PROJECT AREAS, ADAMANT PLUTON & STRUCTURAL AUREO

STRUCTURAL AUREOLE

6056

1 OF

55 Bigmouth Ck.

▲ ARGONAUT MTN.

20F

▲ TRIDENT MTN.

▲ NEPTUNE PK.

Windy Ck

Austerly

118°00'

30F

fig. 5

OVERLOOK
RK.

EDFALLS
MTN.

LAKE SARAH

40f

117°45'

fig. 5

MAJOR PEAKS WITHIN & ADJACENT

Camp location 1975
1976
1977

Columbia

River

Double Eddy Ck.

Swan Ck.

MT
DOUBLETOP

117°45'

50F

HIN & ADJACENT TO STUDY AREA

Camp location 1975
1976
1977

51°50'

51°45'

60x

51°40'

REMILLARD
PEAK

7015

Stitt C. K.

C. K.

MTN.

MT.
SIR GRAHAM

MT.
SIR DAVID

MT.
SIR WI

MT.
SIR A

M
S

AUSTERITY
PASS

REDAN
MTN.

80F

C K.

LAKE SARAH

MT.
DOUBLETOP

MT.
SIR WILLIAM

CYCLE
PEAK

MT.
SIR ANDREW

MT.
SIR HENRY

MT. ENTERPRISE

MT. COLOSSAL

QUADRANT
MTN.

HOUDINI NEEDLES

UNICORN
MTN.

SENTINEL
PEAK

THE IRONMAN

AUSTERITY MTN.

TURRET PK.

PIONEER PK.

ADAMANT MTN.

YGDASIL
MTN.

THE
GARGOYLE

GIBRALTER PK.

BLACKFRIARS PK.

BELVEDERE PEAK

SILVERTIP
MTN.

AZIMUTH
MTN.

REDAN
MTN.

90F

PALISADE

TABERNACLE
MTN.

MT.
STOCKMER

1005

120F

SILVERTIP
MTN.

REDAN
MTN.

REDAN
PASS

PALISADE
MTN.

PALISADE
PASS

ALPINA
DOME

RAVE
MTN.

MINARET CO

VIDET
PEAK

SIR SANDFORD
PASS

CITADEL
MOUNTAIN

MOBERLY
PASS

118°00'

130F

▲ AZIMUTH
MTN.

Palmer

▲ GUARDSMAN
MTN.

▲ RAVELIN
MTN.

▲ MOUNT SIR
SANDFORD

▲ MT. PALMER

MINARET COL

▲ VIDETTE
PEAK

□ CORNICE
PK. ▲

▲ SHAW
PEAK

Gold River

▲ SONATA MTN.

140F

1 of

fig. 6

TOPOG

Contour interval 10

Ice or snow field

NEPTUNE. PK

A fragment of a topographic map is shown at the bottom of the page. It features several contour lines of varying thickness and style (solid and dashed). A label 'NEPTUNE. PK' is printed on the map. The map fragment is partially cut off by the bottom edge of the image.

20F

TOPOGRAPHY AND DRAINAGE - ZONE A.

Interval 1000 feet

W field

30F

N

km.

mi's

3

2

9 of 9

1 OF 1

fig 7. Station Location Map - Zone ALegend

- Station location.
- Pluton contact.
- ||| ||| extrapolated or assumed.

0 1 2
km.

N

1 308 1

Columbia River

4 of 1

50F

Windy Creek

402* 403 399* 400
398* 401
404* 410* 405* 409
411* 408
412* 407
413* 406

395
394
392

396* 393
390* 391
397*

158* 379
378

156* 157 377
154* 155

151* 150 153
381* 380* 383* 382* 376
163* 152 149

385* 162
161* 384*
387 160

60F

Norman Wood Creek

• 363

• 364

372•

371• 368•

369•

• 365

375•

• 367

374• 373•

366

370

Creek

Stitt

Goldstream

River

361•

357•

342•

341•

• 340

343•

352•

• 350

362•

359•

356

355

353•

360•

358

• 354

90F

1 of 1

LOWER F

TOP

1e" Rusty n

1e' Rusty p
& trem

1e' Transiti
pelite, s

1d' Massive

1d' Amphib

1c' Thin cor

1b' Grit ba

1b' Interbed

1a' Marble

1a' Pelite v

BASE NOT

LOWER PELITE MEMBER

TOP

- 1e" Rusty marble
- 1e' Rusty marble/carbonate rich pelite, diopside & tremolite common.
- 1e Transition zone: interbedded marble, rusty marble, pelite, semi-pelite, psammite, quartzite.
- 1d Massive, discordant amphibolite bodies.
- 1d Amphibolite of varying types, with rusty pelite.
- 1c Thin concordant amphibolite bands, with pelite.
- 1b' Grit band.
- 1b Interbedded zone: psammite, semi-pelite, pelite.
- 1a' Marble band
- 1a Pelite with occasional psammite bands.

BASE NOT RECOGNIZED

MIDDLE MARBLE MEMBER

TOP

- 2c Upper main marble band.
- 2b Central zone: carbonate rich pelite predominant.
- 2a Lower main marble band.

BASE _____

LOWER PELITE MEMBER

fig. 8 LITHOLOGICAL MAP — ZONE A.

MEMBER

UPPER PELITE MEMBER

IGNEOUS ROCKS

TOP NOT RECOGNIZED

- 3e Pelitic sequence, metamorphic index minerals common.
- 3d Thick sequence of grits
- 3d Massive quartzite with thin pelite bands.
- 3d Quartz rich sequence: quartzite, grit bands, psammite, pelite.
- 3c Massive, quartz-pebble conglomerate.
- 3b Grey pelite with brown or green carbonate bands. Traces of copper minerals.
- 3a Interbedded sequence of semi-pelite, pelite, psammite, quartzite.
- 3a Thin interbeds of psammite, quartzite, grit.
- 3a Transition zone: carbonate rich pelite, rusty marble.

4 Amygdaloidal basalt

BASE _____

MIDDLE MARBLE MEMBER

4 of 1

2

ROCKS

KEY TO SYMBOLS

al basalt

- Limit of outcrop studied.
- Exposed contact.
- Extrapolated or interpolated contact.
- Sedimentary tops.
- Exposed pluton contact.
- Extrapolated or interpolated pluton contact.
- Line of section.
- Fault.

1505 1

3e

3d

3d

3d

3c

3b

60F

7015

Windy Creek

BASE
MIDDLE MARBLE MEMBER

[illegible]

16

1e

1e

le'

1e

10

[illegible]

Pluton.

2

7c

10

10

1106

Pluton

gap

3a''

3a'

3a

2c

2b

2a

1e

1d

3a''

Norman Wood Creek

3d

2c

Creek

1d

1e

1d

1d

1d

1d

1d

15 OF

B

3d

3b

1c

3a''

3a'

3a

2c

2b

2a

1e

1d

G

3a'

2c

2b

2a

1e

J

3a''

3a'

3a

2c

2b

2a

K

Norman Wood Creek

Goldstream

[160F]

Adamant Pluton

Norman Wood Creek

3a

3a

2

2

Stitt Creek

3b

3b

1

2

2

2

Goldstream

River

170F

B

3d

3b

3a

3a
3a
2c

2b

2a

1c

(base not exposed)

A

1c

1b

1b

1b

1a

1d

1a

(base not exposed)

E

[50m. Thicknesses are uncorrected for structural effects.

200P20

1 OF

✓
STRIKE & DIP OF BEDDING & OF
MINOR FOLD AXIAL PLANES, CLEAV

PLUTON CONTACT.

" " ASSUMED OR
✓

4

fig. 10

ORIENTATION OF S_0 & S_1 - ZONE

D_1
VAGE.

INFERRED.

5

50

12

28

25

50/60

34

50

S₁ - ZONE A

25
28
50
12

34
50

COLUMBIA
RIVER

fig. 10

WINDY CREEK

506

35
60
45
45
40

85
80
59
60
68
54
75
65
70
75
78
80

ADA

CREEK.

AUSTERITY CREEK

ADAMANT PLUTON

60F

85
40

SWAN CREEK

ADAMANT PLUTON

7012

69
75
68

AD

NORMAN WOOD CREEK

55
75
65

STITT CREEK

90F 1

GOLDSTREAM

RIVER

ADAMANT PLUTON

70 52 35 40 20 35 25

28

32 30

40 60

36 25

70 60

46

58

40 70

55 64

1005

18°00

1 of 1

DOMAIN LOCATION MAP - ZONE A

20F

fig. 11

STEREOPLOT OF $D_{0/1} - D_2$

3 OF 1

D₂ & D₃ FABRIC ELEMENTS - ZONE A.

LEGEND

Stereoplot

Pluton co

40f

LEGEND

Stereoplot of $D_{0/1}$, D_2 & D_3 fabric elements:

pole to $S_{0/1}$

" " S_2

" " S_3

plunge F_2 hinge line, L_2

" F_3 " L_3

Pluton contact,

" " assumed or inferred,

150F

D₃ fabric elements:

ole to S_{0/1}

" " S₂

" " S₃

unge F₂ hinge line, L₂

" F₃ " " L₃

or inferred.

N

1

60F 1

7015

ed or inferred.

1005

5145-

1005

5145-

110F

ADAMANT PLUTON

| 120F |

118°00'

ADAMANT PLUTON

130F

1 OF

STRIKE & DIP OF D₂ MINOR FOLD AX
TREND & PLUNGE OF D₂ MINOR FOLD
INTERSECTION LINEATION. S₀/S₂

PLUTON CONTACT.

ASSUMED OR INF

fig 12 D₂ MINOR STRUCTURES — ZON

20F

OLD AXIAL PLANE, CLEAVAGE.

FOLD HINGE LINE, S₀₋₁ S₂

2

R INFERRED.

27

13

—

...

38
38
25
20
40
44
35
35

22

8
8

NE A

1 300 1

0 1 2 3
km.

N

15 10
COLUMBIA RIVER

40f

COLUMBIA
RIVER

WINDY CREEK

1
3
4
5
6

55 60

45 55 50 55

55 58 60 75 60

55 70 55 80 60 80

78 80

70 75 70

78

85

85

50F

ADAMA

ADAMANT PLUTON

160F.1

SWAN CREEK

ADAMANT PLUTON

70°

8

8 65

30
1/3

SWAN CREEK

SMITH CREEK

PLUTON

80F

NORMAN, WOOD CREEK

STITT CREEK

GOLDSTREAM RIVER

ADAMA

90F

18
57
60
70
85

71 80 70 78 88 85

ADAMANT PLUTON

100'

118°00'

100F

118° 00'

NT PLUTON

PALMER CREEK

GOLD RIVER

120F12

120512

[For]

Fig. 13

D₂ & D₃ FOLD AXIAL SURFACES

D₂ on D₃ axial surface trace (defined / approximate / assumed)

D₂ fold structures:

major antiform / synform

intermediate: —||—

minor: —||—

D₃ fold structures:

major antiform / synform

intermediate: —||—

minor: —||—

Lithological contact (defined / assumed)

Fault zone

AL SURFACE TRACES, WITH STRUCTURAL CR

assumed)

————— - - - - -

D₂ fold vergence :

known

assumed

D₃ fold vergence :

known

assumed

Adamant Pluton

" " " " contact (defined/ap

(For a description of the lithology
see figure 8).

————— - - - - -

~~~~~

305

RAL CROSS-SECTIONS - ZONE A.

n
med

n
med

N

N

0 1 2

km.

(defined/approximate)

the lithological units

40f

50F 1

80F

80F

90F

1.30F

160514

1 of 1

STRIKE & DIP OF D_3 MINOR FOLD AXIAL
TREND & PLUNGE OF D_3 MINOR FOLD HIN
INTERSECTION LINEATION
NORMAN WOOD CREEK FAULT ZONE

20F

fig. 14

D₃ MINOR STRUCTURES - ZONE A

D AXIAL PLANE, CLEAVAGE.

OLD HINGE LINE, S₀₋₁ - S₃

3 OF

ZONE A

40f

0 1 2 3
km

N

COLUMBIA RIVER

WANDY CREEK

37
50
35 45
50 60

70 20
70

50F

ADAMAN

ANDY CREEK

AUSTERLY CREEK

ADAMANT PLUTON

60F

ADAMANT

NORMAN WOOD CREEK

50 55 40 60
58 80 55 60

STITT CREEK

90F

GOLDSTREAM RIVER

ADAMANT PLUTON

ADAMANT PLUTON

1 OF 1

fig. 15

BIGMOUTH

M/I

20F

g. 15

STEREOPLOT OF $D_{0/1}$ & D_2 FABRIC ELEMENTS —

BIGMOUTH PLUTON

30F

MENTS — ZONE B

9/I

8/I

9/II

7/I

40f

8/I

7/I

3/I

3/II

41/I

2/I

2/II

McCULLOCH CR

1/II

50F

11/I

11/Π

4/I

4/Π

McCULLOCH CREEK

1/Π

1/I

FRENCH CREEK

605

7/I

9/II

7/II

8/II

6/I

6/II

NORMAN WOOD CREEK

7015

Legend

Stereoplot of $D_{0/1}$ & D_2 fabric
poles to S_0
plunge F_2 h

0 1 2
km

90F

D₂ fabric elements:

poles to S_{0/1} & S₂

plunge F₂ hinge line, L₂

Arabic numerals — Domain

Roman numerals — Phase

N

2

100

numerals — Domain number.

numerals — Phase of deformation.

Bigmouth Pluton

3
4

2

Goldstre

Domains 1 to 4

5 11

0 km

110F

118°15'

Domains 1 to 4 inclusive — Van Der Leeden, 1976.
 " 5 to 11 " — Franzen, 1974.

0 km 5

N

120F12

1 OF

fig 16

BIGMOUTH P

11/11

fig. 16 STEREOPLOT OF D₃ & D₄ FABRIC ELEMENTS

BIGMOUTH PLUTON

10/III

10/IV

11/IV

11/III

LEMENTS — ZONE B

40f

6/III

7/III

3/III

3/IV

2/III

2/IV

1/III

McCULLOCH

505

4/II

4/IV

1/IV

CULLOCH CREEK

1/II

FRENCH CREEK

6/IV

605

9/IV

8/IV

7/IV

6/II

246/II

NORMAN WOOD CREEK

ADAM
PL

47015

7/III

51°45'

7/IV

ADAMANT
PLUTON

NORMAN WOOD CREEK

80F

6/III

Legend

Stereoplot of D_3 & D_4 fabric
poles to S
plunge F_3

90F

5/ II

4 fabric elements:

holes to S₃ & S₄.

hinge F₃ & F₄ hinge line, lineation

Arabic numerals — Domain n

Roman numerals — Phase of

2

100

s — Domain number.

s — Phase of deformation.

Domain 1 to 4 - Inclusion

110F

0 5

118° 15'

Domains 1 to 4 inclusive - Van Der Liden, 1978

0 km 5

120F12

LEGENDAxial surface trace of D₁" " " " D₂" " " " D₂" " " " D₃" " " " D₃

Norman Wood Creek fault zone

Shear zone/fault

BIGMOUTH PLUTON

fig 17 AXIAL SURFACE TRACE MAP — ZONEe of D_1 nappe▪ D_2 antiform with plunge direction▪ D_2 synform " " "▪ D_3 antiform " " "▪ D_3 synform " " "

ek fault zone

.....

3 OF

MAP — ZONE B

0 1 2 3 4
km.

N

WINDY GREEN

4 of

0 1 2 3 4
km

N

WINDY CREEK

AUSTERITY CREEK

506

WINDY CREEK

ADAMANT PLUTON

70°F

CREEK

WINDY CREEK

ADAMANT PLUTON

51°45'

80F

5

McCULLOCH

FRENCH CREEK

GOLDSTREAM

BREWSTER CREEK

RIVER

90F

1106

120F

BREWSTER CREEK

OSTREAM

RIVER

O'REILLY CREEK

130F

DOWNIE CREEK

140F

118°15'

GOLDSTREAM

RIVER

SORCERER CREEK

150F

GOLDSTREAM

RIVER

SORCERER CREEK

160F16

fig 19 Deflection of Regional Trends around Adamant

ction of Regional Trends around Adamant Pluton

~ Fault zone

N Nepheline syenite gneiss

B Bigmouth granitic pluton

4 Hamill Group

HORSETHIEF CREEK GROUP

3 Upper Pelitic member

2 Middle Marble member

1 Lower Pelitic member

- 3 U
- 2 M
- 1 L

118°00

- 3 Upper Pelitič member
2 Middle Marble member
1 Lower Pelitic member

Progressive tightening of Argonaut Mtn. structure

Argonaut Mtn.

Z

0

1

2

gonaut Mtn. structure away from Adamant Pluton.

fig. 21

30F

Adamant
Pluton

4 of 4

after Franzen 1974

Legend

Foliation (inclined, vertical)

Lineation

Geological contact (defined, approximate, assumed)

Adamant Pluton:

Hypersthene-augite monzonite

Monzonite, transitional between 1 and 2.

Hornblende granodiorite, quartz monzonite.

Biotite-hornblende granodiorite, quartz diorite

WINDY

20F

fig. 23 FABRIC ELE

0 1 2
km.

- 1
- 2
- 3
- 4

WIND

BRIC ELEMENTS WITHIN THE ADAMANT PLUTON

(from Fox, 1965)

40f

SWAN CREEK

50F

SWAN CREEK

SMITH CREEK

51°45'

NORMAN WOOD CREEK

60F

3

2

80 80 65 55

75 75

60 60 60 60 60 60

60 60 60 60

75

75

75

60

60

60 60

60

WINDY CREEK

STITT CREEK

70F

AUSTERITY CREEK

90F

51°45'

3

4

PALMER CREEK

1000

1

2

NORMAN WOOD CREEK

3

00-00-55-55

1-2

2

00-1

00-1

110F

118°00'

130F

LEGEND

Planar structure
Linear

DETAILED MAP OF FABRIC WITH

140F

LEGEND

Planar structure
 Linear

DETAILED MAP OF FABRIC WITHIN EASTERN CORE ZONE

150P15

1 of

Met

- staurolite garnet biotite mus
- ▲ kyanite staurolite garnet b
- kyanite garnet biotite
- △ sillimanite kyanite garnet
- sillimanite garnet biotite

--- isograd (defined by first appearance or disappearance of a mineral)

Metamorphic assemblages adjacent to the.

biotite muscovite quartz

garnet biotite

otite

garnet biotite

biotite

first appearance or
presence of a given mineral)

t to the Adamant pluton

30F

0 km 4

COLUMBIA

mant. pluton

4 of

fig. 26

50F

WINDY

51°45'

CREEK

AUSTERITY

CREEK

• Mt. Sir Willi

160F 1

COLUMBIA

RIVER

SWAN
CREEK

• Mt. Sir William

7015

COLUMBIA
RIVER

SWAN
CREEK

SMITH
CREEK

80F

51°45'

51°45'

CREEK

WOOD

NORMAN

• Remillard, Pk.

△

CREEK

STITT

906

Pk.

E.K.

1000
4.6

Goldstream Mtn

◦ Adamant Mtn.

PALME

◦ Mt. Sir Sandford

110F

SMITH

CREEK

51°45'

◦ Adamant Mtn.

◦ Mt. Stockmer

PALMER

CREEK

120F

◦ Mt. Sir Sandford

NORMAN

WOOD

◦ Remillard Pk.

△

GOLDSTREAM

RIVER

STITT

CREEK

130F

PK.

• Goldstream Mtn.

140F

118°00

◦ Adamant Mtn

PALMER

◦ Mt. Sir Sandford

150F

GOLD RIVER

◦ Adamant Mtn.

◦ Mt. Stockmer

PALMER

CREEK

◦ Mt. Sir Sandford

GOLD

RIVER

160516

FIG. 29

DISTRIBUTION OF ZIRCON WITH

- Sample location (Fox) containing zircon
- + " " (Shaw) " "
- " " (Fox) devoid of zircon
- " " (Shaw) " " "

- 1 Hypersthene-augite monz
- 2 Monzonite, with variable a
- 3 Hornblende granodiorite, c
- 4 Biotite hornblende granod

20F 2

CON. WITHIN ADAMANT PLUTON

ne-augite monzonite

, with variable amounts of hypersthene, augite, biotite, hornblende

le granodiorite, quartz monzonite

rnblende granodiorite, quartz diorite

MILES

KILOMETRES

FIG. 30 DISTRIBUTION OF TiO_2 WITHIN

2052

WITHIN ADAMANT PLUTON

fig. 31

Dist

Distribution of Elements, Layout 1

130F

Layout 1

Y

50F

m. 10

6056

1 of 1

fig 32

Ke

32 Key to Nodes, Layout 1

2

3

●7

●8

●9

●10

●16

●18

●20

22●

●17

●19

●21

●23

●24

25●

●31

●32

●33

●34

●35

●36

●37

●38

●39

40●

47●

●48

●49

●50

52●

51●

53●

●54

55●

45●

46●

60●

69●

71●

73●

75●

79●

77●

61●

80●

●62

●63

●68

70●

72●

74●

76●

78●

●81

87●

89●

●85

●86

●88

●90

●91

92●

●96

●97

●98

1 30F 1

4 of 1

60F6

1 of

fig. 33

Principal

?

2

20F

Principal Stress Components, Layout 1

1305

Layout 1

long bar - Principal Stress 2
short " - " " 1

40f

Principal Stress 2

0 km 10

" " 1

505

6056

1 of 1

fig. 34

Trend

Trend of Principal Stress 2, Layout 1

Layout 1

30F

point of divergence

approximate boundary of structure

40f

ence

0 km. 10

boundary of structural aureole

50F

60F6

1 of 1

fig. 35

DISTRIB

20F

DISTRIBUTION OF ELEMENTS, LAYOUT 2

130F

2

4 of 1

0 km. 10

1505

0 km. 10

6056

1 OF

fig. 36

20F

fig. 36 KEY TO NODES, LAYOUT 2

304

35

61

62

46

63

86

75

79

85

H7

88

H9

2

5

1

11

15

20

15

6

10

8

25

26

9

7

31

30

27

28

29

40P

1505

46

58

63

86

57

75

79

85

87

67

70

83

88

89

84

90

60F6

20F

Principal Stress Components, Layout 2

130F

s, Layout 2

long bar - Principal s
short bar - "

40f

- Principal stress 2
- " " 1

0 km. 10

50F

km. 10

60F6

1 of

fig. 38

Trend

Trend of Principal Stress 2, Layout 2

305

Layout 2

Divergence point

Approximate boundary of struc

6 6

OF / DE

0 km 10

of structural aureole

1504

km

10

60F6

END

0	3	0	9	8	2

FIN