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GEOLOGY OF VASEAUX LAKE AREA

by

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ABSTRACT

A local structural lithologic succession comprised of 5 map-units totalling more than 4,000 feet in present thickness has been established in the Vaseaux Formation (Bostock, 1940). Units 1-5 are comprised of high grade metamorphic rocks derived from possible greywacke suite sediments and volcanics that have undergone a complex 5-phase history of deformation, metamorphism and igneous intrusion.

Phases 1, 2 and 3 each gave rise to large scale recumbent fold sets along respective northerly, northwesterly and westerly trends. Each in turn brought about tightening and re-folding of earlier formed structures.

Associated metamorphism reached upper greenschist facies during phase 1 and culminated in middle amphibolite facies at the time of emplacement of a synkinematic, granitic pluton during phase 2. Metamorphism again reached at least lower amphibolite facies during phase 3, possibly at a time of re-activation of earlier formed phase 3 structures during the Upper Jurassic.

Phases 1, 2 and 3 are all of pre-late Mississippian age but their exact ages are not known. They are believed to be all related in time to the lower Mississippian Caribooan Orogeny.

Phases 4 and 5 of deformation gave rise to respective northerly and northwesterly open, flexural-slip folds. Phase 4 is associated in time with early Tertiary volcanism and hydrothermal alteration and has been K/Ar dated at 44 m.y.B.P. (Ross and Barnes 1972).

Phase 5 folding, pre-Miocene in age is associated with extensive fracturing and faulting in the district.

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CHAPTER ONE

GENERAL INTRODUCTION

PURPOSE AND SCOPE

This study was undertaken to determine the geometry, style, and relative time of development of successive phases of polyphase deformation within a small but well exposed segment of the Shuswap metamorphic complex. To this end, detailed mapping was necessary to establish local stratigraphy and structure, and to interrelate structural evolution, granitic intrusion, and metamorphic events.

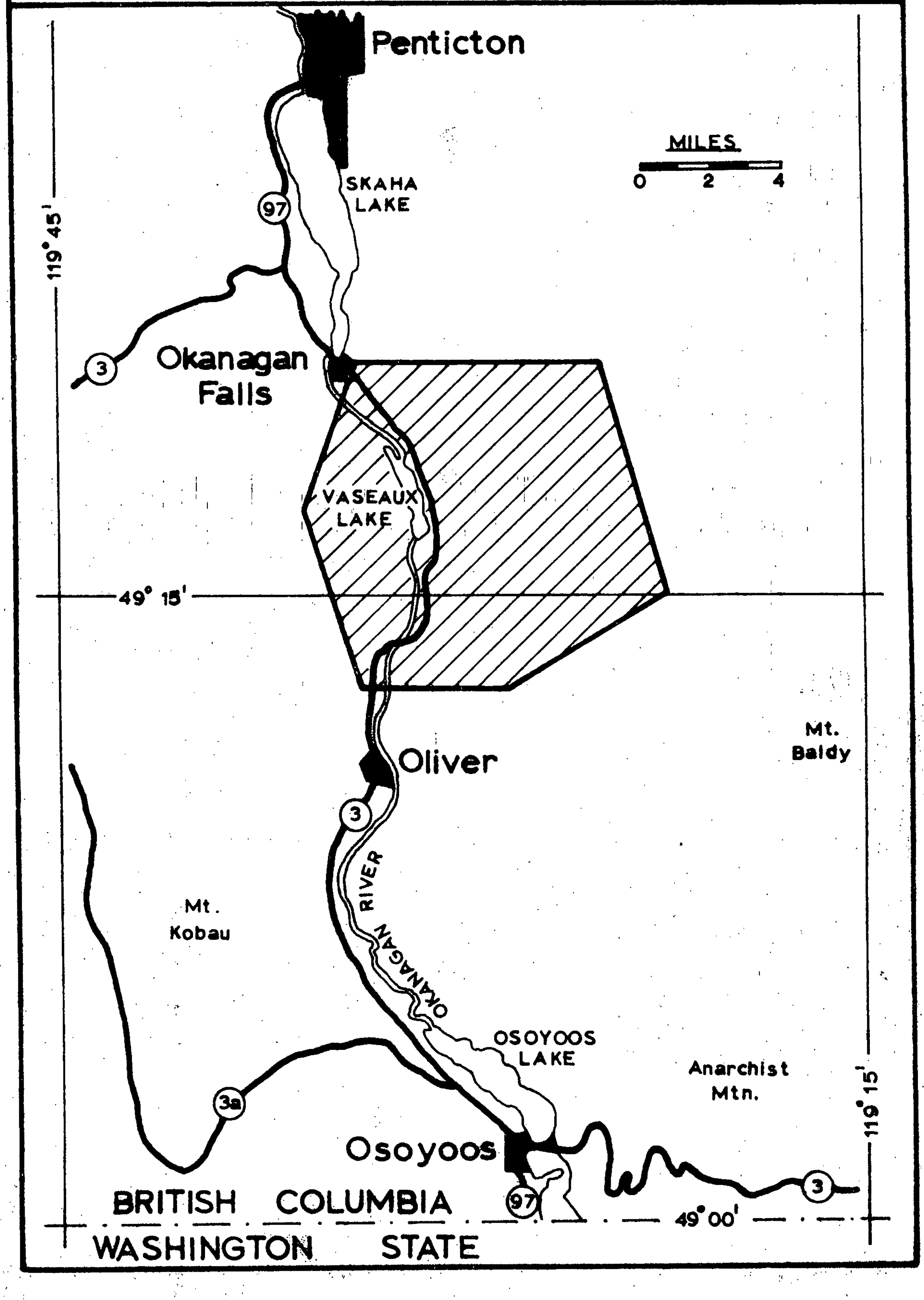
In addition, it was anticipated that this study might allow some statement about the age of the Shuswap complex by means of structural comparison with nearby lithologies of known age.

LOCATION AND ACCESS

Vaseaux Lake map-area is roughly centered on the Okanagan Valley of south-central British Columbia, some 20 miles north of the forty-ninth parallel. It includes about 60 square miles east of the Okanagan River between latitudes 49° 12' and 49° 21' north mapped by the author, and an adjacent area west of the Okanagan mapped by J.V. Ross in 1968.

Easy access is provided by Highway 97 in the Okanagan Valley, and secondary road systems which leave the highway east of Okanagan Falls and east of Vaseaux Lake. These secondary roads were developed initially to service independent logging operations, but at present are not much used for logging.

Figure 1.1: Location of Map-Area



The main roads are in good repair and well travelled by the general public, but many of the branch roads have fallen into disuse, although most are still passable by vehicles with reasonable clearance.

Access to southeastern parts of the area is more difficult from the Wolfcub Creek road system which originates east of Oliver on Indian Reserve No. 1.

All of the above mentioned roads are shown on accompanying maps.

FIELD WORK

Mapping was carried through the 1967 and 1968 seasons with a total of 9 months being devoted to field work. During this period most bedrock exposures were visited and mapped in detail on aerial photographs with approximate scale of 4" = 1 mile. Geologic information thus recorded was later transferred to advance 1:50,000 topographic sheets which had been enlarged to the scale of 4" = 1 mile. This transfer was accomplished with a Saltzman projector using a "best-fit" technique and dependent on topographic features and barometric elevations recorded in the field.

NATURE OF THE MAP AREA

Vaseaux Lake map-area is part of the steep and rocky western flank of the Okanagan Highland (Holland 1964), formed through deep dissection of a highstanding Tertiary erosion surface by the Okanagan River (local base-level about 1,100 feet) and tributaries. At elevations above 4,500 feet gently sloping remnants of this erosion surface, variably mantled by glacial drift, stand out in contrast to the steep valley slopes.

Polished and striated bedrock exposures are found at all elevations, and further evidence of glaciation is abundant. Kettled outwash and glacial lake deposits in the Okanagan Valley are striking examples. Nasmith (1962), has studied and described the late glacial history and surficial deposits of the region.

Vegetation is highly variable within the area. Except near watercourses, the floor of the Okanagan Valley and the lower slopes are extremely arid, supporting little but sagebrush, bunch-grass, cactus and scattered ponderosa pine. At higher elevations, and on north facing slopes fir and hemlock become dominant and form dense forests. South facing slopes may have large open grass-covered tracts, or open forests of ponderosa pine, fir and hemlock.

Forest fires have laid to waste large areas in the uplands which are presently covered by an almost impenetrable second-growth of jack-pine and spruce.

PREVIOUS WORK

Highgrade metamorphic rocks loosely referred to the Shuswap terrane because of their highly crystalline nature or indeterminable age have been mapped through south-central British Columbia and north-central Washington State over an area of some 3000 square miles. Whether the Shuswap as such contains rocks of a single age, or includes rocks of many different ages is highly conjectural, but the latter seems probable.

Early geologists hypothesised that parts of the Shuswap terrane represented a westerly extension of the Precambrian Shield, and that other parts included overlying Proterozoic and possibly Lower Paleozoic strata. Alternate suggestions have resulted from subsequent studies, but this original hypothesis remains to be proven or discredited.

Difficulties arise in most aspects of Shuswap geology. Fossils have seldom been found, and could hardly be expected even if present originally, because of the extreme deformation and metamorphism in these rocks. Contacts with dated rocks are controversial or unknown for a variety of reasons, and thus far radiometric ages determined by the K/Ar method have given only ages of metamorphism and igneous intrusion.

Many Shuswap problems arise from the fact that most of the terrane has been mapped in reconnaissance only, and details of lithology and structure are poorly known. Thus lithologic comparisons and correlations is extremely tenuous even though some similarities have been noted between parts of the Shuswap and Proterozoic and Lower Paleozoic sequences further east. Such correlation is beyond the scope of this thesis but it is necessary to review previous work from other parts of the Shuswap terrane to see the background and development of geologic problems pertinent to this study.

G.M. Dawson (1877), while conducting reconnaissance surveys in the southern interior of British Columbia, described schists and gneissic rocks in the vicinity of Shuswap Lake which he later named the Shuswap Series. In 1898 the Shuswap Sheet, with geology and explanatory notes by Dawson was published, and the Shuswap Series was from then on referred to the Archaean on the basis of lithologic similarity with the Precambrian Grenville Series of eastern Canada. Dawson placed the sedimentary Nisconolith and volcanic Adams Lake Series of supposed Cambrian Age above the Shuswap.

R.A. Daly (1912) conducted a geological survey of the North American Cordillera along the 49th parallel. South of Vaseaux Lake area, Daly mapped meta-sedimentary and volcanic rocks of probable Paleozoic age which he named the Anarchist Series. He also mapped several granitic batholiths and stocks in the region, but he did not associate any of the above rocks with the Shuswap complex.

In 1911 Daly compiled a comprehensive report on the Shuswap Sheet, previously mapped by Dawson. Based on an unconformity at Albert Canyon, near Revelstoke, which has since been discredited, (Gunning, 1928 , Okulitch 1949 , Wheeler, 1962 , Daly concluded that both the Nisconolith and Adams Lake series were of Pre-Beltian age and were stratigraphically equivalent to the more highly metamorphosed Shuswap Series. Accordingly in 1915, Daly enlarged the Shuswap Series to include all of these pre-Beltian rocks and further subdivided the Shuswap into formations. At the same time he introduced the term Shuswap terrane in reference to the entire assemblage of metamorphic, granitic and pegmatic rocks comprising the complex.

Throughout his work, Daly was impressed by the metamorphism in the Shuswap which he considered a classic example of load metamorphism. In a 1917 paper entitled Metamorphism and its Phases, Daly defined load metamorphism as one in which the stress directing recrystallization was induced by deep burial and dead weight resulting in schistosity sensibly parallel to the planes of stratification.

H.S. Bostock (1940-1941), mapping on a scale of 1 inch to 1 mile covered part of the present map-area, and introduced the name Vaseaux Formation for the schists and gneissic rocks around Vaseaux Lake. Bostock considered the Vaseaux Formation to be older than the less metamorphosed Kobau Group sediments of questionable Carboniferous age, which he also named and mapped on Mt Kobau southwest of the Vaseaux Lake area.

In 1934 Daly's postulated load metamorphism in the Shuswap was questioned by J.A. Gilluly who showed that the metamorphism was of the dynamic type by means of petrofabric interpretation of planar and linear structures. In the same year B.B. Brock related schistosity and linear structure in Shuswap gneisses east of Okanagan Mountain to the upward thrusting of granitic magmas in post-Triassic time.

The geology of Kettle River West map-sheet, on which Vaseaux Lake is centrally located, was compiled by C.E. Cairnes in 1940. He showed that the Shuswap metamorphic complex was continuous from the Shuswap Lake area along the east side of the Okanagan Valley, as far south as the 49th parallel. Cairnes presented evidence to support his view that the metamorphism in the Shuswap was a comparatively recent event in the geologic history of the terrane, and was related to Mesozoic batholithic intrusions. He believed that the "sill-sediment complex" and structures conformable with bedding were fundamental characteristics of the Shuswap, while adjoining less metamorphosed formations where characterized by steeper structures. These differences Cairnes attributed to depth of burial during an episode of deformation, metamorphism and granitic intrusion which occurred during Mesozoic time. The large batholithic masses he said, represented an extreme phase of granitization which occurred at great depth in the metamorphic complex, and were gradational through the "sill-sediment complex", a hybridized zone, to less altered lithologies.

In 1959 A.G. Jones mapped and described the Vernon map-area which includes a large part of the Shuswap Sheet originally mapped by Dawson. Jones re-organized the Shuswap stratigraphy and divided the terrane into the Monashee, Mt. Ida and Chapperon Groups whose stratigraphic relations with one another are still uncertain. Cache Creek rocks of questionable Carboniferous and Permian age were said by Jones to overlie the Shuswap unconformably, and a Precambrian age was postulated for the Shuswap. Jones also recognized older and younger episodes of metamorphism, deformation and granitic intrusion and assigned a pre-Permian and probable Precambrian age to the older of these.

H.W. Little (1961), revised Cairnes' Kettle River West map and extended the undivided Monashee Group southward to include the Vaseaux Formation. Little also correlated the granitic rocks of the region with the Nelson and Valhalla plutonic rocks which occur further east.

In 1964 V.A. Preto attempted to document the unconformity between the Shuswap and the overlying Cache Creek by mapping in detail the localities cited by Jones. He was unable to confirm the existence of the unconformity except at Salmon River, where the rocks involved may or may not belong to either the Shuswap or the Permian Cache Creek Formation.

J.R. Snook (1965) studied the Tonasket Gneiss of north-central Washington State, a direct southerly extension of the Shuswap terrane. He was unable to determine the stratigraphic position of the Tonasket Gneiss, but outlined a complex geologic history comprised of early high grade metamorphism and deformation followed by later mylonization, gentle folding and faulting.

N.B. Church (1967), described the Early Tertiary continental volcanic and sedimentary rocks of White Lake map area which lie unconformably on various pre-Tertiary lithologies west of Vaseaux Lake. Faulting at intervals during and after deposition and an episode of gentle folding of probable pre-Miocene age were recognized.

In 1969 A.V. Okulitch described the geology of Mt Kobau and was concerned particularly with the geologic history of the Kobau Group of meta-sediments and meta-volcanics. Okulitch correlated the Kobau with the lower more deformed parts of the Anarchist Group which are of pre-Permian or possibly pre-Carboniferous age, and suggested that the Kobau may be equivalent with the Chapperon Group (uppermost Shuswap in the Vernon area). He described a 3-phase deformational history in the Kobau and tentatively correlated earliest Kobau structures with phase 2 structures found in the nearby Vaseaux Formation and suggested that this deformation is of pre-Permian and possibly pre-Carboniferous age.

In recent years much geologic work has been done along the eastern margin of the Shuswap and the adjoining Selkirk Mountains and Kootenay Arc, and is pertinent to stratigraphic and structural correlations and radiometric dating within the Shuswap. Information in papers by Fyles (1964), Hyndman (1968), Preto (1968), Read (1971), Reesor (1965), Ross (1968), and Wheeler (1962, 1964, 1966), is of interest, but is much too complex and lengthy for review here.

GENERAL GEOLOGY

High grade metamorphic rocks of the Shuswap complex (Vaseaux Formation of this study) are the oldest known rocks in the southern Okanagan region of British Columbia. Their contact relationships with rocks of known age may in some instances be inferred, but are generally not well understood for a variety of reasons, among which obliteration as a result of subsequent deformation and metamorphism is paramount.

Relationships with some older rocks in the district-Kobau Group (Okulitch, 1970) and the Old Tom and Shoemaker Formations (Ross and Barnes, 1972)-have been established as a result of recent work, and it is now apparent that the Vaseaux Formation was in existence and underwent an early (phase 1) episode of deformation and metamorphism in which the Kobau, Old Tom or Shoemaker Formations did not participate. Later phase 2 and phase 3 deformation affected all of the above-mentioned lithologies and phase 3 has been shown to be of probable pre-late Mississippian age. (Ross and Barnes 1972). The Vaseaux Formation is thereby inferred to be of probable pre-mid-Paleozoic age.

The Vaseaux Formation is bounded in large part by granitic rocks of Mesozoic and probably older age (see figure 1-2) which comprise the "Okanagan Composite batholith" (Daly, 1912). On the west volcanic and sedimentary rocks of early Tertiary age lie unconformably above and/or are in fault contact with the Vaseaux Formation, but have participated in only the latest phases 4 and 5 of deformation.

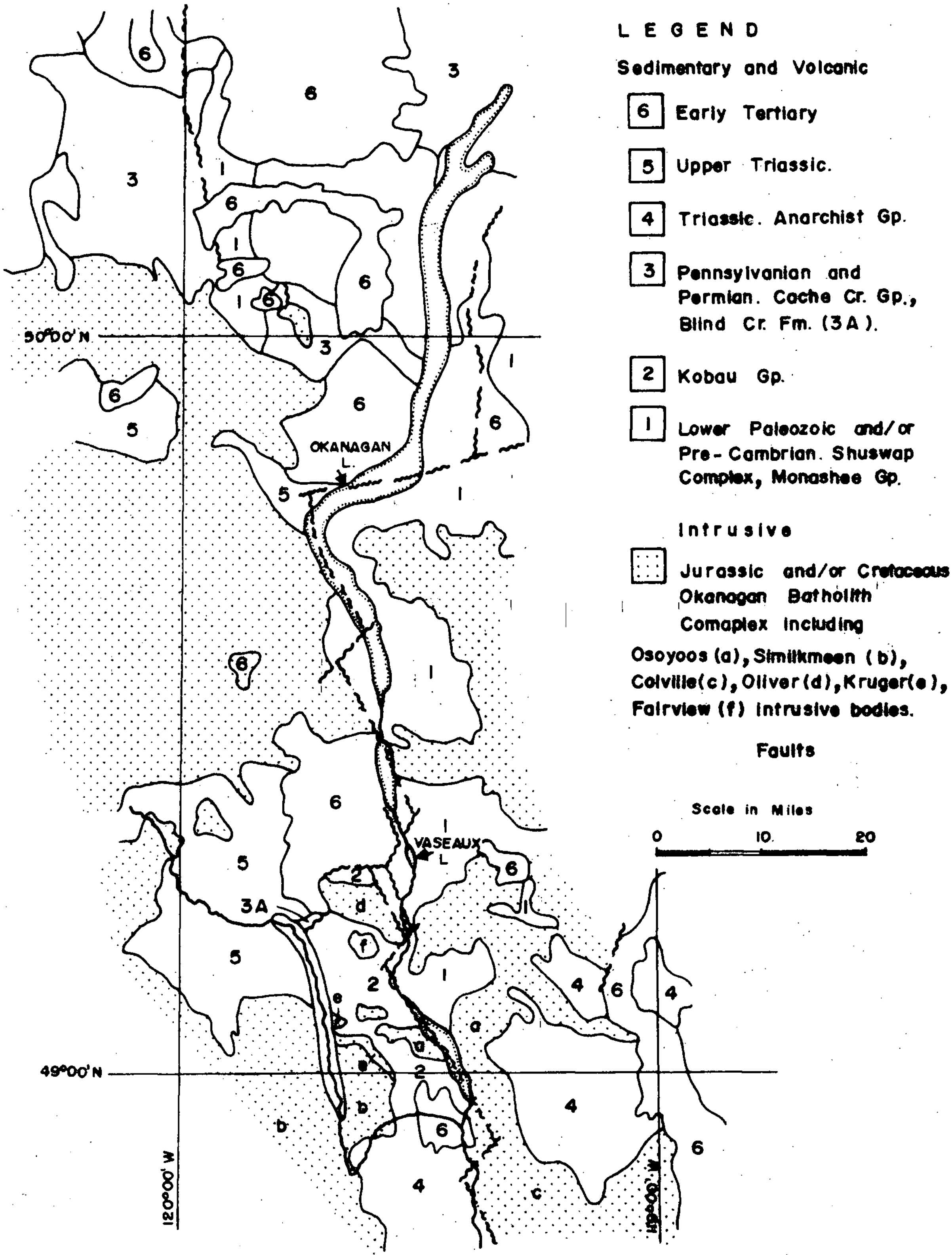


FIGURE 1-2

GENERAL GEOLOGY OF THE SOUTHERN OKANAGAN
After A.V. Okulitch 1969

As a result of the present study, the Vaseaux Formation has been shown to consist of 5 distinctive map-units comprised of granulite, schist and amphibolite with minor quartzite and carbonate. The specific mode of origin and environment of deposition of the succession is not known, but original bedded character is implied by compositional layering present on all scales. Affinity with synorogenic sediments and basic volcanics of the greywacke suite is suggested but not substantiated by field evidence.

Map-units 1-5 form a structural succession in which the relative age of units is unknown. Five phases of deformation are recognized, and large scale recumbent folding associated with each of phases 1-3 has brought about much repetition within the succession. Metamorphism in the amphibolite facies and intrusion of granitic plutons accompanied phases 2 and 3.

Phases 4 and 5 of deformation gave rise to open folds and fractures and these same structures are developed in nearby early Tertiary rocks. Phase 4 is related in time to early Tertiary (44 m.y. B.P.) volcanism and localized high heat flow (Ross and Barnes, 1972). Phase 5 folding and faulting of probable pre-Miocene age post-dates deposition of the early Tertiary White Lake sediments (Church, 1967).

CHAPTER TWO

STRUCTURAL SUCCESSION

Previous mapping of high grade metamorphic rocks in the Southern Okanagan was essentially reconnaissance in nature (Bostock,1928-30, Cairns,1940, Little,1961) and did little more than outline the principal masses of paragneiss and orthogneiss. Bostock placed all of the paragneiss into a unit named the Vaseaux Formation, and it is with a part of the Vaseaux Formation that this study is concerned.

Within the Vaseaux Formation of the present map-area, a local structural succession exceeding 4000 feet in present thickness has been established. The succession is made up of 5 lithologic units (Units 1-5), but neither top or bottom of the succession, nor the relative ages of the map-units are known.

Among the 5 map-units, Unit 2, composed largely of schist, and Unit 4, of amphibolitic character, are lithologically distinct markers. Units 1, 3 and 5, although differing slightly from each other, consist almost entirely of various types of granulite[1]

1. The A.G.I. Glossary defines granulite as follows:
"(1.) A metamorphic rock composed of even sized interlocking granular minerals. (2.) A metamorphic belonging to a high-temperature facies characterized by the presence of mica and hornblende. Coarse and fine bands alternate to produce a regular planar schistosity."
Turner and Verhoogen (1960, p.454) in defining granulite state; "Some degree of segregation banding and especially alignment of flat lenses of quartz or feldspar typically impart a regular foliation to the rock."
As a textural term used in the above sense, granulite describes many of the granular gneissic rocks of Vaseaux Lake map-area more fully than the almost synonomous but more general term gneiss. Granulite is specifically not used as a qualifying term for a metamorphic facies, and regional metamorphism which gave rise to the granulites was in the amphibolite facies.

and semi-pelitic granulite, and are distinguished by subtle variations in composition and character as summarized in Table 2-1.

Although lithology is relatively simple, and the succession superficially resembles a gently folded stratigraphic sequence, many structural and metamorphic complexities exist and require mention before the lithologic units are described. In detail, the units are deformed internally by numerous minor folds and associated transposition structures, and regionally by large recumbent folds and slides[1]. Deformation is polyphase, and three superposed large scale recumbent fold sets have given rise to much repetition of map-units. Further complexity stems from shearing and local imbrication at lithologic contacts and dislocation along slides, but in most instances lithology is sufficiently distinctive to allow recognition of such structures and correlation across them.

The oldest megascopic fold in the map-area is a northerly trending, westerly closing isocline named McIntyre Bluff Fold. Whether it is an anticline or a syncline is not known, but parts of its core and hinge have been mapped by Ross near McIntyre Bluff,

1. The A.G.I. Glossary defines slide as follows;

<u>Slide</u>

A term proposed by Fleuty (1964) for a fault formed in close connection with folding, and that is conformable with the fold limb or axial surface. It is accompanied by thinning and/or disappearance of the folded beds.

Usage of the term slide in this study is consistent with the above definition.

TABLE 2-1

SUMMARY OF THE CHARACTERISTICS OF MAP UNITS 1-5

Units	Lithology
1	- biotite semi-pelitic granulite with very little or no hornblende - schistose biotite rich layers characteristic
2	- biotite muscovite schists with interbedded semi-pelitic granulite layers - minor marble, calc-silicate, quartzite
3	- semi-pelitic granulites typically with more hornblende than biotite - thin biotite rich schistose layers common
4a	- of amphibolitic character - basal fissile biotite rich granulites grading to laminated amphibolites - minor impure quartzite, calc-silicate, marble
4b	- laminated and massive amphibolites - no granulites
5	- basal fissile biotite semi-pelitic granulites - upper hornblende granulites - occasional amphibolite layers - thin biotite rich layers common

* See Chapter Five for Mineral Assemblages.

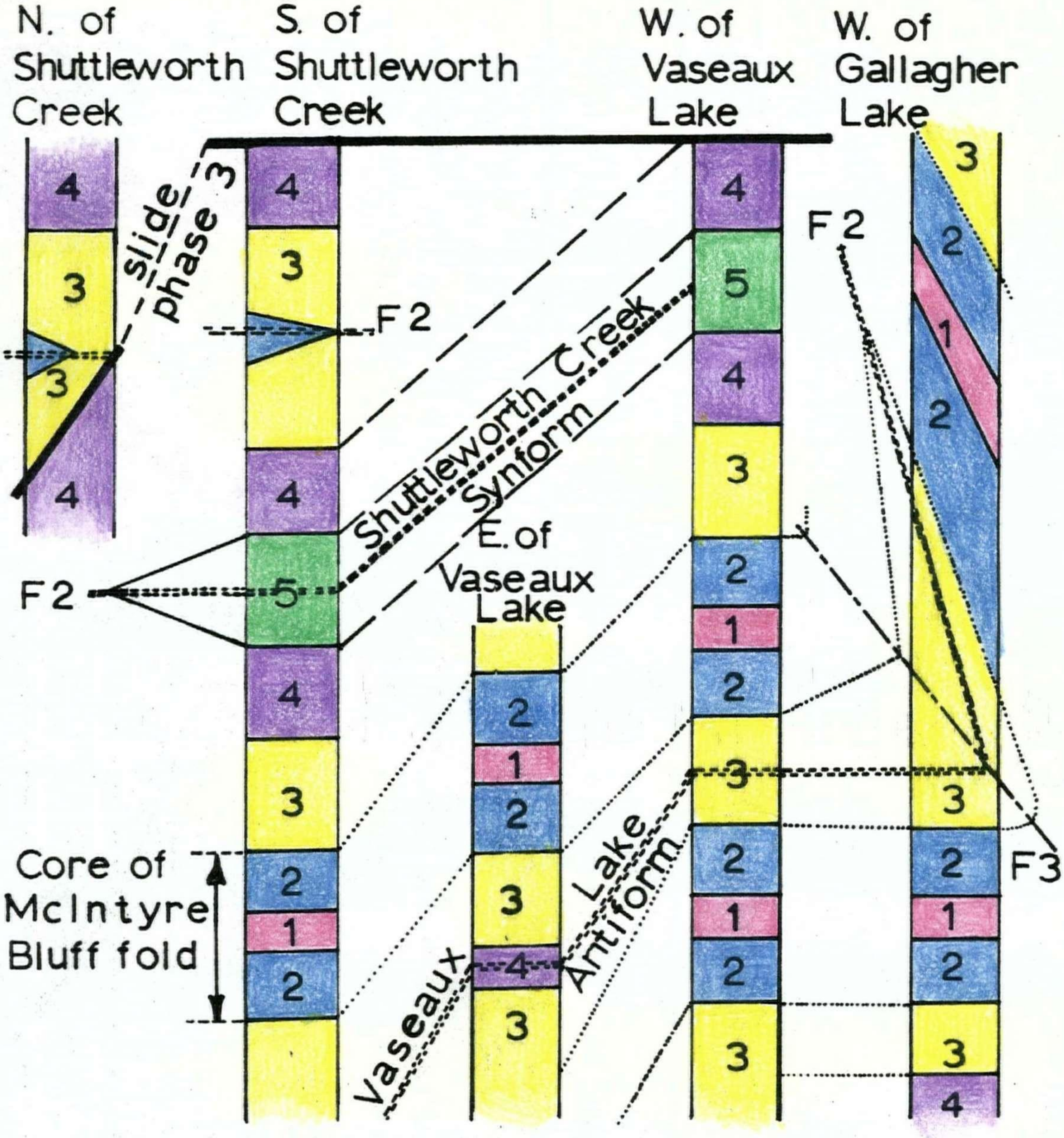


Figure 2-1 Schematic structural lithologic succession.

Major structures affecting distribution of map units 1 - 5 are shown. Units 1 and / or 2 may, in addition, be locally missing against a slide (not shown).

and continuity of the core lithology and repetition of map-units are evidence of its regional development. Because deformation is polyphase and nothing is known about relative ages of map-units, it is necessary to describe the units with respect to their structural positions on the oldest fold recognized. This has been done by numbering the Units 1-5 as they occur respectively from core to envelope of McIntyre Bluff Fold as illustrated schematically on figure 2-1. Repetition of the units due to later phase 2 and phase 3 folding is also illustrated, by means of schematic columnar sections representing different parts of the map-area.

Thicknesses of the map-units are far from uniform. Variation from hinge to limbs of the larger folds accounts for significant differences, but other factors contribute to even larger local variations. Among these gradual truncation against slides, dilation through injection of concordant granitic and pegmatitic material, and repetition due to small-scale internal folding are prominent. In view of these factors it is impractical to attempt estimates of original thickness. Total present thickness of the units has been estimated where possible at several localities on the limbs of phase 2 folds which are structurally representative of most of the area mapped. Maximum differences obtained are expressed as thickness ranges, and are meaningful only as an approximation of thickness most commonly observed.

Complex fabrics characterized by intersecting planar and linear elements are found in all of the map-units. Rather than deal with such elements as cleavage and lineation in isolated lithologic descriptions which would call for much repetition, all fabric elements are described in context with structure and metamorphism in Chapters 3 and 5.

Among the elements of fabric however, compositional layering is of prime concern in lithologic description. Compositional layering is seen on all scales in all map-units and some generalizations may be made concerning its nature and origin in order to avoid repetition. The terms segregation, layering, and gneissic structure, have been used here to describe different degrees of development of compositional layering in response to dynamic and metamorphic processes.

Quartzo-feldspathic segregations impart a distinct layered structure to all of the map-units. Typically they form discontinuous but closely spaced lamellae a few fractions of an inch thick parallel to lithologic layering or a prominent cleavage. Slightly thicker through-going lamellae have been localized by shear planes and separate areas of discontinuous lamellae to which they are parallel or sub-parallel.

Gneissic structure is restricted to more highly sheared parts of the map-units. Quartz-feldspathic layers may be several times as thick and more continuous than in rocks which are less sheared. Gneissic zones in some instances localized numerous concordant pegmatitic and granitic sheets which further enhance their gneissic structure.

LITHOLOGIC UNITS

Unit 1

Unit 1 consists entirely of grey to brownish grey semi-pelitic granulite wherein medium to fine grained plagioclase and quartz are the most abundant mineral components. Biotite, ranging up to about 40%, is a highly variable component, while hornblende, muscovite, and reddish-brown garnet occur in minor proportions only. Compositional layering defined by inequal distribution of biotite within Unit 1 may be a relict feature of primary sedimentation and could represent bedding. Biotite enriched layers ranging from thicknesses of 2-3 feet to thin schistose partings grade both sharply and imperceptibly to biotite deficient layers. Such layers are always bounded by narrow shear zones and cannot readily be ascribed to a unique primary sedimentation process. Mineral segregation layering is well developed throughout Unit 1 and forms the conspicuous foliation. In exposures near McIntyre Bluff gneissic structure locally predominates.

The minimum thickness of Unit 1 has been estimated at 150 feet, but its total thickness is unknown as the Unit is not completely exposed. Contacts with schists of Unit 2 are highly sheared and much of the movement has been within the schist. Although Units 1 and 2 appear conformable it is likely that parts of both units are missing due to this movement. Where Unit 1 is truncated by a slide, imbrication of Units 1 and 2 on anastomosing secondary shear planes is evident.

Unit 1 is restricted to the cores of the phase 1 McIntyre Bluff Fold. East of the Okanagan River phase 2 and phase 3 folds have refolded and phase 1 structure, such that Unit 1 appears on the lower limb of phase 2 Shuttleworth Creek Synform, and further south on the inverted limb of phase 3 Gallagher Lake Synform. At both occurrences Unit 1 eventually disappears against a slide.

Unit 2

Unit 2 is composed primarily of reddish brown to grey weathering schist with interbedded semi-pelitic granulite and subordinate impure quartzite, marble and calc-silicate. Biotite is the dominant mineral component of the schists, but coarse flakes of muscovite lying in the plane of compositional layering are a characteristic feature which persists especially in highly sheared portions of the unit. Quartz, feldspar and frequently reddish-brown garnet are variable but significant components of the mineral assemblages. Distribution of the various lithologic types within Unit 2 is not uniform. Homogenous sections of schist tens of feet thick, separated by much thinner schist layers enveloped by semi-pelitic granulites are charactertistic.

Layers of semi-pelitic granulite, medium to fine grained mixtures of feldspar, quartz, and biotite with minor hornblende, epidote and garnet, make up no more than 20% of Unit 2, and are fairly evenly distributed. Thickness of the granulite beds is never in excess of 3 feet and is most commonly in the order of 3-8 inches.

Blue-grey diopside marble and greenish grey to brown calc-silicate granulite form less than 1% of the total volume of Unit 2, but are a widespread and distinctive part of the lithology. These occur as discontinuous layers and pods which are as much as 20 feet thick on the hinges of phase 2 folds and continuous for 40-60 feet along strike. More commonly they are only a few feet thick and continue for 10-20 feet along strike.

Mineral segregation layering is developed within the schists of Unit 2, but not to the extent that it is seen within the interbedded granulites, or the other granulitic units of the map-area. Gneissic structure is only seen in association with granitic rocks where it is the result of lit-par-lit injection of granitic materials and metasomatism.

Unit 2 ranges from 350-550 feet in thickness and contacts with Units 1 and 3 are highly sheared as a result of slip during the various phases of folding. Changes in attitude are sometimes seen across these contacts but more commonly they appear concordant and may have been initially conformable. Over much of the area Units 2 and 3 are in contact across a slide along which both are obliquely truncated.

Unit 2 is widely distributed throughout the map-area and is useful in confirming all of the major structure. Unit 2 closes on the hinge of the phase 1 McIntyre Bluff Fold, and east of the Okanagan it is present on the limbs of phase 2 folds. East of Gallagher Lake imbricate slices of Unit 2 outline the hinge of the phase 3 Gallagher Lake Synform.

Unit 3

A thick sequence of remarkably uniform grey to grey-brown weathering granulites comprises Unit 3. These rocks include both fine to medium grained, and semi-pelitic varieties of granulite in which feldspar and quartz combined account for about 75% of the total mineral assemblage. Hornblende is typically somewhat more abundant than biotite, but biotite enriched layers are present and include a little muscovite and garnet.

Bedding, if ever developed in Unit 3, is no longer easily recognized, but local subtle changes in proportions of hornblende and biotite probably reflect original compositional differences. Thin schistose partings enriched in biotite and inequally spaced throughout the Unit may represent original bedding surfaces.

Extremely well developed mineral segregation layering is characteristic of the lithology of Unit 3 and is seen in virtually all exposures. Gneissic structure is also well developed, especially in the core of the Vaseaux Lake Antiform (phase 2) which is exposed along the east shore of Vaseaux Lake.

Unit 3 is repeated at several structural levels as a result of folding and appears on the limbs or in the cores of all major folds. Best exposures are in roadcuts near Vaseaux Lake, in the canyon section of McIntyre Creek, and in the canyon section of Shuttleworth Creek. North and southeast of Shuttleworth Creek a thick section of Unit 3 lies above a slide developed during phase 3 deformation, and probably occupies the core of a major phase 2 antiform (plate 1-pocket). Unit 3 at these localities is greatly altered as a result of probable Early Tertiary hydrothermal activity (Chapter 5).

Thickness of Unit 3 is difficult to estimate because of incomplete exposure. North of McIntyre Creek up to 1300 feet of section is present but the Unit thins northward to about 200 feet against a slide. The contact with Unit 4 is gradational, apparently conformable but weakly to strongly sheared. On the hinges of major phase 2 folds Unit 3 attains thicknesses greatly in excess of 1300 feet measured parallel to the axial planes. On the limbs of the Vaseaux Lake Antiform and the structurally higher phase 2 antiform north of Shuttleworth Creek thicknesses of 1200-1500 feet have been estimated in sections perpendicular to the strike of Unit 3.

Unit 4

Unit 4 consists of a mixed assemblage of metasedimentary and metavolcanic rocks which are characterized by abundant amphibole. Additional lithologic distinctions allow subdivision into Units 4a and 4b within most of the map-area, as follows.

Unit 4a consists of highly fissile semi-pelitic granulite interbedded with amphibolite and minor impure quartzite, calc-silicate and marble. The fissile granulites form a zone about 100 feet thick at the base of Unit 4a, above which layers of fine grained laminated amphibolite ranging up to several feet in thickness appear and become progressively more abundant. A few beds of rusty weathering quartzite as much as 12 feet thick and a few discontinuous marble and calc-silicate layers occur in the structurally higher parts of the Unit.

Unit 4b is composed of several types of amphibolite but contains little or no granulite. Well laminated medium to dark gray amphibolite forms the bulk of the Unit within which layers of fine grained massive amphibolite up to 10 feet thick, and very thin layers of biotite rich amphibolite are inequally distributed.

Laminated amphibolites consist of alternating dark and light layers in which medium to fine grained mixtures of hornblende, plagioclase, epidote, clinopyroxene, biotite and quartz make up the mineral assemblages. Colour variation is dependent upon respective dominance of hornblende or plagioclase, and to a lesser extent biotite, which forms schistose partings between some layers.

In contrast, massive amphibolites display little internal variation in composition, and medium to fine grained hornblende is in excess of 70% of the total mineral content.

Mineral segregation layering is best developed within the granulites of Unit 4a but is also seen within massive and laminated amphibolites where lamellae rich in plagioclase and occasionally clinopyroxene are present. Gross compositional layering in the laminated amphibolites, due possibly in part to primary sedimentation, is greatly enhanced by this segregation layering.

Units 4a and 4b are well exposed on the ridge south of Shuttleworth Creek where they outline the hinge and limbs of phase 2 Shuttleworth Creek Synform, and they have been mapped in the same structural position west of the Okanagan River. Further south they appear again on the hinge of phase 3 Gallagher Lake Synform. Near Vaseaux Lake a few slices of Unit 4a are present in a gneissic zone within the cores of phase 2 Vaseaux Lake Antiform, but the complete section is not exposed.

The contact between Units 4a and 4b is highly sheared and shows some characteristics of a slide. Changes in attitude across the contact are common and parts of one, or both Units may be missing. Contacts with Units 3 and 5 are also sheared but appear conformable.

Thickness of Unit 4a ranges from about 200-800 feet and Unit 4b ranges from 300-850 feet. Much of the variation in thickness is sympathetic in the sense that combined thickness of Units 4a and 4b remains fairly constant throughout the area.

Amphibolitic rocks thought to be part of Unit 4a and mapped as Unit 4 undifferentiated on plate 1, are exposed in northwest and northeast parts of the map-area, above the phase 3 slide. At the northwest occurrence they lie on the lower limb of a major phase 2 antiform while at the northeast they appear to lie in the core of the complimentary structurally higher synform.

The rocks at the northwest occurrence are laminated amphibolites much like Unit 4b but rocks resembling Unit 4a were not found. These laminated amphibolites may be in tectonic contact with Units 3 and 5 such that part of Unit 4 is missing. Contact relations are no longer easily discernable and lithology and internal structure have been obscured by pervasive hydrothermal alteration which has drastically affected all of the rocks in this area (plate 4-pocket and Chapter 5).

At the northeastern occurrence alteration is much less intense, and the lithologic succession comprising the amphibolitic unit is somewhat different than that found elsewhere within Unit 4. Above Unit 3 several hundred feet of fissile semi-pelitic granulite with minor interbedded schist, quartzite and laminated amphibolite lead upwards to a contact with uniform amphibolite 1100 feet or more in thickness. While the rocks beneath this contact are not unlike the rocks of Unit 4a, the overlying uniform amphibolites bear little resemblance to the laminated amphibolites of Unit 4b. They contain noticeably less hornblende and more plagioclase which here are present in about equal proportions and together form at least 90% of the mineral assemblage. Minor quartz, biotite, epidote, garnet and sphene also occur, but diopside which is rather abundant in laminated amphibolites was not found. Segregation layering involving plagioclase and a little quartz is well developed within the uniform amphibolites, and apart from infrequent schistose and pegmatitic layers, forms the only compositional layering found therein.

Unit 5

Unit 5 is composed of brownish grey and grey semi-pelitic granulites rich in quartz, plagioclase and sometimes biotite with lesser hornblende, garnet, epidote and rare muscovite. Lower parts of the Unit are brownish fissile mica rich granulites, but biotite decreases upwards and the upper parts are grey hornblende granulites containing occasional layers of amphibolite. Biotite enriched layers and schistose partings occur throughout Unit 5 and may be an expression of bedding, but segregation layering forms the most conspicuous foliation.

Unit 5 occupies the core of Shuttleworth Creek Synform east and west of the Okanagan River. It is also present in a limited area on the hinge of Gallagher Lake Synform and is in intrusive and fault contact with highly altered granitic rocks. In the northwestern map-area part of Unit 5 may be present in tectonic contact with laminated amphibolites (Unit 4 undifferentiated) within a zone of intense hydrothermal alteration above the phase 3 slide.

Unit 5 is the uppermost member of the structural succession and its total thickness is unknown. It is apparently conformable with Unit 4 and up to 600 feet of section is known within the map-area.

ORIGIN AND DEPOSITIONAL ENVIRONMENT

Complex metamorphism and deformation within the Vaseaux Formation make speculation on the origin of these rocks tenuous. Primary structure, if ever present, can no longer be recognized, and knowledge of the chemical composition of various rock types comprising the Vaseaux Formation is presently insufficient to allow speculation about origin from a compositional basis.

Compositional layering on all scales within the Vaseaux Formation is thought to be in part an expression of an original bedded character of the succession, and is the only real clue as to the origin. Several hypothetical origins and environments of deposition are therefore possible in view of the nature of metamorphism and deformation.

The author would favour a view suggesting that the succession has affinity with the greywacke suite. Best evidence for a near shore environment is seen in the granulites and semi-pelitic granulites where alternating but tectonically separated biotite enriched and biotite deficient layers suggest possible original graded bedding on many scales, and therefore a turbidite origin. Granulites are by far the most abundant lithologic type within the map area and it seems possible that they are in fact metamorphosed greywackes. Shales and basic volcanic rocks, also sometimes part of the greywacke suite, would under such a hypothesis be represented by Units 2 and 4 of the Vaseaux Formation.

An alternate, perhaps less tenable hypothesis, is that the succession was formed in an open marine environment and is the product of metamorphism of a mixed assemblage of argillaceous cherts, shales and basic volcanic rocks. Minor carbonate found within the succession could well be present in either open marine or near shore environments.

LITHOLOGIC CORRELATION

Rocks of the Monashee Group of the Vernon area (Jones, 1959) and the Tonasket Gneiss of Washington State (Snook, 1965) are similar in many ways to the metamorphic rocks of the Vaseaux Formation. Although detailed mapping has not been done in either of the above areas and comparison of stratigraphy is not possible, it is suggested that these rocks may all be of approximately the same age and may have accumulated in the same basin of deposition. They all have undergone complex geologic histories, and now form part of a northerly trending high grade metamorphic belt lying in large part east of the Okanagan Valley. More easterly parts of the Shuswap terrane are also lithologically similar to the Vaseaux Formation but no basis for correlation has been established or is warranted at this time.

CHAPTER THREE

STRUCTURE

INTRODUCTION

Composite structure within the metamorphic rocks near Vaseaux Lake is the result of superposition of five successive phases of deformation. Major folds have been formed during each successive phase, and the later phases have in addition, produced fractures. Geometries of these fold sets and fractures are subject to comprehensive description on the following pages, as are their mutual time and interference relationships. Maps, cross-sections, schematic diagrams, lower hemisphere stereographic plots, and wherever possible photographs are used to illustrate and substantiate these descriptions.

Associated metamorphism, plutonism, metasomatism, and the evolution of fabric as seen in thin-section are subjects covered in Chapters 4 and 5.

OUTLINE OF STRUCTURAL HISTORY

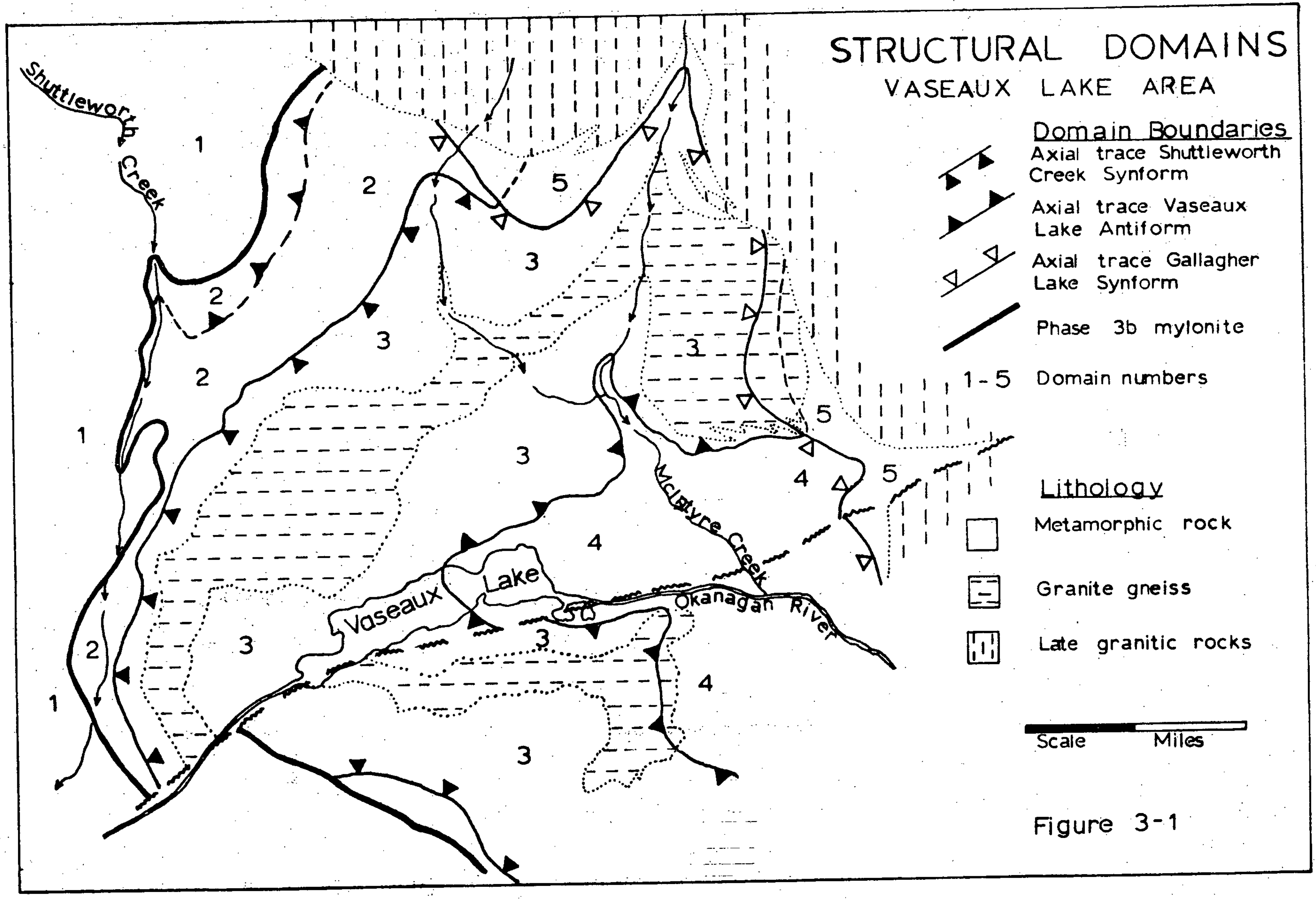
Table 3-1 summarizes the evolution of structure within the Vaseaux Lake area and presents the structural elements related to each phase of deformation. The earliest structures (phase 1) are a northerly trending fold set upon which northwesterly trending phase 2 folds have been superposed. Phase 1 and 2 folds are both of similar style, and are associated with contemporaneous regional metamorphism which probably reached its highest grade during phase 2 folding.

Phase 3 folds are of diverse trend and are grouped into subsets 3a, 3b, 3c. Subset 3a structures include westnorthwesterly

TABLE 3-1

SUMMARY OF THE STRUCTURAL ELEMENTS

FOLD SETS	FOLD STYLE	PLANAR STRUCTURES	LINEAR STRUCTURES	ASSOCIATED DISCONTINUITIES
1	Similar; isoclinal rootless; long planar limbs, sub-rounded hinge	F1 -axial cleavage, quaquaversal dip	L1 -fold axes and penetrative lineations variably plunging N and S	slides
2	Similar; tight often rootless; planar limbs, sub-rounded to angular hinge	F2 -axial cleavage, quaquaversal dip	L2 -fold axes and penetrative lineations gently plunging NW and SE	reactivated F_o/F1
3a	Similar; open, planar limbs, sub-rounded to angular hinge	F3 -axial strain-slip cleavage, inclined gently to SSW	L3 -fold axes and penetrative lineations gently plunging WNW and ESE	reactivated F_o/F1, F2
3b	Similar; tight to open minor folds	F3b -axial strain-slip cleavage, inclined gently to NNE - locally developed	L3b -fold axes and penetrative lineations gently plunging WNW and ESE	slide inclined to NE
3c	Flexural-flow, open minor folds	F3c -axial cleavage variably inclined to E and W - locally developed	L3c -minor fold axes plunging NW and NE	slide inclined to NE
4	Flexural-slip, open, rounded limbs and hinge	J1 -steeply dipping NE'ly fractures	L4 -rare minor fold axes gently plunging N and S	reactivated earlier foliations
5	Flexural-slip, open, rounded limbs and hinge	J2 and J3 -steeply dipping W to NNW fractures	L5 -minor fold axes gently plunging NW and SE	steeply dipping faults



STRUCTURAL DOMAINS
VASEAUX LAKE AREA

Figure 3-1

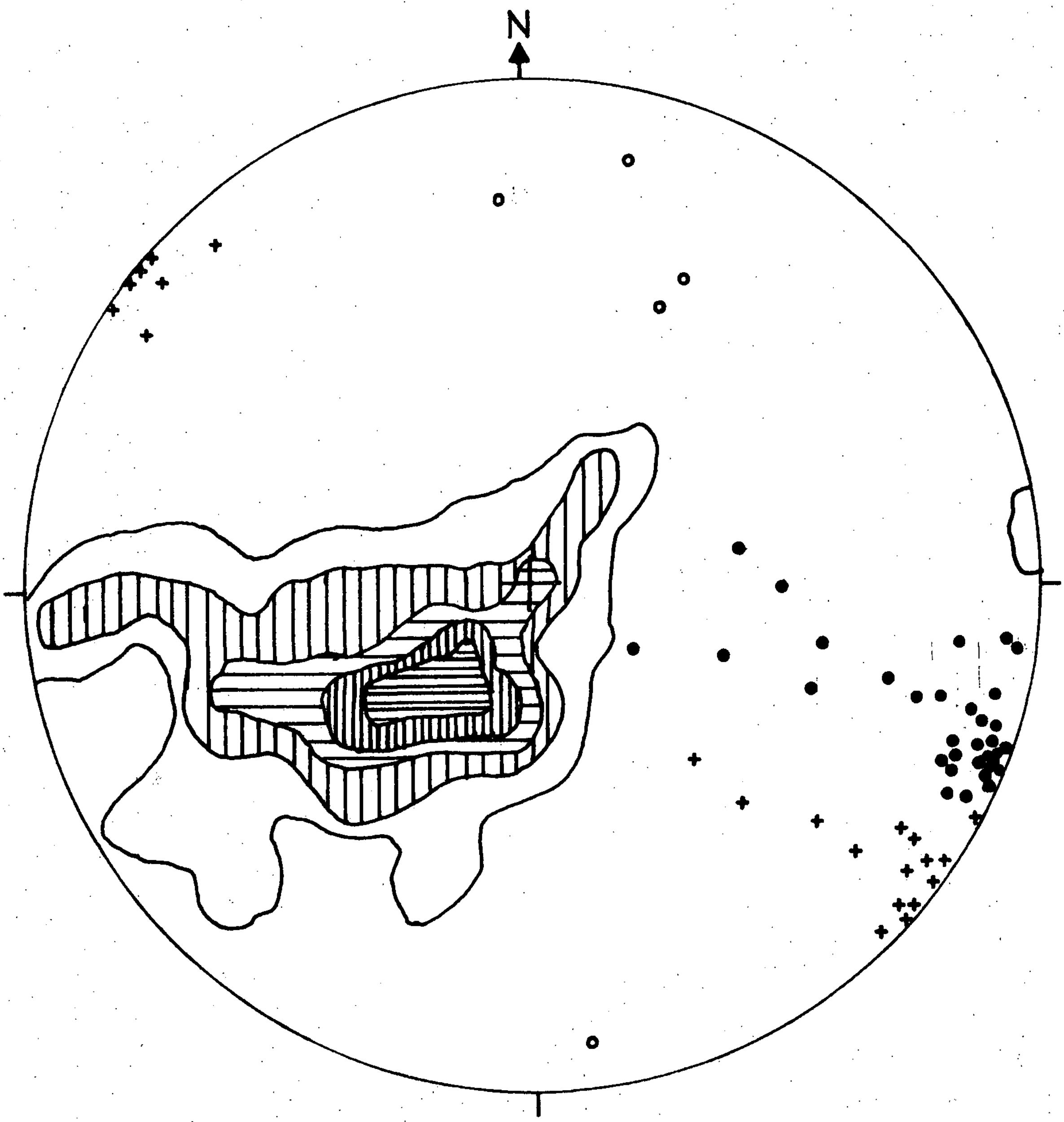
trending megascopic folds of similar style and were the first structures produced during phase 3. Subsets 3b and 3c formed later and are associated in space and time with the development of a slide marked by mylonite.

Phases 4 and 5 of the polyphase deformation produced broad, open flexural-slip folds along successive north to northeasterly and northwesterly trends. Shear on the limbs of these folds gave mylonite and gouge. Steeply dipping joint and fault sets (J_1, J_2, J_3, J_4) are related to extensive fracturing which accompanied these latest phases of deformation,and perhaps even later faulting.

STRUCTURAL DOMAINS

Selection of perfectly homogeneous structural domains for analysis was impractical in view of all scale 5 phase folding. A very large number of domains would be required to isolate properly zones of homogeneity, and insufficient data was available to allow this. It was decided that most could be gained by selecting domains sufficiently homogeneous to allow analysis of the effects of phase 2 and 3 deformations. This was done by taking the axial traces of demonstrable major phase 2 and 3 folds, and the phase 3 slide as domain boundaries. The five resulting domains are shown on figure 3-1. Attitudes of compositional layering and phase 1, 2 and 3 planar and linear structures have been plotted for each domain (figure 3-2 and 3-10) and these diagrams are utilized in the text.

Limitations are imposed by this selection of domains. Isoclinal phase 1 folding has been ignored and cannot therefore be fully described, although the re-orientation of phase 1



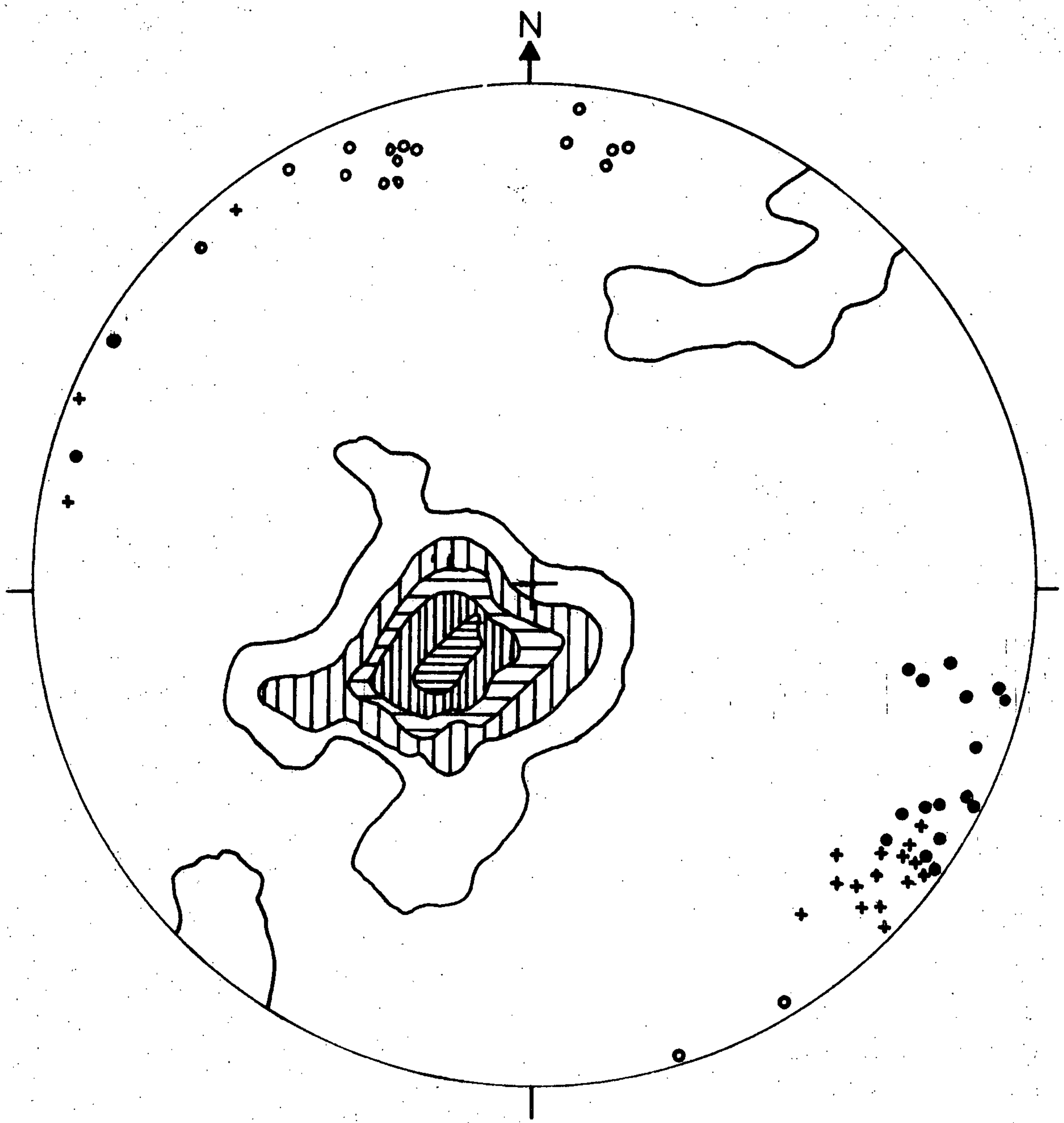
Domain 1

Figure 3-2 113 poles to F_0 / F_1, contoured at 1-2-4-8-12% per unit area.

o L_1

+ L_2

• L_3



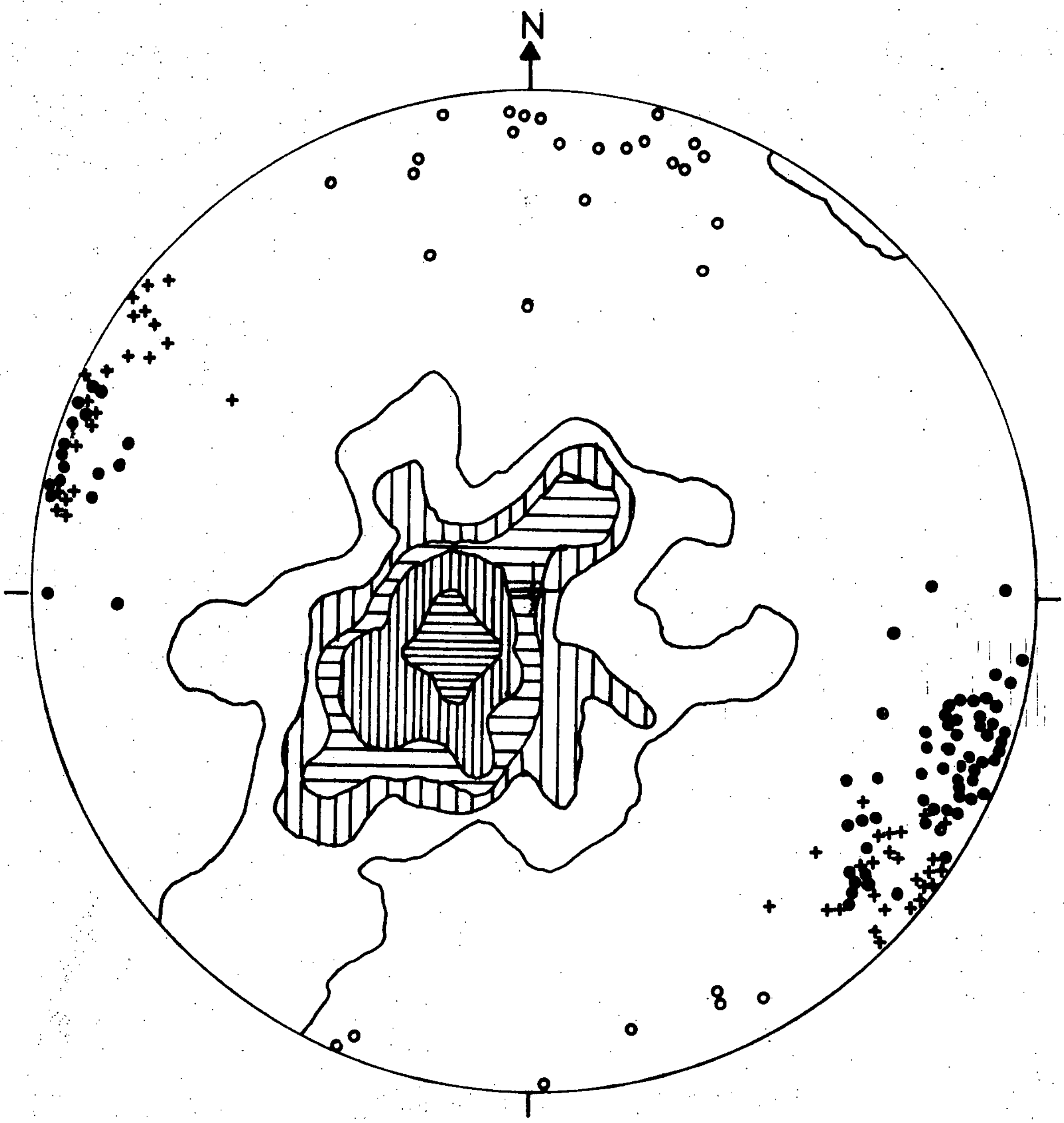
Domain 2

Figure 3-3 37 poles to F_0/F_1, contoured at 1-2-4-8-12% per unit area.

∘ L_1

+ L_2

• L_3



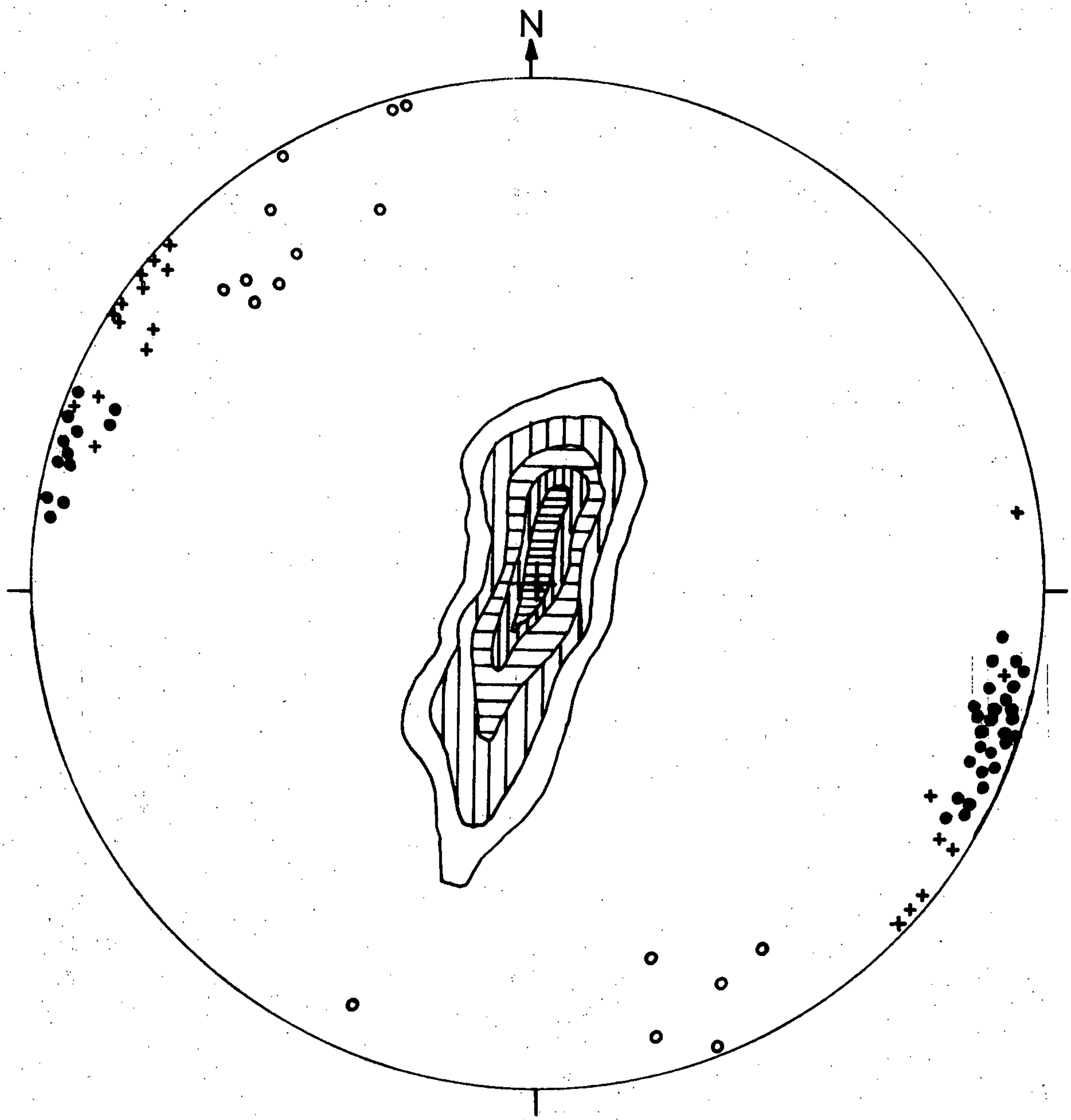
Domain 3

Figure 3-4 125 poles to F_0/F_1, contoured at 1 2 4 8 12% per unit area.

o L_1

+ L_2

• L_3



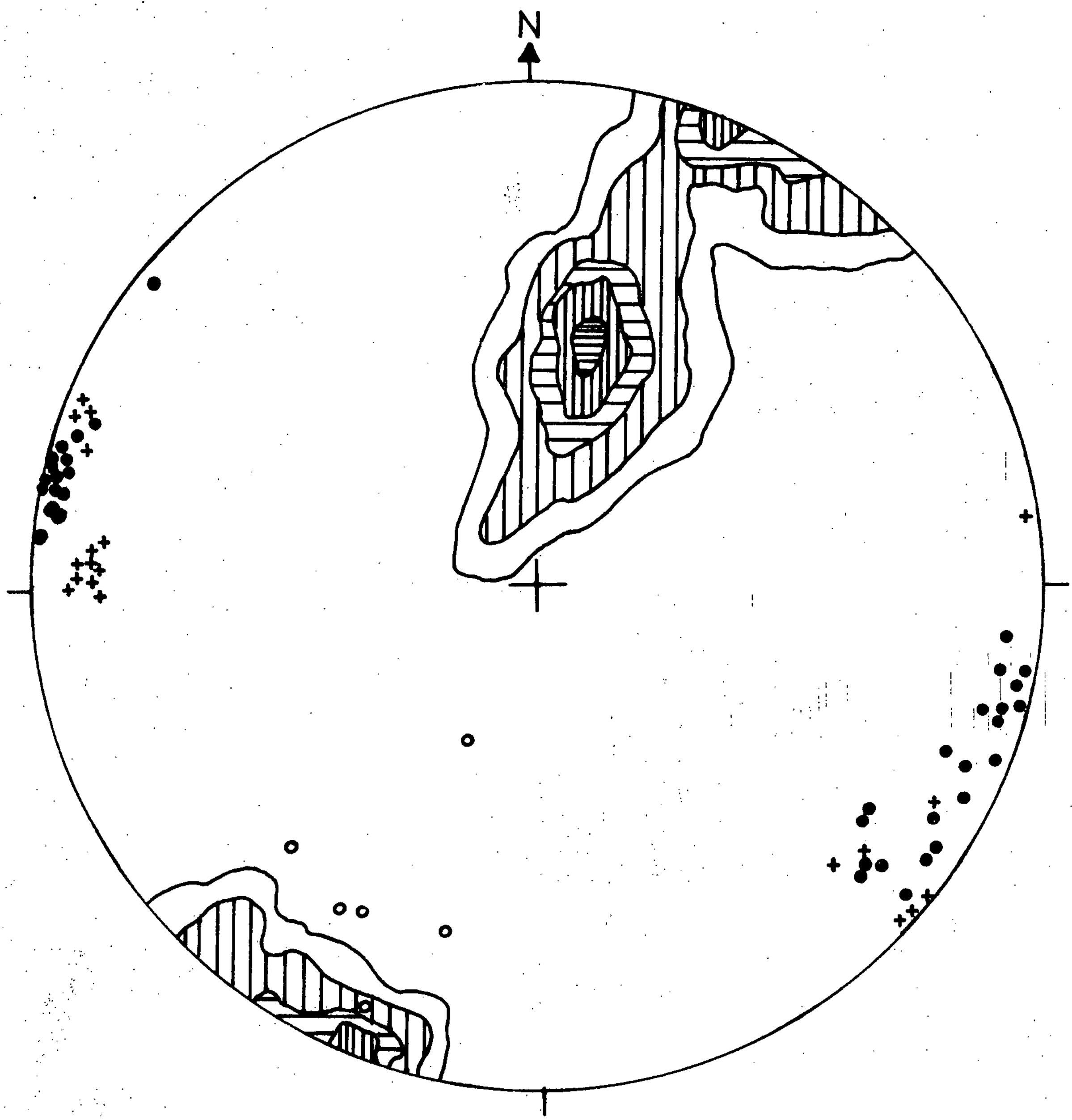
Domain 4

Figure 3-5 48 poles to F_0/F_1 contoured at 1-2-4-8-12% per unit area.

o L_1

+ L_2

• L_3



Domain 5

Figure 3-6 41 poles to F_o/F_1 contoured at 1-2-4-8-12% per unit area.

o L_1

+ L_2

• L_3

structures as a result of later folding may be seen. For the same reason, no inference about the present orientation of bedding may be drawn from the attitudes of compositional layering which are plotted for each domain.

Open phase 4 and 5 folding has also been ignored in the selection of domains and this leads to scattering of data on figures 3-2 to 3-10. Scattered data has been selected from these figures and plotted with synoptic phase 4 and 5 data (figure 14 and 15) to illustrate generally the geometries of phase 4 and 5 folding.

FOLD SETS

PHASE 1

Phase 1 folds are extremely appressed recumbent isoclines found on all scales. Originally they may have been abundant, but now are rare, perhaps because of almost ubiquitous destruction resulting from transposition of compositional layering which outlines phase 1 folds. Where seen, they show all of the features of similar folds and are characterized by sub-rounded to sub-angular northerly trending hinges (plates 3-1, 3-2).

McIntyre Bluff Fold, named for the exposure of its core and hinge near McIntyre Bluff, is a megascopic phase 1 structure which closes to the west and brings about repetition within the succession. The limbs of McIntyre Bluff Fold are isoclinal, and a system of slides developed in the core have caused imbrication and slicing of Units 1-3, in response to extreme attenuation of this structure (plates 1, 2, 5-pocket).

Minor folds are typically rootless cores in an envelope of

Plate 3-1 Northerly trending phase 1 fold in Unit 3 1/4 mile north of McIntyre Canyon.

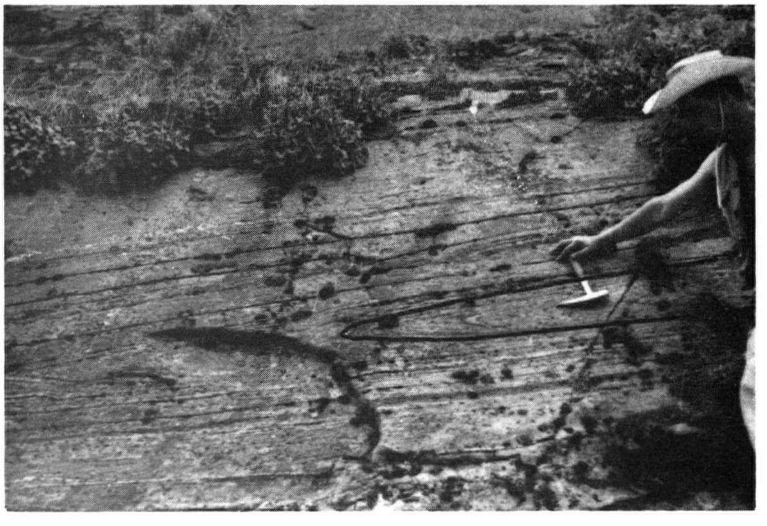


Plate 3-2 Isoclinal phase 1 fold in Unit 3 at Shuttleworth Canyon.

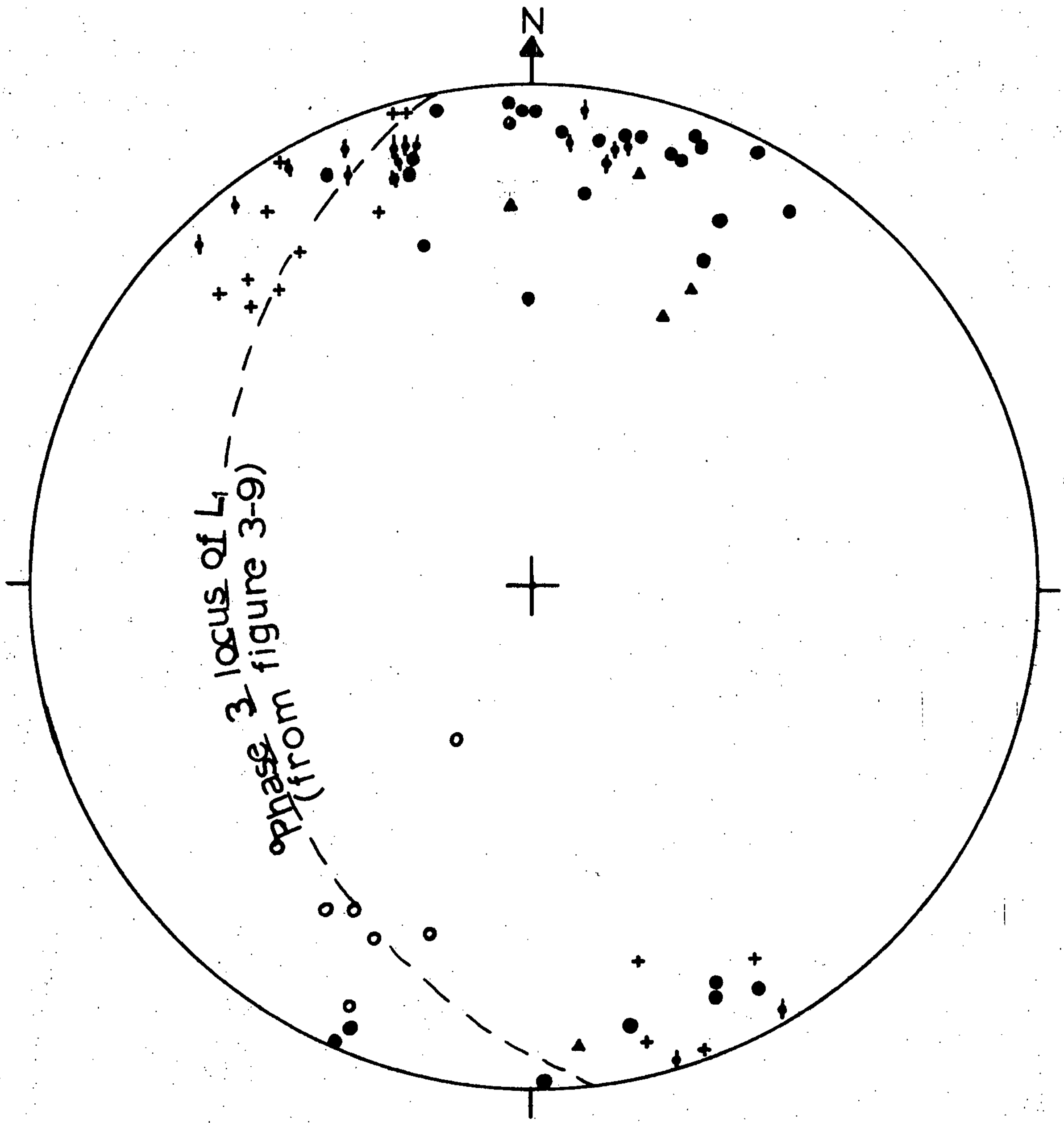


Figure 3-7 Synopsis of phase 1 linear structures.

Lineations L_1 - ▲, ♦, ●, +, o, Domains 1-5 consecutively.

Plate 3-3 Isoclinal phase 1 folds crossed by cleavage F_{3b}. Unit 3 at Shuttleworth Canyon.

Plate 3-4 Northerly trending phase 1 folds deformed about F_2 and crossed by cleavage F_{3a}. Unit 2 south of Shuttleworth Creek.

rock where compositional layering may be almost transposed to the plane of F_1 (plates 3-2, 3-3). Thus F_1 cleavage which is extremely well developed cannot always be readily separated from compositional layering (F_o) other than on the hinges of relict folds. Lineations L_1 include elongate mineral grains and aggregates, crenulations and intersection structures. These also are recognized mainly in proximity to relict phase 1 cores, having been obliterated elsewhere by ensuing deformation and recrystallization.

Despite destruction and obliteration of phase 1 structures as a result of later deformation and metamorphism, enough data has been obtained to outline roughly the geometric re-orientation of phase 1 structures resulting from re-folding. Obvious effects are seen where the limbs and axial planes of mesoscopic phase 1 folds are deformed about phase 2 and phase 3 axial surfaces (plates 3-4 to 3-6). Similar relationships exist on a larger scale (plate 5-pocket) and have been recognized by mapping and observation of a systematic change in the orientation of L_1 across the hinges of some major folds (figure 3-7, plate 2-pocket).

In general L_1 trends west of north on inverse limbs of phase 2 folds and north to northeast on upright limbs, but this is not entirely evident on figure 3-7 which is a plot of all measured L_1 data. Some ambiguity stems from the fact that domain 2 contains a phase 2 antiformal hinge, and large phase 2 folds probably also exist within domain 1 (plate 2-pocket). The linear structure L_1 has been measured on both limbs of these folds.

Curvilinear phase 1 fold axes (plates 3-7 and 3-8) must also be responsible for some of the diversity in trend of L_1 seen on figure 3-7. Curved axes probably developed as phase 1 folds were

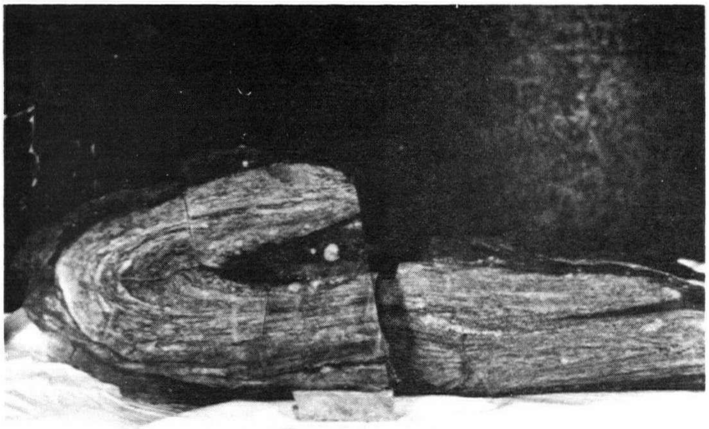


Plate 3-5 Northerly trending phase 1 folds outlined by early granitoid material in Unit 2 and re-folded about F_2. South of Shuttleworth Creek.

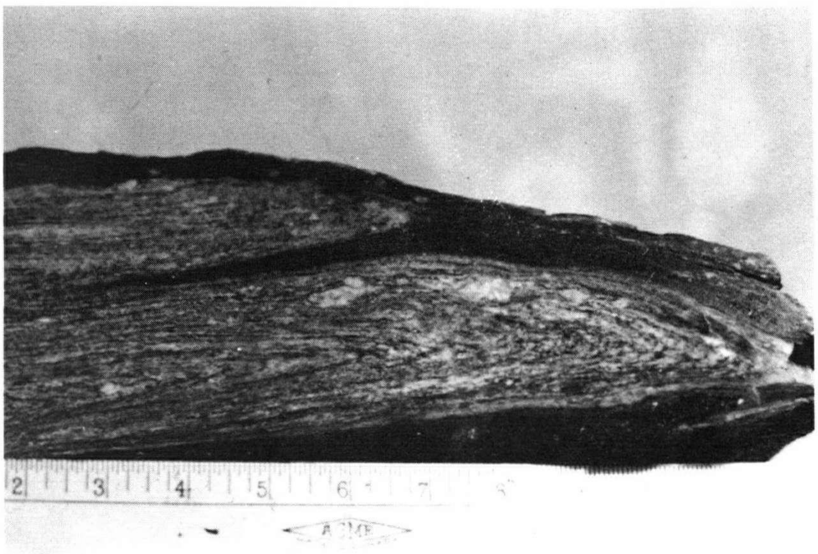


Plate 3-6 Detail of above phase 1 hinge zones.

Plate 3-7 Phase 1 folds with curvilinear axes exposed on northerly trending J_1 joint surface, and crossed by later cleavages F_{3a}, F_{3b}, and fractures J_2.

Plate 3-8 Phase 1 fold with curvilinear axis exposed on an almost planar northerly trending surface. Later cleavages F_{3a}, F_{3b}, and fractures J_2 are shown. Western end of Shuttleworth Canyon near Oliver Ranch.

tightened in later phases of deformation. In becoming tightly appressed, any differential movement of remobilized core material within the plane of F_1 could easily give rise to the curvature.

Variation in the trend of L_1 resulting from phase 3 folding is not well known because of limited exposure and obliteration of L_1 on inverted phase 3 limbs. With respect to Gallagher Lake Synform (phase 3), L_1 ranges from northnorthwest to northnortheast on the lower limb because of phase 2 re-folding, and appears to change from a northnorthwesterly trend in domain 4 to a southsouthwesterly trend in domain 5 across the hinge (compare domains 4 and 5 and see figure 3-9).

The orientation of L_1 has been further modified by late flexural-slip folding. Phase 4 folding along northerly axes broadly parallel to L_1 has had less effect than phase 5 folding along oblique trends. Phase 5 has brought about gentle culmination and depression of L_1 across the hinges of antiformal and synformal folds, and therefore is responsible for much of the variation in plunge angle seen on figure 3-7.

PHASE 2

Phase 2 folds are similar in style and are abundant on all scales. In many structural positions these are tight recumbent folds but are usually more open than the isoclinal phase 1 structures.

Megascopic phase 2 folds with amplitudes of 7-8 miles dominate the local structure and include Vaseaux Lake Antiform, Shuttleworth Creek Synform, and a third poorly exposed antiform in domain 2, and probably part of the same antiform and complimentary overlying synform in domain 1 which have been offset

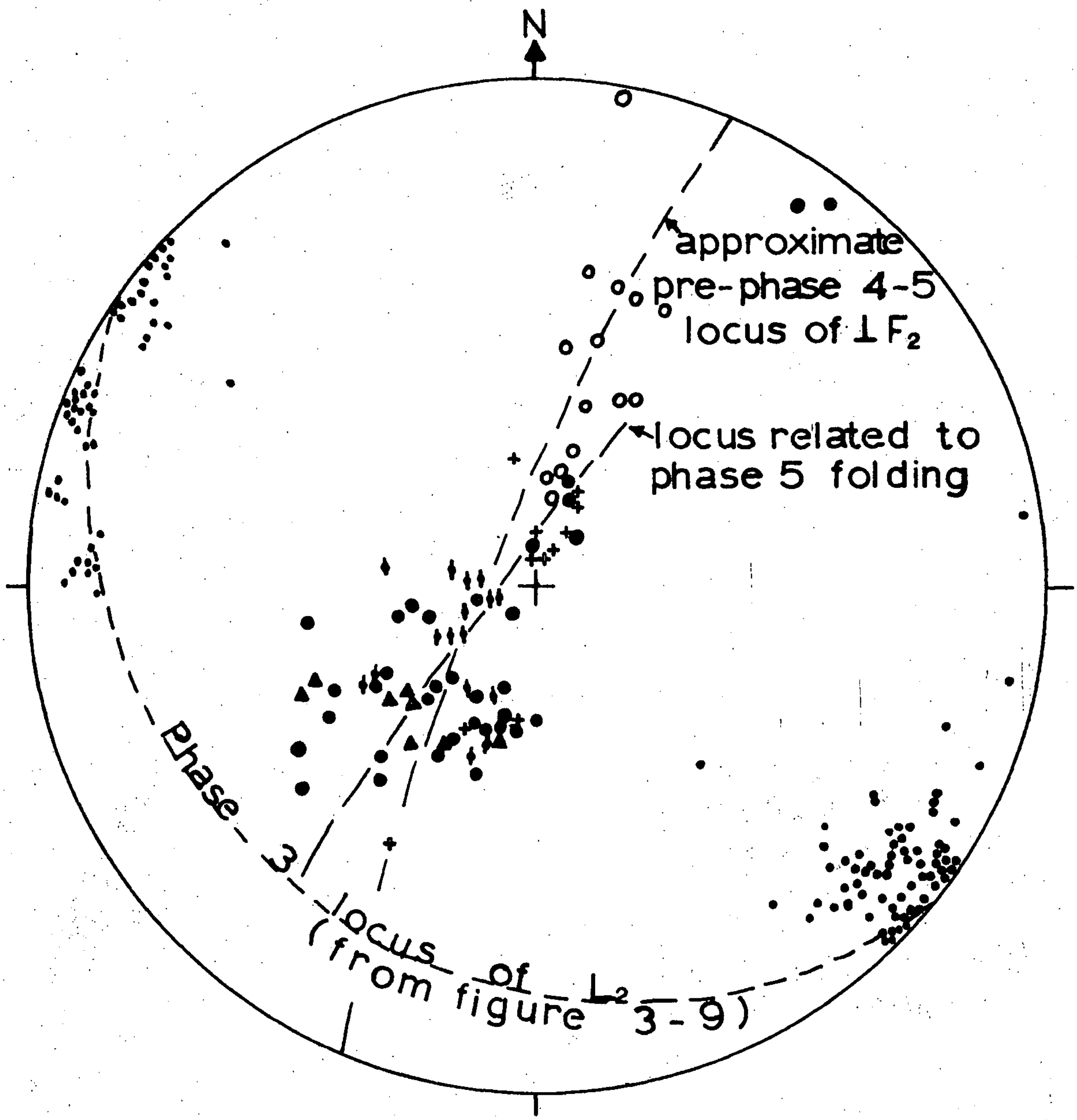


Figure 3-8 Synopsis of phase 2 structures.

Linear structures L_2 - • - all domains

Poles to F_2 cleavage and minor fold axial planes - ▲, ⫯, ●, +, ∘, - in domains 1 - 5 consecutively.

by movement on a phase 3 slide (plates 1-2-5-6-pocket). These major folds are formed about northwesterly trending axes, and their axial planes dip variably but seldom steeply northeast and southwest as a consequence of later folding. Axial plane cleavage F_2 outlined by mica and flattened mineral aggregates is extremely penetrative and forms a small angle with compositional layering on their limbs. Hinges are sub-rounded to angular, and the limbs of the major folds are curviplanar and almost isoclinal.

Phase 2 minor folds are congruent with the major structures, and feature small but measurable angles between their limbs (plate 3-9). These minor folds may be either autochthonous or rootless interfolial folds in most rock types, but within semi-pelitic rocks and schist they are nearly always rootless, and may be isoclinal.

Linear structures L_2 associated with phase 2 folding consist of elongate mineral grains, quartz rods, and the axes of small folds, crenulations, and intersection structures all of which parallel the megascopic axes.

Re-folding of phase 2 structures along phase 3 axes has taken place on all scales. Among major structures, re-folding of Vaseaux Lake Antiform about the axial plane of phase 3 Gallagher Lake Synform is best known (plates 1 and 5-pocket), and mesoscopic examples are numerous (plate 3-10).

Megascopic phase 3 re-folding has also had the effect of tightening phase 2 folds about their original axes, by flattening and remobilizing rocks within their cores. Slides have developed and rocks of Units 3 and 4 for example, are highly sheared in the core of the Vaseaux Lake Antiform as seen in roadcuts east of Vaseaux Lake. Gneissic structure is extremely well developed and

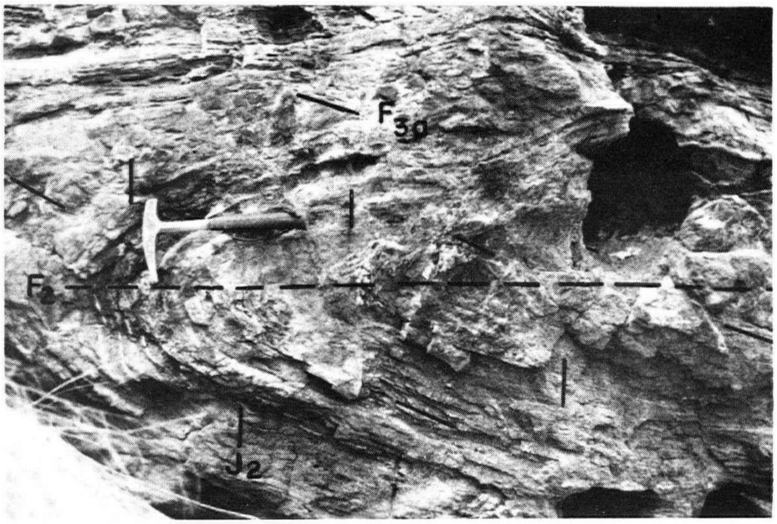


Plate 3-9 Northwesterly trending phase 2 fold crosscut by cleavage F_{3a} and fractures J_2. Unit 3 Shuttleworth Canyon.

Plate 3-10 Phase 2 folds outlined by sheared pegmatite in Unit 2 and re-folded about F_{3a}.

minor folds are tightly appressed. In some instances phase 2 minor folds form rootless cores which have moved en-masse away from the hinge of Gallagher Lake Synform (plates 3-11 and 3-12). There and elsewhere, phase 2 folds have developed curved axes in response to this tightening (plates 3-13 and 3-14), and in some instances phase 2 folds are re-folded about almost parallel axes as a result of local reversals in shear direction on their limbs.

Re-orientation of phase 2 structures as a result of phase 3 and later folding is also evident of stereographic plots. Poles to F_2, plotted for each domain, are shown on figure 3-8 where they are scattered along a broad northeast-southwest trending zone which represents the combined effects of all later folding. The locus of poles to deformed F_2 is no longer a simple great circle, although phase 3 folding may have given a cylindroidal geometry (figure 3-9). The locus has been modified to its present form by open flexural-slip folding during phases 4 and 5. The average locus related to northwesterly trending phase 5 folds is shown on figure 3-8. This locus is not well defined because poles to F_2 were previously spread along an almost perpendicular locus related to northerly trending phase 4 folding.

On figure 3-8 domains 1-4 represent the lower limb, and domain 5 the inverted limb of Gallagher Lake Synform (phase 3). In terms of the orientation of F_2, domains 1-4 were likely homogenous after phase 3, and an average F_2 pole from these domains compared with an average from domain 5 would give an approximate locus representing the deformation of F_2 during phase 3. This approximation has been made on figure 3-8 and is significant in that the pre-phase 3 orientation of F_2 must be represented by a pole lying on or close to this locus, and its angle of dip must have been somewhat steeper

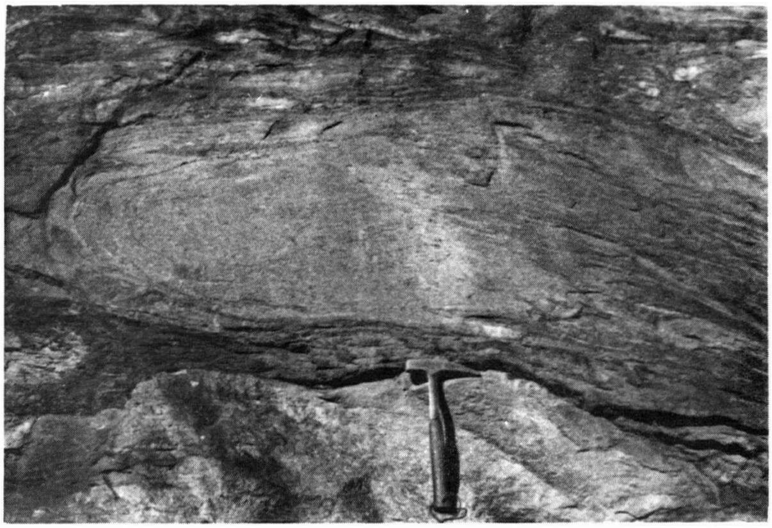


Plate 3-11 Mobilized phase 2 hinge in core of Vaseaux Lake Antiform.

Plate 3-12 Mobilized phase 2 hinge in core of Vaseaux Lake Antiform.

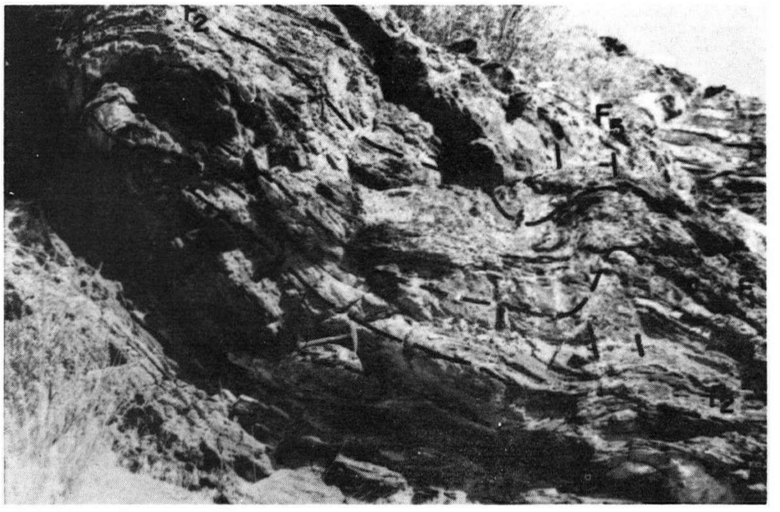


Plate 3-13 Phase 1 folds re-folded by a phase 2 antiform which has a curvilinear axis. L_2 trends almost perpendicular to plane of photograph in upper left but is almost parallel at lower center.

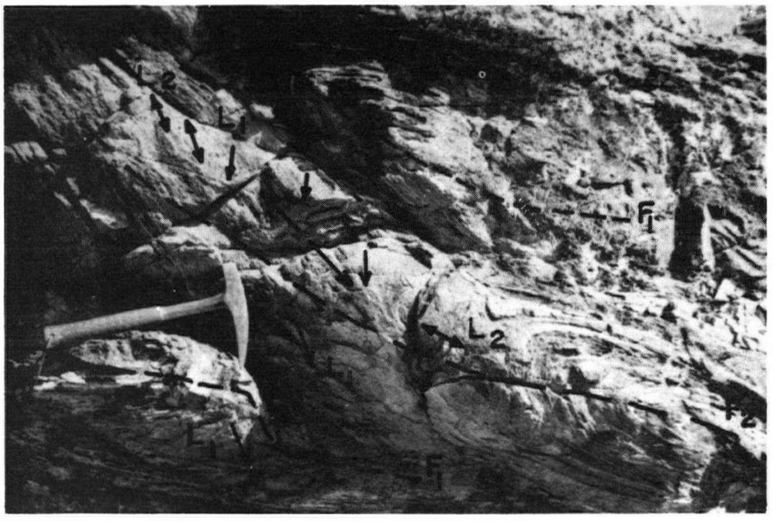


Plate 3-14 Detail from above showing curvilinear L_2, northerly trending phase 1 hinges and deformed L_1. Unit 4b Oliver Ranch south of Shuttleworth Creek.

than on the present phase 3 lower limb. From this it may be concluded that prior to phase 3, F_2 was inclined at some moderate angle to the northeast.

Linear structures L_2, also plotted on figure 3-8, are shown deformed along a great circle locus. Relationships are somewhat confused because of the regional culmination and depression of L_2 produced during northerly phase 4 folding with respective northwesterly and southeasterly plunges of L_2 coinciding with the dip directions of phase 4 limbs.

Actually in many parts of the map-area, phase 2, 3 and 5 axes are almost parallel, and re-folding during the later of these specific phases has not profoundly changed the orientation of earlier linear structures. Linear structures L_2, L_3 and L_5 are now all horizontal or sub-horizontal structures and have probably always been so.

Since L_2 was originally a nearly horizontal structure it may be further argued that phase 1 folds may have been originally recumbent folds. This follows from the facts that L_2 is defined by the intersection between planar structures F_2 and F_o/F_1 and that linear structures L_2 and L_1 make rather large angles with each other. The original dip component of F_1 along the intersection direction L_2 may therefore have been small, and the dip angle of F_1 may not have been much greater than the original plunge of L_2. An unknown amount of intense flattening about F_2/L_2 during phase 2 or as a result of phase 3 precludes any definite statement about the pre-phase 2 orientation of F_1.

PHASE 3

Phase 3 folds are grouped into subsets 3a, 3b and 3c. This

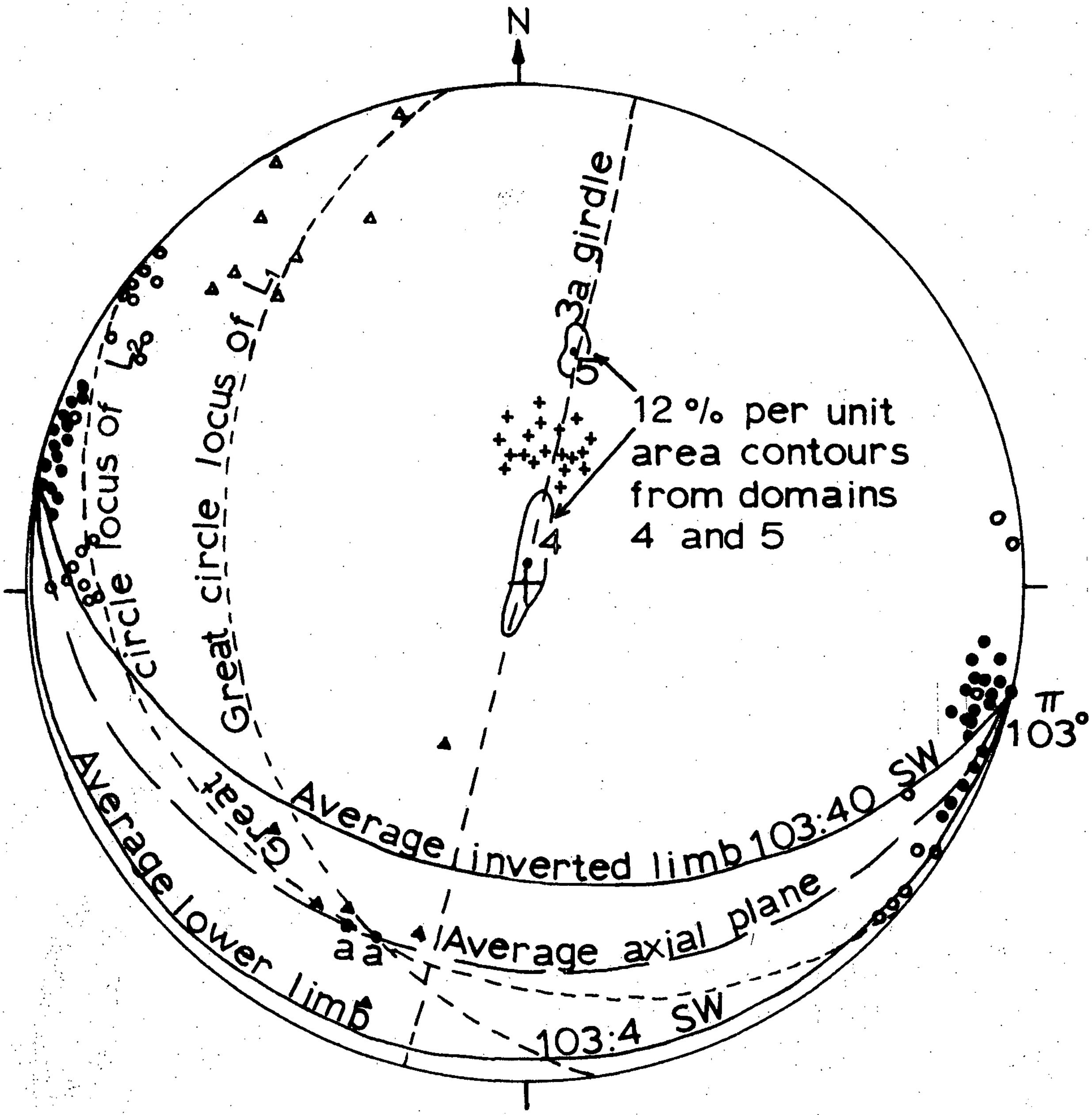


Figure 3-9 Geometry of subset 3a Gallagher Lake Synform in southern part of map-area

+ ⊥ F_3
● L_3
○ L_2
△ L_1 - lower limb
▲ L_1 - inverted limb

order of grouping does not exactly correspond to the relative ages of these structures. It is used as a convenient means of classifying and separating distinctive fold geometries developed at various stages in phase 3 deformation.

Subset 3a

Subset 3a folds include Gallagher Lake Synform, a major southerly closing recumbent structure, and congruent minor folds which are well developed on both limbs. Part of the inverted limb and hinge of Gallagher Lake Synform are exposed in southern parts of the map-area, (plates 1-3-5-pocket) and its geometry there is summarized on figure 3-9. Its axial surface dips southsouthwest at 25°, and contains a near horizontal fold axis trending on the average 103°. Compositional layering dips 4° and 40° southsouthwest on respective average lower and inverted limbs. With the exception of the schists of Unit 2 which form an attenuated wedge on the hinge of the synform, the other map units have attained sub-rounded forms.

Axial plane cleavage F_{3a} is a penetrative structure and a plane of flattening normally outlined by tiny flakes of biotite. The intensity of F_{3a} increases towards the hinge of Gallagher Lake Synform, and within its core and on the inverted limb it becomes extremely penetrative and the rocks are highly fissile within the F_{3a} plane. Associated linear structure L_{3a} include intersection structures, elongate mineral aggregates, the axes of minor folds and crenulations, all of which are parallel with the axis of Gallagher Lake Synform (figure 3-9).

The orientation of L_{3a}, when considered across the entire map-area (plate 3-pocket, figure 3-10) varies moderately from

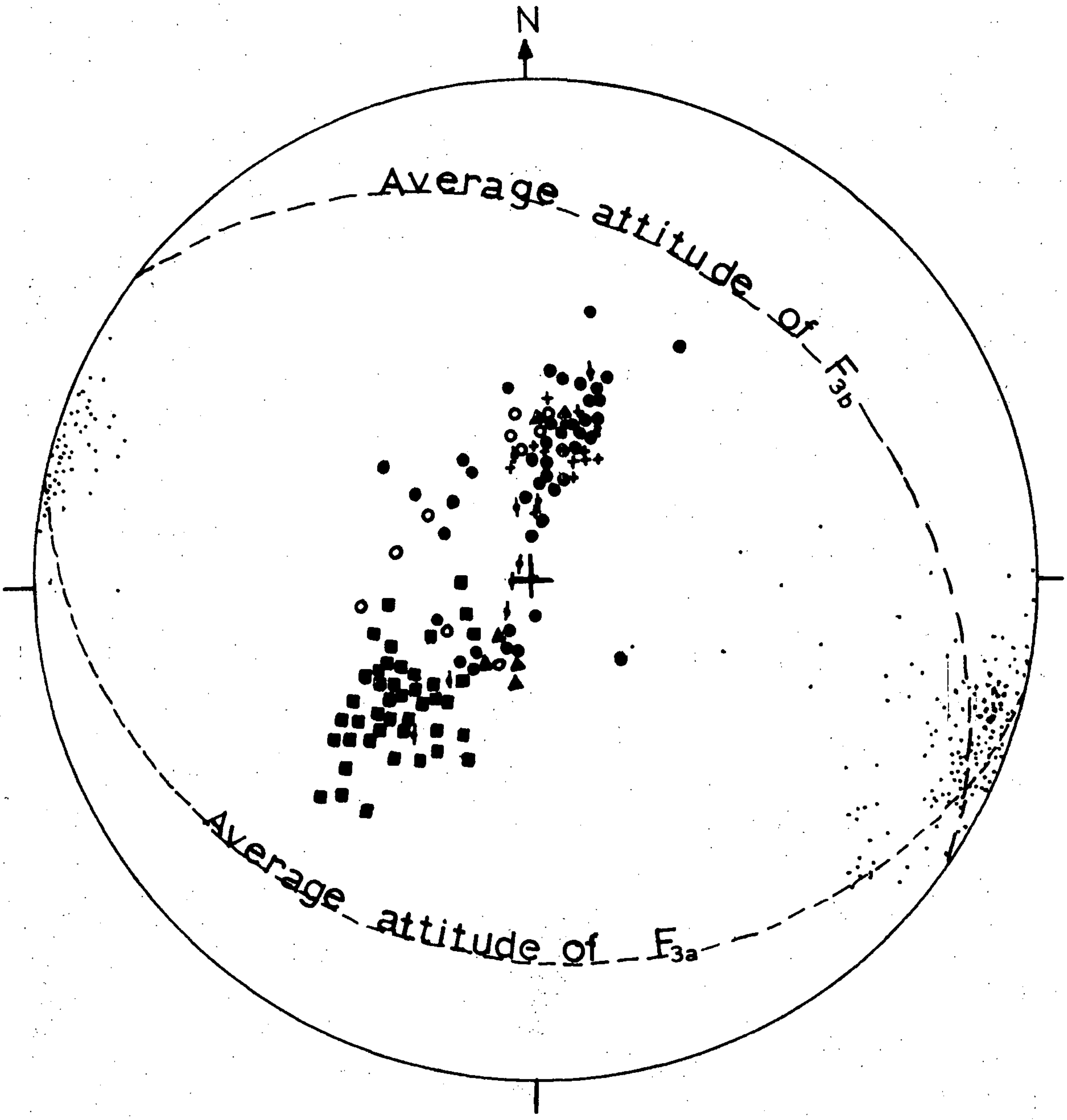


Figure 3-10 Synopsis of subset 3a and 3b structures.

. Lineations L_{3a} and L_{3b}
Poles to F_{3a} cleavage and axial planes - ▲, ⫯, ●, +, ○, - in domains 1-5 consecutively.
▪ Poles to F_{3b} - all domains.

Plate 3-15 Phase 3 fold (subset 3a) viewed from the east. Unit 4a, south of Shuttleworth Creek.

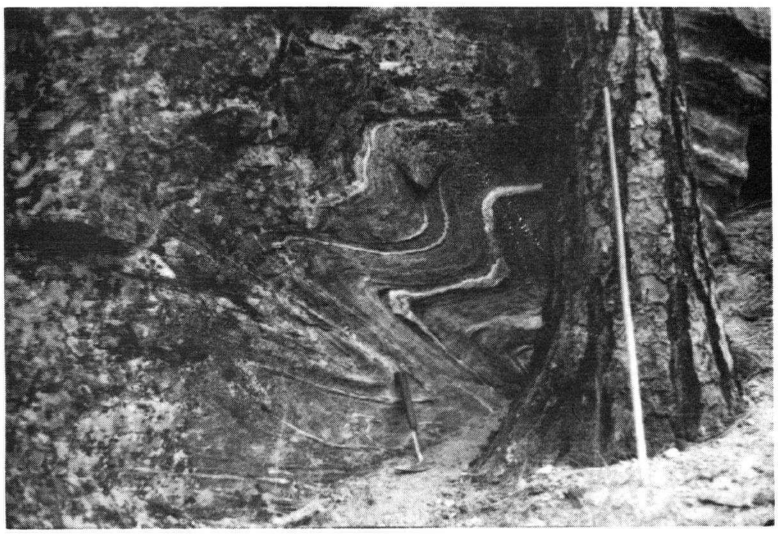


Plate 3-16 Phase 3 folds (subset 3a) viewed from the west. Unit 3 south of McIntyre Canyon near the core of Gallagher Lake Synform.

the trend of Gallagher Lake Synform. Some of this variation may be attributed to the effects of superposition of F_{3a} on the limbs of pre-existent folds which would give rise to variable L_3 intersection directions, and some of the variation is the effect of later folding.

Older linear structures L_1 and L_2 appear to be systematically deformed about L_{3a} as a result of subset 3a folding. Although data is scanty on figure 3-9, and difficult to analyse, both L_1 and L_2 appear to lie along a great circle loci indicating that the folding is probably similar in style (Ramsay 1960). These great circles intersect the axial surface F_{3a} along southsouth-westerly inclined lines (a-kinematic axes) which are approximately normal to L_3. Alternately, since there is also a suggestion of a small circle loci of L_2 and L_3 flexural-slip folding may have been a factor in phase 3 deformation. It is believed that phase 3 folds first may have developed by a mechanism of flexural-slip but continued to develop by a mechanism of similar folding as they became tighter.

Minor folds of subset 3a are abundant in all map units and resemble the major structure in geometry and style. They are congruent with Gallagher Lake Synform and show the same northerly vergence in all positions. Because most of the map-area is underlain by the lower gently dipping limb of the Synform subset 3a folds with the characteristic geometry of this limb position are most abundant. These are relatively open intrafolial and mesoscopic folds essentially of similar style characterized by a planar gently dipping limb, and a steeper southwesterly dipping inverted limb (plates 3-15 to 3-17). Hinges of minor folds are sub-rounded in most rock types but may be angular to sub-angular

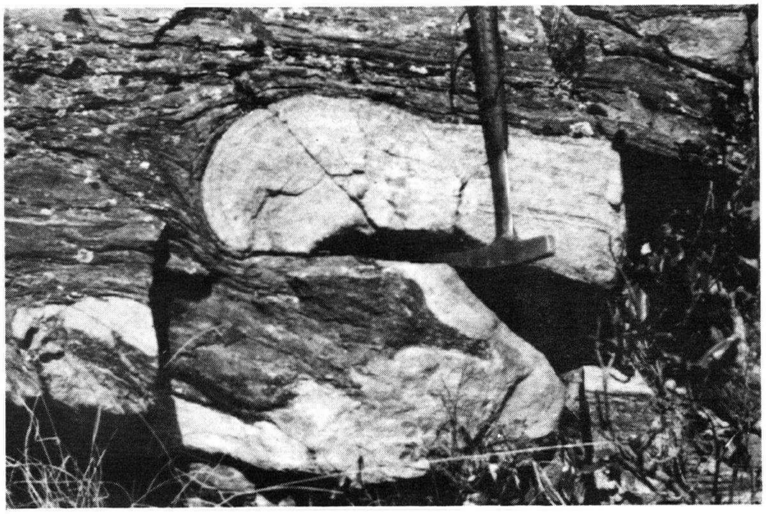


Plate 3-17 Phase 3 folds (subset 3a) viewed from the west. Unit 3 in roadcut near Vaseaux Lake.

Plate 3-18 Phase 3 folds (subset 3a) viewed from the west. Unit 2 east of Vaseaux Lake.

in schist and some semi-pelitic rocks (plates 3-18, 3-19). On the inverted limb of Gallagher Lake Synform and in its core, subset 3a folds are tighter than on the lower limb, and the core structures are much less assymetric than those on either limb.

Subset 3b

Folds of subset 3b are restricted to mesoscopic and microscopic scales, and are believed related in time and space to outward (northerly) movement of a segment within the core of Gallagher Lake Synform along a northerly dipping slide. This slide is marked by a mylonitic zone 40-60 feet or more in thickness which cross-cuts compositional layering and megascopic folds formed during the earlier phase 1 and phase 2 deformations (phase 3 mylonite on plates 1-5-6-pocket). Subset 3b folds are found within and near proximity to the mylonites, and a penetrative cleavage F_{3b} slightly oblique to the slide often forms their axial surface.

The mylonite zone itself, when considered in a regional sense, includes sheared derivatives of most rock types known in the map-area. It also exhibits extreme variation in degree of shearing and groundmass recrystallization from place to place, and many lithologic and textural variations are therefore found within it. Characteristic rocks are well laminated fine grained mylonites ranging in colour through light to very dark grey and brown, often with numerous fine augen of quartz and feldspar. Mylonitized rocks sometimes form anastomosing layers from a few inches to tens of feet thick, between slices of coarser grained augen gneiss and even less sheared and recrystallized wallrock.

Within the mylonites tight isoclinal folds with axial planes

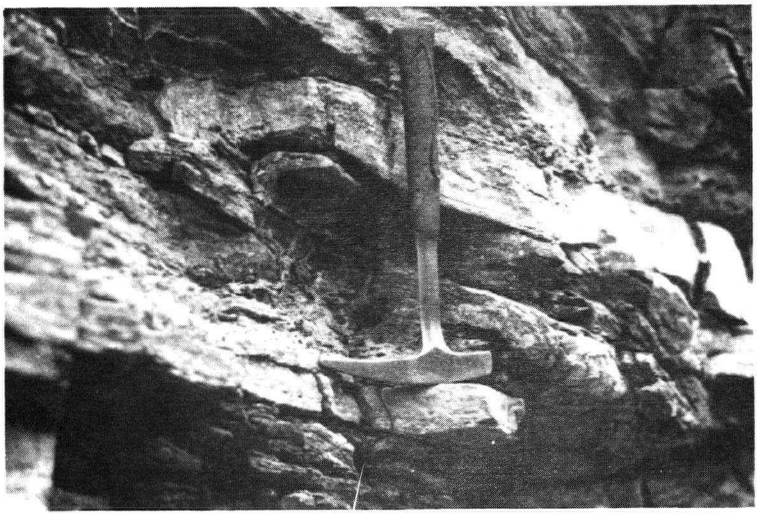


Plate 3-19 Phase 3 folds (subset 3a) viewed from the west. Unit 4a south of Shuttleworth Creek.

Plate 3-20 Open subset 3b flexural-flow folds in mylonitic rocks of Unit 4a. Viewed from the west.

parallel to transposed layering occur. Their vergence is consistent with northerly movement of the hanging-wall (same as Gallagher Lake Synform) and are therefore possibly phase 3 folds formed during mylonitization. Alternatively they may be relict phase 2 folds which survived mylonitization as their vergence is also consistent with an inverted limb position with respect to Shuttleworth Creek Synform (phase 2) at the localities where they have been found. Subset 3b folds refold the isoclinal structure, and their vergence is exactly opposite to that of the isoclinal structure.

Subset 3b folds are often similar in style, but are sometimes better described as flexural-flow folds (Donath and Parker 1964), as they often appear to have been controlled by competent lithologies (plates 3-21). They are co-axial with subset 3a structures, but verge in an opposite (southwesterly) direction about axial planes inclined to the northeast (plate 3-pocket, figure 3-10).

Strain-slip cleavage F_{3b} may or may not be well developed in proximity to subset 3b folds within mylonites, and is even less intense in other parts of the map-area. It is not uniformly developed, but appears from place to place as a spaced strain-slip cleavage and gives rise to weak crenulation structures.

Subset 3c

Members of a third set of minor folds related to phase 3 deformation also occur within the mylonitic zone and these in many ways resemble subset 3b structures. They are flexural-flow folds (Donath and Parker 1964) outlined by lithologies which appear to have been the more competent at the time of deformation. Subset 3c folds diminish rapidly in amplitude both up and down their axial

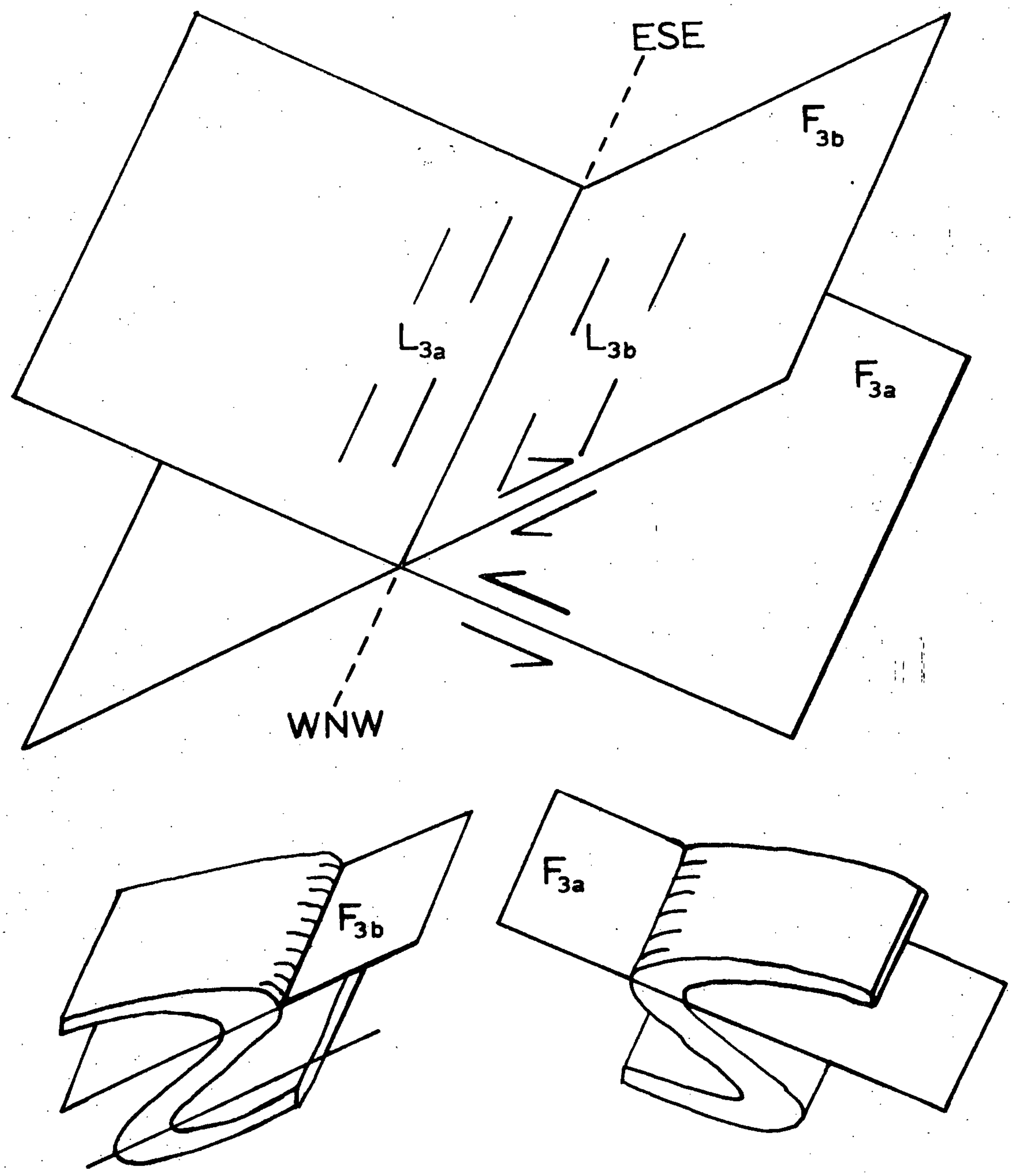
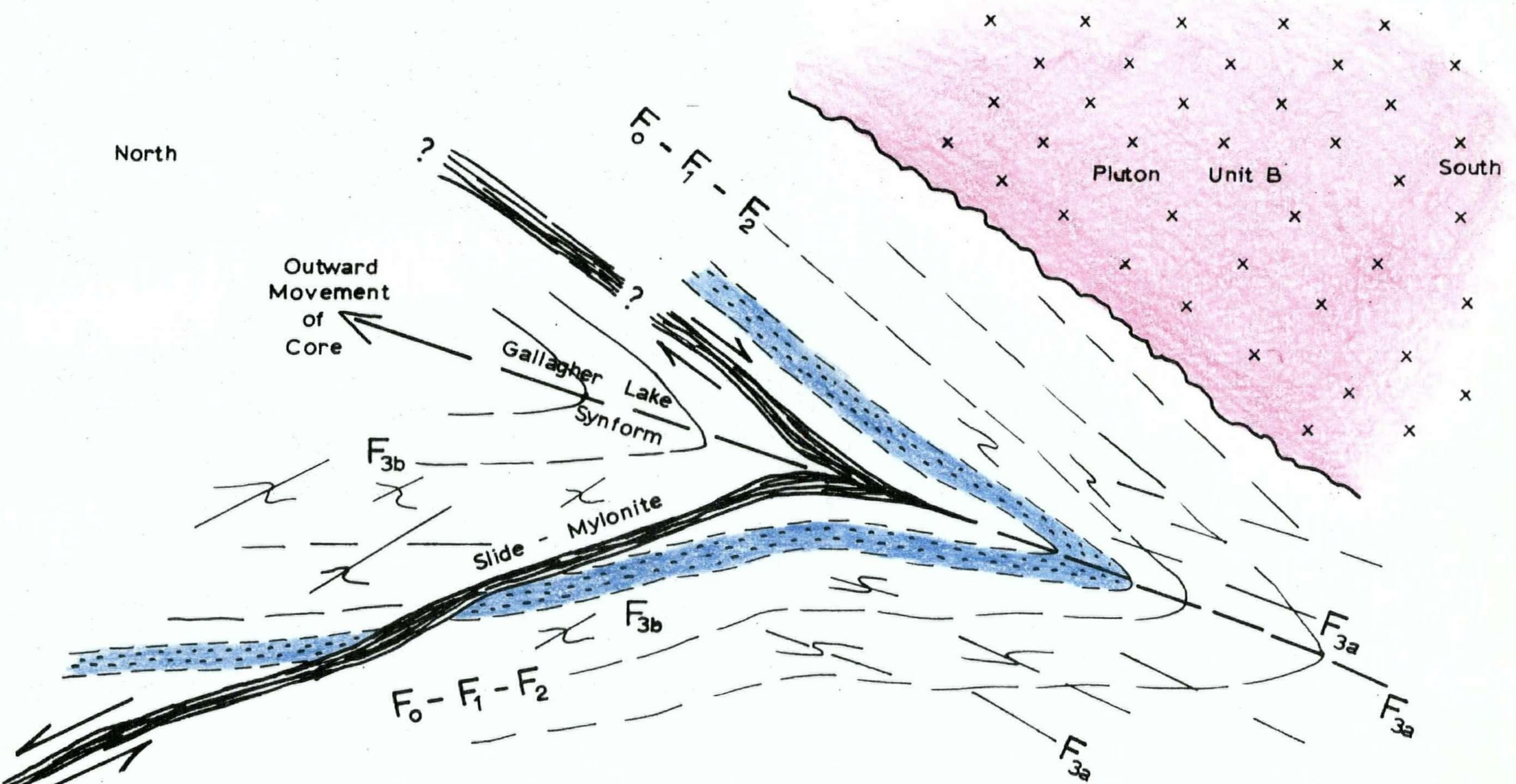


Figure 3-11 Vergence and conjugate relationships between subset 3a and 3b structures.



<u>Figure 3-12</u> Schematic Cross-Section Illustrating Relationships Between Subset 3a & 3b Folds, the Slide and a Pluton (Unit B).

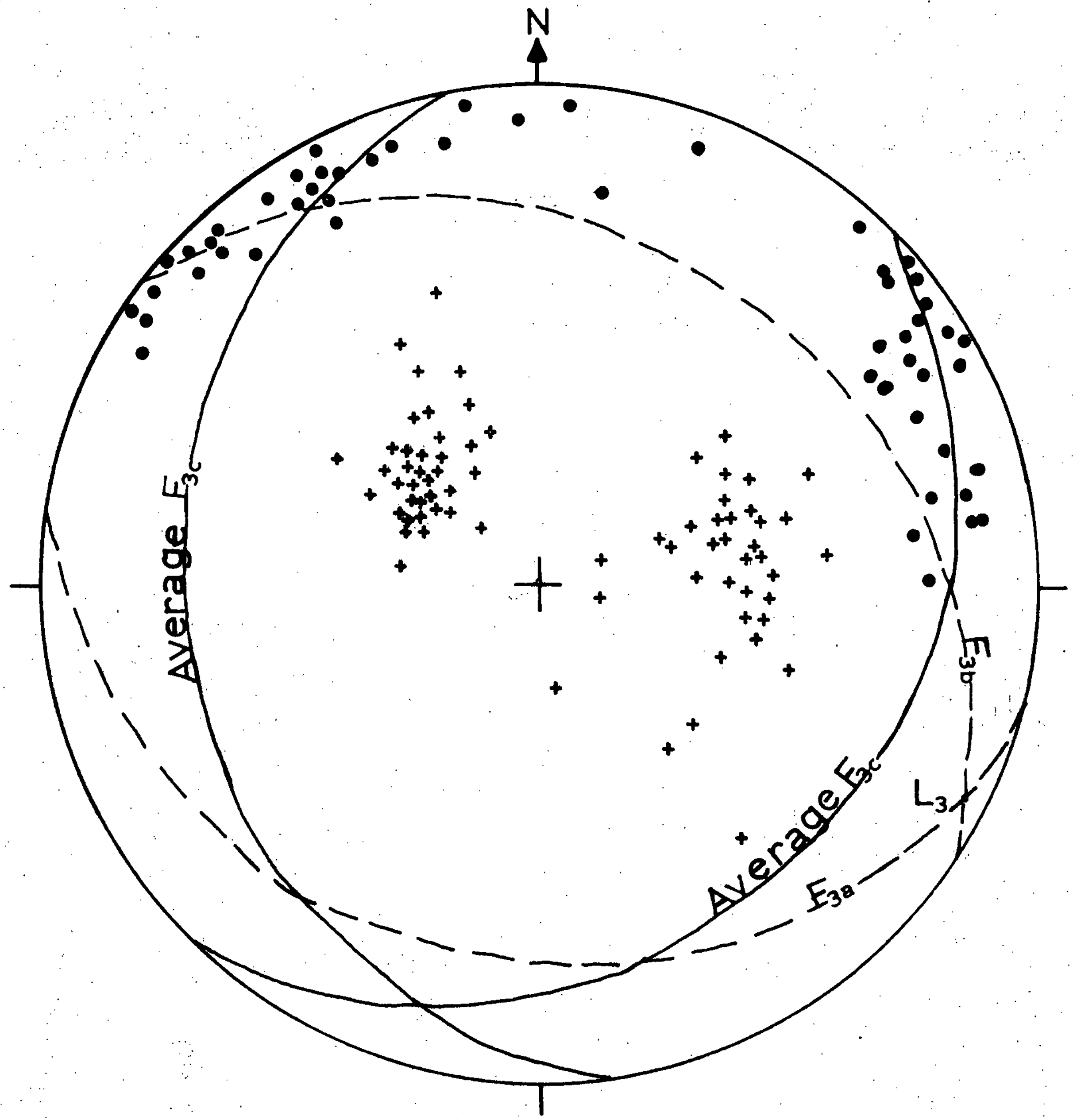


Figure 3-13 Subset 3c structures compared to the geometry of subsets 3a and 3b.

+ ⊥ axial planes of subset 3c folds.
• subset 3c fold axes.

surfaces and die out on passing into more highly sheared lithologies. In most instances subset 3c folds are rooted in these sheared materials which appear to have been simply injected into their cores.

Subset 3c folds are formed along highly variable northeasterly and northwesterly trends (figure 3-13) and occur as single folds and in conjugate arrangements (plate 3-22). As a whole, the orientations of these folds are broadly consistent with a conjugate pattern, but do not relate in any obvious way to the geometry of phase 3.

Relationships between Subsets 3a, 3b and 3c folds

Subset 3a and 3b folds, as illustrated on figures 3-10 and 3-11, appear to be a conjugate fold set developed about strain-slip cleavages F_{3a} and F_{3b}. Of the two, F_{3a} is by far the best and most uniformly developed and is the dominant structural element of phase 3 deformation. The cleavage F_{3a} probably originated as a strain-slip structure and continued to localize componential movements throughout phase 3 deformation. It also acted as a plane of flattening in the later stages of phase 3 deformation, and movement on F_{3a} probably outlasted significant movement on F_{3b}, although locally F_{3b} has produced weak crenulation across subset 3a folds.

The cleavage F_{3b} is thought to have developed at an intermediate stage in phase 3 deformation, perhaps as the style of deformation changed from flexural-slip to similar folding. This would be the time when the slide bounded wedge began to move out of the core of Gallagher Lake Synform and mylonite was formed. Resistance to this northerly motion may have given rise to the

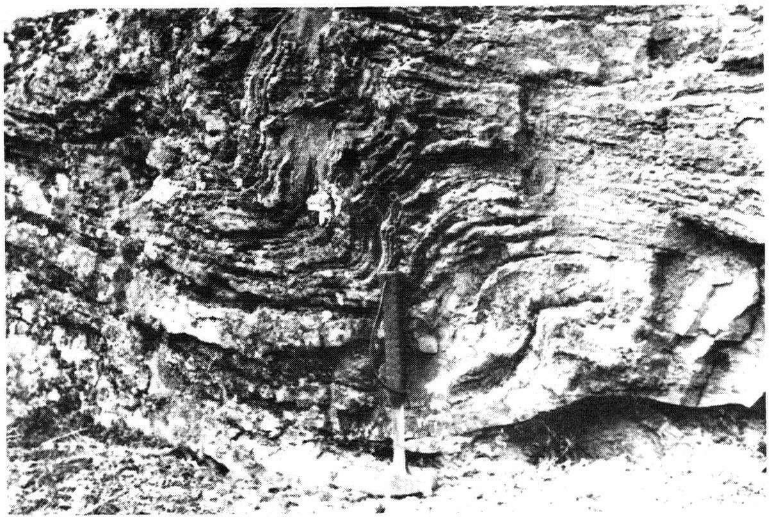


Plate 3-21 Phase 3 folds (subset 3b) within mylonite north of Shuttleworth Creek. Viewed from the east.

Plate 3-22 Phase 3 folds (subset 3c) developed about conjugate axial surfaces.

cleavage F_{3b} as well as the southwesterly verging flexural-flow folds of subset 3b (figure 3-12). Subset 3c folds were probably formed at about the same time and may owe their origin to lateral restriction within the developing mylonites. As shown on figure 3-13, subset 3c geometry does not directly relate to the overall phase 3 geometry, and cannot therefore reflect the mean strain which occurred within the mylonite zone.

After the mylonites were developed, and movement on the slide had ceased, phase 3 deformation continued by movement parallel to F_{3a}. The passive mylonite zone became deformed into open subset 3a folds, and the penetrative cleavage F_{3a} was developed across it.

The reason for the change in style of deformation during phase 3, and the continued development of F_{3a} after other movements had ceased is not known, but a tentative explanation is given in Chapters 4 and 5. Simply stated, the forceful emplacement of a synkinematic pluton (Unit B) along the inverted limb of Gallagher Lake Synform appears to have been in part responsible for the continued development of F_{3a}, and may have also brought about a change in style of deformation by changing the P/T environment (figure 3-12).

PHASE 4

Total geometry of phase 4 folding is not known. The hinge and parts of the limbs of a single megascopic antiform are seen within the map-area, and parasitic minor folds are rare. The major antiform is outlined by compositional layering and culminates east of Vaseaux Lake along a northerly trending axis which is poorly defined because of interference with later phase 5 folds (plate 4-pocket). The hinge and limbs are rounded (plate 6-pocket) and the style of folding is flexural-slip. Shear parallel to older foliations F_o/F_1 and F_2, is characteristic of phase 4 deformation and narrow zones of dark mylonite have formed along re-activated surfaces. Phase 3 structures are offset, micas are sheeted, and trains of granulated mineral fragments are drawn out in an east-west direction approximately normal to the phase 4 fold axis.

Minor folds are occasionally developed along phase 4 directions (plate 4-pocket, figure 3-14) and these include open flexures and crenulation structures. Crenulations in particular are associated within closely spaced fractures (J_1) in an axial plane orientation.

Variation in the orientation of J_1 throughout the area is shown on plate 4 (pocket) and is plotted on figure 3-14 where J_1 superficially appears to be a fanned fracture cleavage. However, field relationships are not always consistent with this interpretation under a hypothesis of flexural-slip folding, because at many localities two independent steeply dipping fracture sets are developed and are perhaps better termed ab joints.

Maximum development of J_1 fractures near the hinge of the major antiform indicates that J_1 fracturing may have served as a release mechanism within the core zone as folding progressed. They may or may not be exactly parallel to the phase 4 axial plane. Since the exact trend of phase 4 folding is not known these J_1 fractures might conceivably be an oblique set of shear fractures related to failure at the final stage of phase 4 folding.

In either case, J_1 fractures are the earliest post phase 3 fracture set, and the only fractures which have consistently

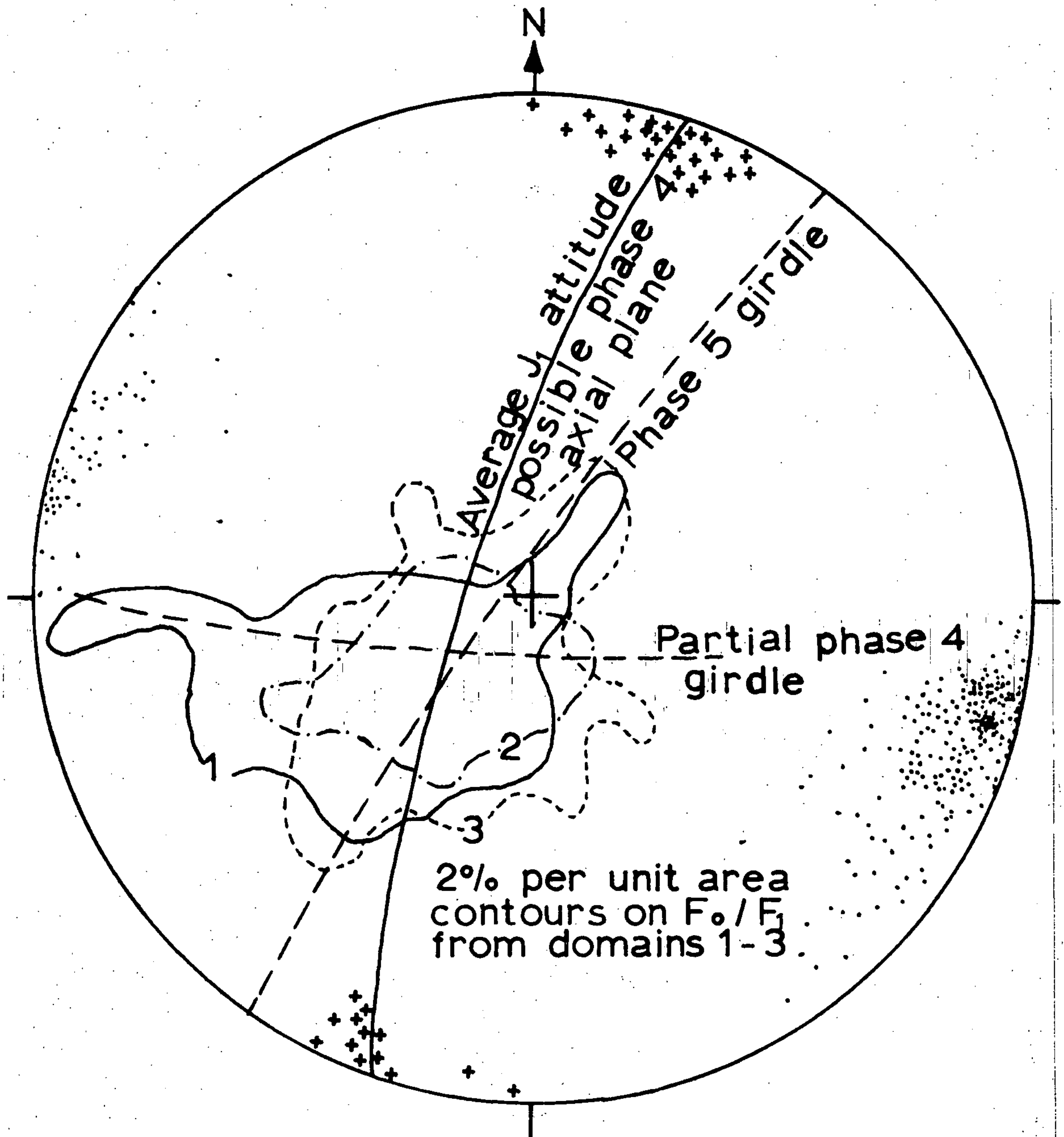


Figure 3-14 Synopsis of phase 4 structures.

· ⊥ J_1 fractures
\+ axes of minor folds and crenulations.

localized hydrothermal deposition of quartz, epidote, sericite, and chlorite. Frequently slickensides are developed in these hydrothermal materials providing evidence of re-activation, and this is discussed more fully in Chapter 5.

PHASE 5

Phase 5 folds outlined by compositional layering, are found on all scales and are typically of flexural-slip style. These are northwesterly trending, gently plunging flexures and include a broad antiformal structure culminating in the vicinity of Vaseaux Lake, and a complimentary synform (Church 1967, Okanagan Falls Syncline) which is hinged just north of the map-area (plate 4 and 5-pocket). Minor folds on several scales are fairly abundant on the gently rounded hinges and limbs of the major structures. Phase 5 folds are open structures developed about steeply dipping planes, and poles to compositional layering are weakly spread along a great circle locus (figure 3-15) as a result of the folding.

Fracture set J_2 appears to be associated with phase 5 folding in much the same way as J_1 fractures are related to phase 4. These J_2 fractures vary considerably in attitude from one exposure to the next (figure 3-15 and plate 4-pocket) and may actually consist of 2 or more individual sets. At some localities these are closely spaced and bear an axial plane relationship to minor folds and crenulations (figure 3-16), but elsewhere they are a joint set approximately parallel to the trend of phase 4. It therefore does not appear that all J_2 fractures are axial plane cleavage, but they do seem to be planes of failure related to phase 5 folding. These J_2 fractures are illustrated on a number

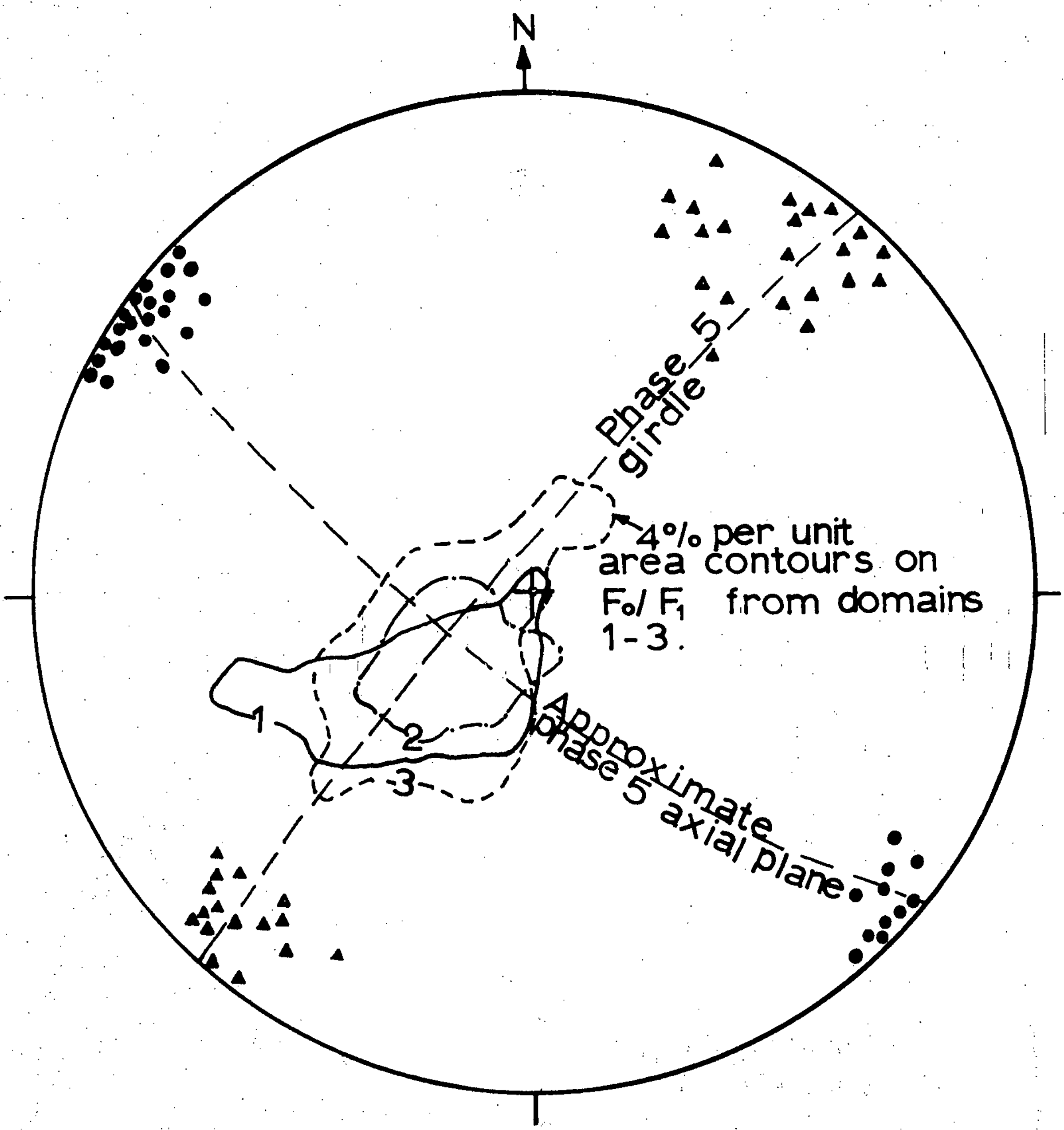


Figure 3-15 Synopsis of phase 5 structures.

▲ ⊥ J_2 fractures
● axes of minor folds.

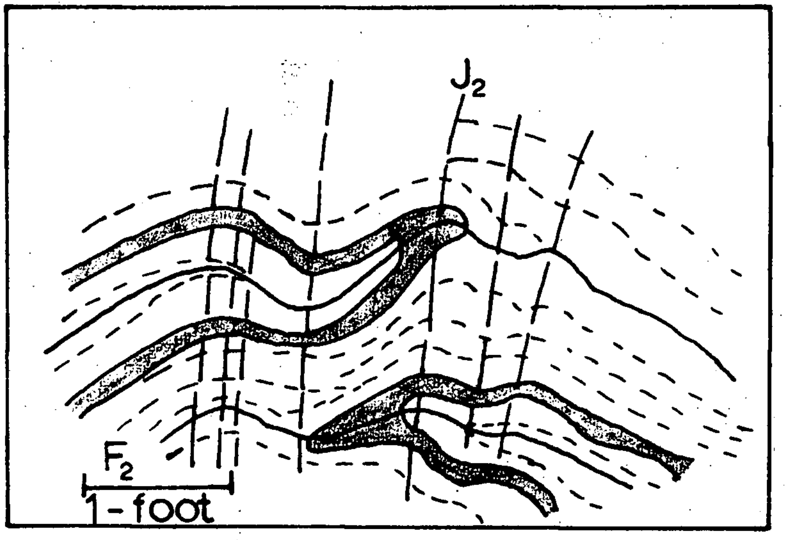


Figure 3-16 Phase 5 folds with fractures J_2 in axial plane orientation. Unit 2 south of Shuttleworth Creek (sketched from photograph).

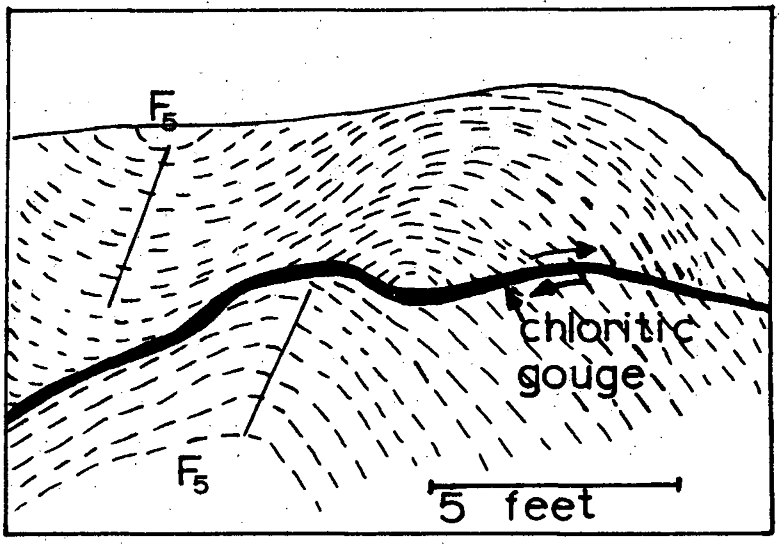


Figure 3-17 Break thrusts associated with phase 5 minor folds viewed from the east (sketched from photograph).

of preceding photographs.

Evidence of slip within the plane of compositional layering, normally expected in association with flexural-slip folding, is abundant, especially where phase 5 minor folds are developed. Gouge filled break thrusts (figure 3-17) and limb shears are very common, and fractures of set J_1 are offset against these younger shear surfaces.

Faulting related to Phase 5

Faulting was an integral part of phase 5 deformation, and apparently facilitated the development to folds by separating blocks then able to buckle independently. This faulting may have proceeded by development of a new set of fractures (J_3), and reactivation of earlier J_1 fractures which happened to be in a convenient orientation to allow buckling. Among the innumerable fractures developed only a few show appreciable offsets, and these are the faults shown on accompanying maps.

None of the faults are well exposed as they underlie linear topographic depressions filled with talus and glacial debris. Adjacent closely spaced fractures show occasional slickensides but little or no offset, and it appears that most of the movement occurred along a central fracture. Slickensides pitch from 0°-90° within these surfaces at different localities, and this pattern is probably consistent with the sort of movements which took place as folding progressed.

To further illustrate the nature of phase 5 deformation elaboration on the environment, and pre-existing geometry of the rocks is useful. At the time of deformation the rocks were brittle, near surface and had previously been deformed into a

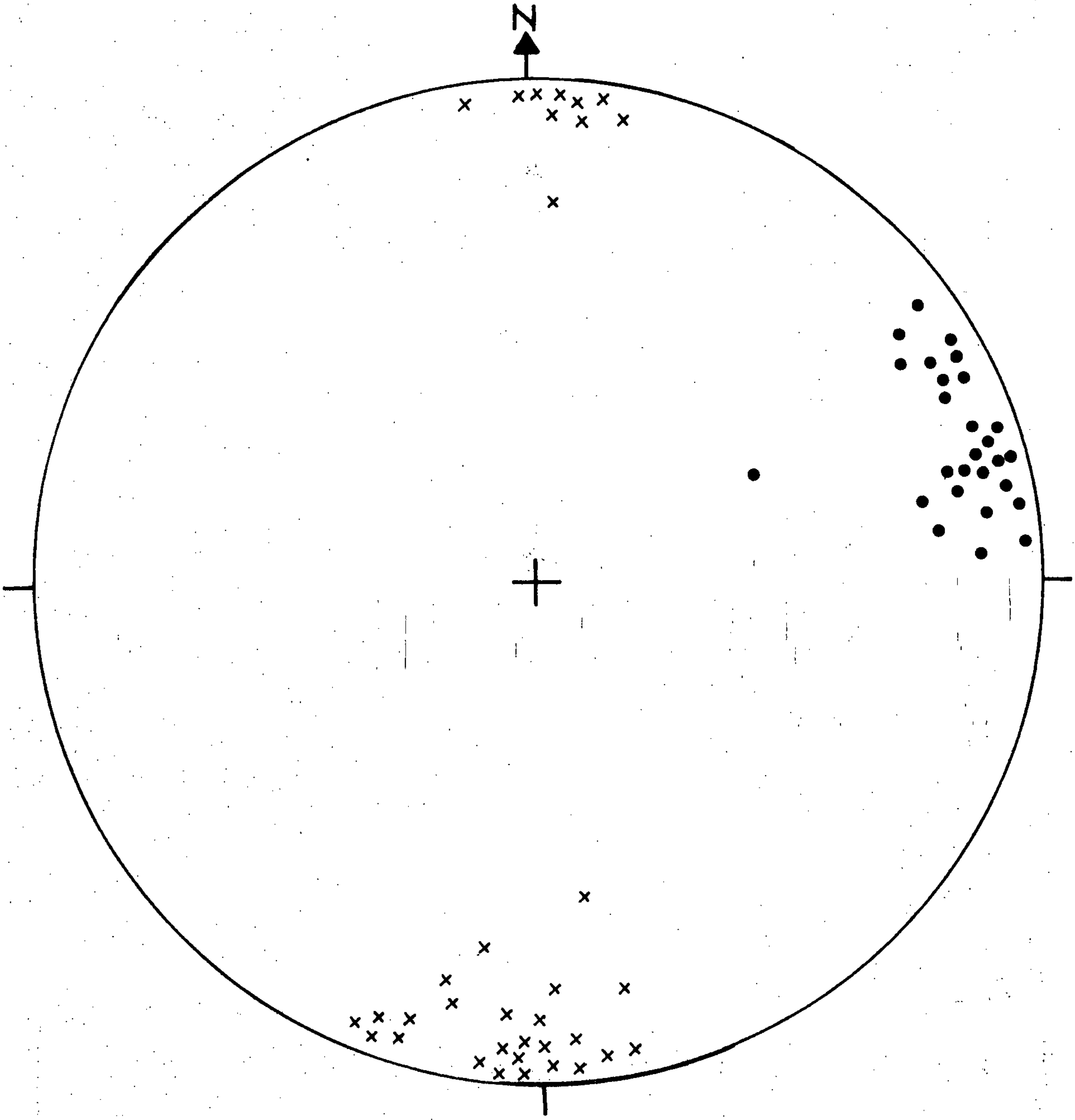


Figure 3-18 Phase 5 and/or later fractures.

• ⊥ J_3 fractures
× ⊥ J_4 fractures

broad northerly trending antiform. Complimentary synforms may have existed beyond the map-area. These pre-existent folds appear to have made phase 5 cross-folding difficult, in that a regionally continuous fold pattern could not develop, and failure was by fracturing rather than folding. The rocks must also have been strongly confined horizontally such that strike-slip movements could not be sustained on the faults. Rather, fracturing weakened the northerly grain and allowed folding to proceed within the smaller fault bounded blocks. Thereafter the faults simply provided free surfaces along which the necessary horizontal and vertical movements resulting from folding could be taken up. Phase 5 folds are essentially normal to these bounding faults and their axes tend to be discontinuous across them (plate 4-pocket).

The downthrown side of each fault is indicated by a bar on plate 4. Of particular note are the two main faults which branch in the south, as both superficially appear to be hinge faults. These apparent hinge effects are related to buckling of the block between, and the upthrown sides of each bound the main phase 5 antiformal zone southeast of Vaseaux Lake. To the north on passing into the realm of Okanagan Falls Syncline the sense of movement is reversed on the more easterly fault, and a similar reversal may occur on the more westerly as it approaches the syncline northwest of the map-area. The youngest fracture sets recognized (J_3 and J_4 on plate 4-pocket and figure 3-18) may be related to phase 5 deformation. In particular J_3 fractures may be early or late-formed oblique planes of failure developed independently within fault bounded blocks. The J_4 fractures may be of similar origin, or altogether younger.

Interference of Phase 3, 4 and 5 structures

Antiformal phase 4 and 5 folds intersect to form a regional domical structure culminating in an area of flat to gently dipping compositional layering southeast of Vaseaux Lake (plates 4, 5-pocket). This structure, in terms of the attitude of compositional layering, is far from an ideal quaquaversally dipping dome. The flanks are actually greatly disrupted by pre-existent phase 3 folds which are relatively open, and inhomogenous fault bounded phase 5 folds, both of which are developed on several scales.

Phase 3 planar and linear structures have been re-orientated in a manner consistent with this domal interference pattern. In general, the northerly trending phase 4 component has caused L_3 to culminate on the crest and depress on the flanks of the dome, while the northwesterly phase 5 component which is broadly parallel with L_3 has caused little re-orientation. Planar structures F_{3a}, F_{3b}, and F_{3c} have been re-orientated, and their poles are scattered along a poorly defined loci representing a combined effect of the two later phases of folding (figures 3-10 and 3-13).

SUMMARY

After deposition of an interbedded sedimentary and volcanic succession exceeding 4000 feet in thickness, the following complex sequence of structural events was imposed on the rocks of Vaseaux Lake map-area.

(1) Phase 1 folding, similar in style and along northerly trends, gave rise to McIntyre Bluff Fold and associated minor structures. These folds were probably originally recumbent, but their vergence is unknown. Tectonic slides were developed and

probably continued to be active at various times during later deformation.

(2) Phase 2 folding, also similar in style but along northwesterly trends re-folded and tightened the earlier recumbent structures. Major folds formed during phase 2 are Vaseaux Lake Antiform, Shuttleworth Creek Synform, and other unnamed structures, and congruent minor folds are abundant in association with these. Axial planes of phase 2 folds were originally inclined at some moderate angle to the northeast and their axes were almost horizontal.

(3) Phase 3 deformation, commenced with flexural-slip folding along westnorthwesterly trends but progressed to a more ductile type of deformation (similar folding) at a later stage. Gallagher Lake Synform and congruent minor folds were formed early about southwesterly dipping axial planes and near horizontal axes and continued to develop about the same directions throughout phase 3. As Gallagher Lake Synform continued to close a slide developed and gave rise to mylonite and local minor folds of diverse trend. Earlier formed phase 1 and 2 structures were re-folded, tightened and variously re-orientated.

(4) Phase 4 folding, flexural-slip in style, gave rise to a major northerly trending antiform with a steeply dipping axial plane and gently plunging axis. Earlier structures were slightly re-orientated on the limbs of this large antiform, and slip within the planes of pre-existing foliations gave local discontinuities along which thin zones of mylonite were developed. Fracturing along steeply dipping northnortheasterly trending surfaces accompanied and/or followed phase 4 folding.

(5) Phase 5 folding, also flexural-slip in style, produced

open all scale northwesterly trending folds with steeply dipping axial planes and shallowly plunging axes. These folds have resulted in further re-orientation of the earlier structures, and a large antiform intersects the earlier phase 4 antiform to give a broad domal structure near the center of the map-area. Phase 5 folding was accompanied by extensive fracturing and faulting and was accomplished primarily by buckling of independent fault bounded blocks.

CHAPTER FOUR

IGNEOUS ROCKS

INTRODUCTION

Igneous rocks, principally of granitic composition, but also including intermediate, basic and ultra-basic types, have been emplaced into the metamorphic complex at various stages of its structural development. The oldest are minor sheets of quartz monzonite which were emplaced into the succession before or during the first phase of deformation. These were succeeded by much larger volumes of granitic rock and pegmatite emplaced during the second phase. These older granitic rocks together form a granitic gneiss-pegmatite complex referred to collectively as Unit A.

Younger less conspicuously foliated granitic rocks (Unit B) were emplaced late in the third phase of deformation. They include a westerly segment of an extensive batholithic complex which underlies much of Okanagan Highland, satelitic stocks, dykes, sills and pegmatites.

Narrow basic to intermediate dykes intruded the succession at some time between the second and third phases of deformation and became folded and metamorphosed during phase 3. Ultra-basic sheets, pyroxenites, dunites and amphibolites, are probably older than these dykes, and may have been tectonically emplaced at some early stage in the second or even the first deformation.

The younger igneous rocks to cut the succession are rhomb-porphyry and basic to intermediate dykes and sills thought to be roughly equivalent in age to the nearby Early Tertiary Marron lavas. These rocks are involved in the phase 4 and 5 deformations.

The principal masses of granitic rock have not received intensive mapping and petrographic study, for the purpose of delineating internal variations in composition, which undoubtedly exist. Emphasis has been placed on their relative ages with respect to the polyphase deformation and the broadest aspects of their mode of origin and emplacement.

To allow reasonably accurate description of the igneous rocks 51 rocks were examined in thin-section, and of these 30 were of granitic composition. Point counts were made on large sodium cobaltinitrate stained slabs for 8 of these, and the results were visually extrapolated to the remainder of the 30, and to a few additional specimens which were also stained. The modal compositions given on the following pages are thus only approximations of the actual modes of these granitic rocks.

Plagioclase compositions were determined principally by flat-stage techniques, but in several instances it was necessary to make use of a universal stage.

UNIT A

GRANITIC GNEISS-PEGMATITE COMPLEX

Sheets of leucocratic granodiorite and rarer quartz monzonite and trondhjemite grading to pegmatite are collectively referred to as granitic gneiss, and are abundant within the succession. A few of these form an older phase and are involved in the first deformation (plate 3-5, 3-6) but the vast majority were emplaced over an interval of time, during the second deformation.

Principal features of the granitic gneisses are strong secondary foliations parallel to F_o/F_1 and/or F_2 outlined by mica, flattened quartz lenticles and alternating coarse and finer grained layers (shear domains). A usually weaker foliation F_3, also outlined by quartz and mica, intersects the older planar structures to define a prominent linear structure L_3 slightly oblique to the older linear structure L_2.

Size and Contact Relations

Sheets of granitic gneiss are found ranging from fractions of an inch to a few tens of feet thick and these are most abundant adjacent to the major sheets which are hundreds of feet thick.

Major sheets, 3 in number, are shown as Unit A on accompanying maps. Among these a lower sheet exposed on both sides of Okanagan Valley near Vaseaux Lake is prominent, locally reaching 1500 feet in thickness. Overlying sheets are thinner (600 feet maximum) and are likely crosscutting apophyses of the lower. (plate 5 - sections in pocket).

Lithology

The major sheets of granitic gneiss are principally composed of leucocratic granodiorite and are of rather uniform internal composition. Their modes, as approximately estimated from stained slabs and thin-sections, range from plagioclase (43-55%), quartz (19-30%), orthoclase (15-30%), biotite (4-10%), hornblende (0-4%), muscovite (0-2%) with accessory sphene, apatite, zircon, opaques and with minor garnet and epidote of possible metamorphic origin. Rocks of slightly different composition, notably quartz monzonite and trondhjemite appear to be confined to smaller ancillary sheets found elsewhere, and in border migmatite complexes adjacent to the main sheets where they are associated with pegmatites and metasomatic looking granitic rocks.

In thin-section the granitic gneisses exhibit cataclastic augen textures, and their original textures, whether igneous or metamorphic, have been destroyed. Plagioclase (An 20-31) in 15 thin-sections is the principal augen forming mineral. It displays very weak normal zoning but the overall composition of plagioclase within a given specimen appears remarkably uniform. Presumably plagioclase compositions were homogenized as a result of metamorphism, and variations now seen, such as the occurrence of more calcic plagioclase in hornblende bearing rocks is a function of the original bulk composition.

Plagioclase augen have also contributed to the annealed groundmass (plate 4-1) in which they are contained. Highly strained quartz forms a matrix which appears to have been more mobile than the other silicates during deformation. Its extreme mobility lead to mechanical grinding and abrasion of the other silicates caught up in the deforming quartz matrix but less able to deform internally.

Contact Relations

The contacts between the major sheets of granitic gneiss and the invaded meta-sediments are of diverse character both from place to place and in different rock types. Contacts with schist may be knife sharp along the lower surfaces of major sheets but grade to narrow zones of migmatite. Upper surfaces tend to be more complex broader zones of migmatite which may contain smaller sheets of uniform granitic gneiss, pegmatite, and hosts of (narrow) metasomatic veins parallel to compositional layering. Semi-pelitic granulites in the vicinity of the contacts are often differentially feldspathized along inch to foot thick layers

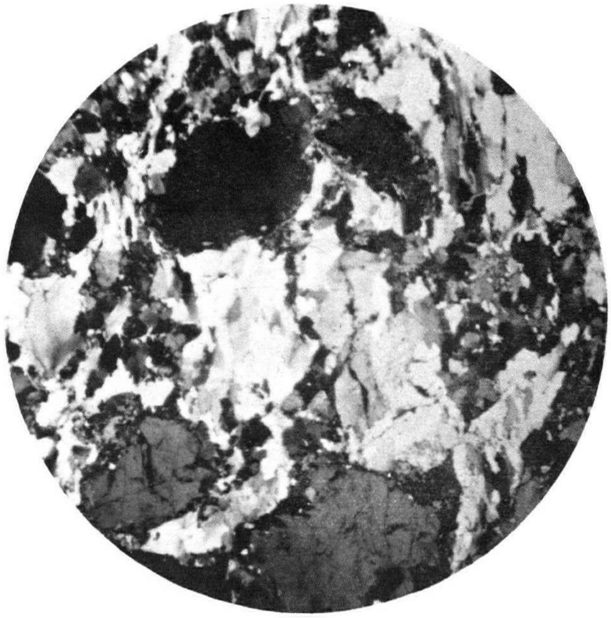


Plate 4-1 Penetrative foliations F_2 in granitic gneiss outlined by deformed quartz and biotite. Crossed polarizers. Field 4.7 mm.

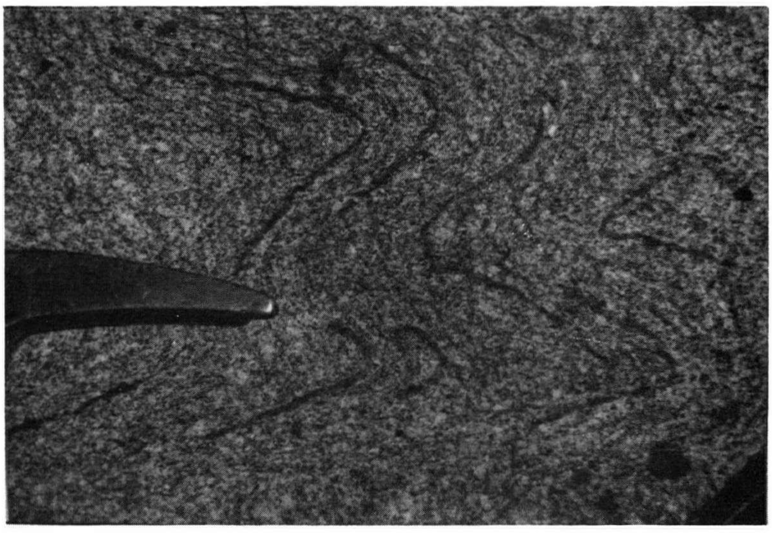


Plate 4-2 Phase 3 folds developed in Unit A (granitic gneiss) outlined by the earlier foliation F_2 on the hinge of Gallagher Lake Synform.

greatly accentuating their original layering. They also may contain ancillary sheets of uniform granitic gneiss and pegmatite and at a few localities the transition from semi-pelitic granulite to granite gneiss is so gradational that a contact cannot be distinguished.

Aside from the metasomatic effects which are prominent at contacts of major sheets, there is no obvious thermal aureole associated with them. One sample of muscovite-biotite schist taken from a contact migmatite zone east of Dutton Creek contains microscopic sillimanite after muscovite, but this is the only occurrence of the mineral or of any aluminum silicate polymorph known within the map-area. Admittedly the immediate contact zone has not received detailed sampling and it is probable that sillimanite may occur elsewhere at the contact.

The metamorphic state of the invaded rocks at the time of intrusion is in doubt. They may have been already metamorphosed to amphibolite facies assemblages and were therefore not responsive to the thermal conditions imposed by the granitic gneiss.

The major sheets of granitic gneiss are not obviously folded as a result of phase 2 deformation but lie along the limbs and axial planes of the megascopic phase 2 folds. They appear to have been emplaced along phase 2 structures which were already in existence and are therefore thought to have participated in only the final stages of the second deformation. Some of the minor granitic sheets and pegmatites display identical relationships with minor phase 2 structures, but many are anomalously involved in tight phase 2 minor folds. Some of these may belong to the earlier phase of granitic gneiss known to have participated in the first deformation, but no trace of a phase 1 structure can be found in these rocks. The author favours a view that small sheets of granitic gneiss and pegmatite were emplaced and extensive metasomatism affected the entire succession before the major sheets came in. The emplacement of the major sheets may coincide with culmination of the thermal event associated with phase 2 and may have been a time of intense deformation.

The time of development of the earliest foliation in the major sheets of granite gneiss is not exactly known. It may be partially of protoclastic origin but has clearly continued to develop in the solid state as the result of the ductile flow of quartz. (plate 4-1). It was highly developed by the time it became deformed about the penetrative foliation F_3 (plate 4-2). Although there is evidence of re-activation of earlier foliations during phase 3 (see Chapters 3 and 5), the author is inclined to believe that phase 2 folds continued to close after the major sheets of granitic gneiss were emplaced, and that some of the cataclastic and ductile deformation textures found therein were formed during the waning stages of the second deformation, and that some formed during the re-activation of F_2 by phase 3 re-folding.

Origin and Emplacement

The granitic gneiss-pegmatite complex of the Vaseaux Lake area are thought to represent the differentiated top, apophyses early and late-stage pegmatitic and metasomatic derivatives of a major granitic pluton which rose and was frozen in its present position towards the end of the second deformation. Evidence for this hypothesis was obtained by reconnaissance mapping in an area immediately north of Vaseaux Lake map-area. Although the total

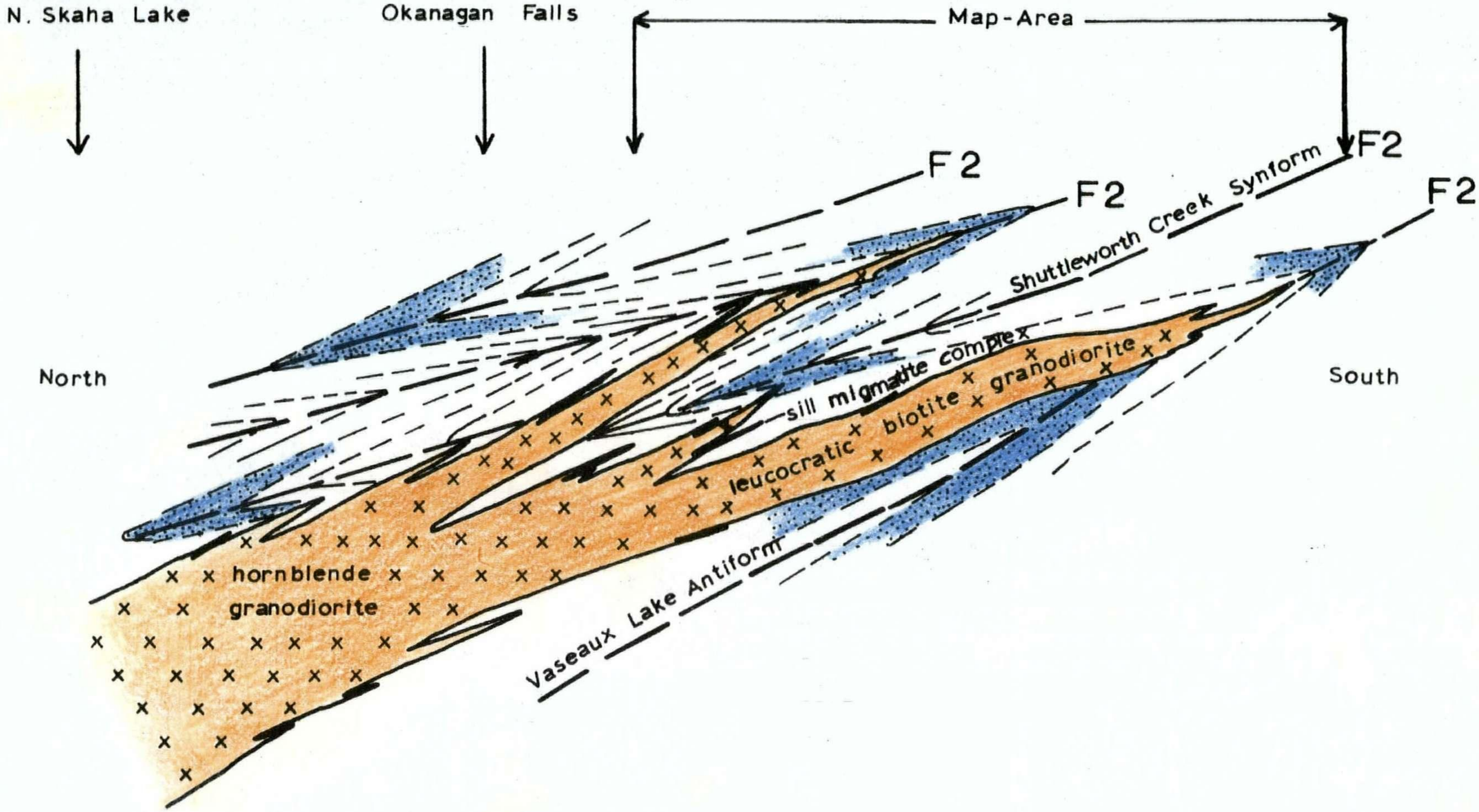


Figure 4-1 Schematic Cross-Section Illustrating Relationships Between Phase 2 Folds and Differentiated Granitic Gneiss Pluton (Unit A) at the End of Phase 2 Deformation.

structure in this northern area is not yet understood, it is apparent that major portions of the same pluton have been unroofed over an area of some 30 square miles east of the north end of Skaha Lake.

The rocks in this northern area are hornblende granodiorite and quartz diorite gneisses which contrast sharply with the leucocratic rocks of Vaseaux Lake area. They represent a much deeper level in the pluton and their more mafic character suggests that crystallization and differentiation of the pluton may have been almost complete when it reached the levels now seen in Vaseaux Lake area. The major sheets of leucocratic granodiorite gneiss are therefore thought to have been formed by a last upward surge of perhaps largely crystalline magma at the top of this freezing differentiated pluton. Metasomatizing fluids and pegmatites may have arrived well in advance of the crystallizing magmas and therefore may have become more involved in phase 2 deformation than the later magmatic phases. The forceful emplacement of the major sheets, probably is responsible for some of the deformation affecting these earlier formed granitic phases.

Emplacement and localization of the major granitic sheets was controlled by pre-existing planes of weakness within the succession. Lithologic layering, most notably within the schists of Unit 2, and the axial foliation F_2 were important localizers. Granitic magmas were injected along these zones of weakness and made room for themselves by dilation of the succession. Since the major sheets lie along megascopic phase 2 folds it is thought these folds may have absorbed the resulting dilation by slowly becoming tighter. This tightening may have been accomplished by successive injections

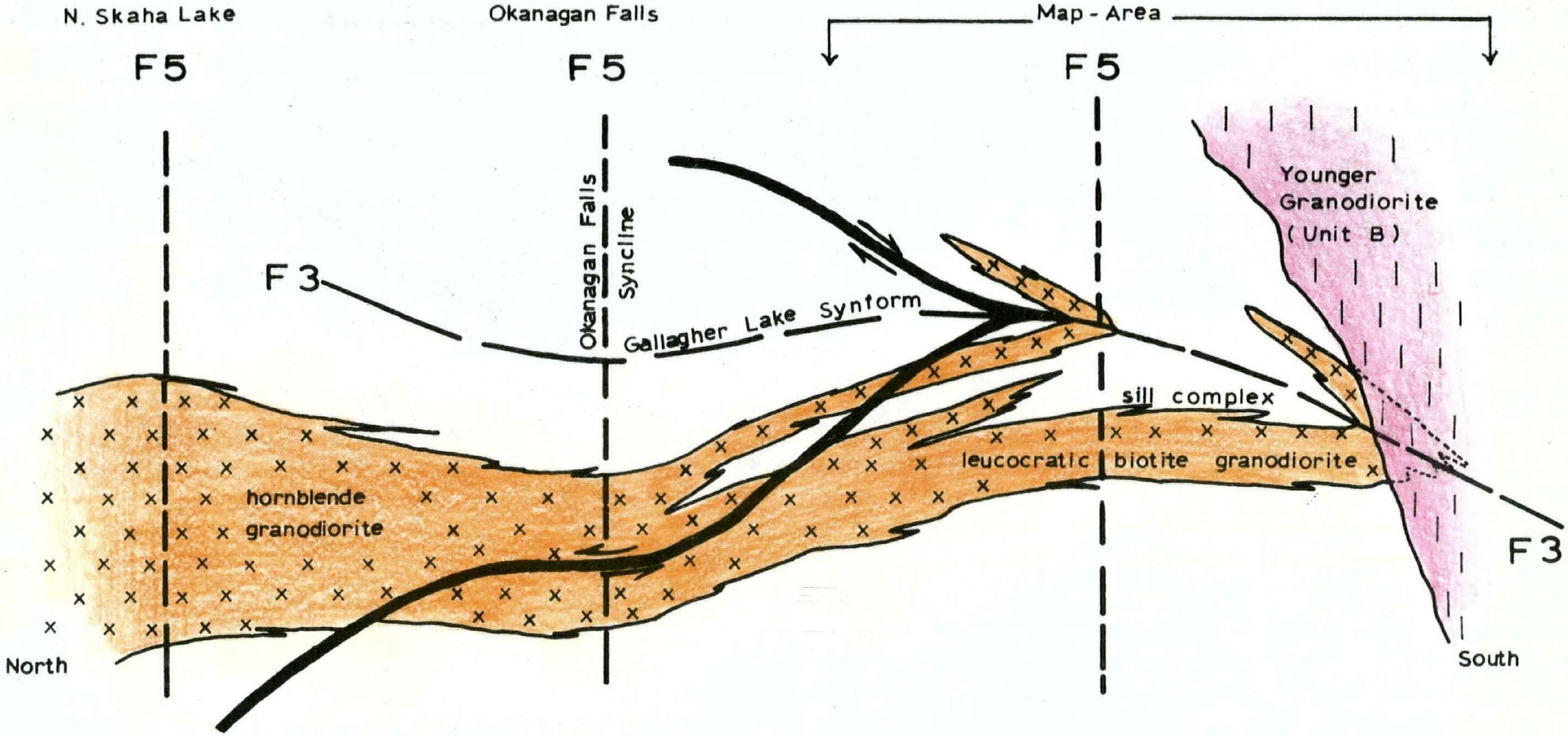


Figure 4-2 Schematic Cross-Section Illustrating the Present Distribution of Granitic Gneiss Resulting from Interference of Phase 3 and 5 Folds.

of magma which "built up" the major sheets to their present thickness leaving narrow-screens of meta-sediment between successive sheets.

Figure 4-1 is a schematic cross-section along the Okanagan Valley which illustrates the structural relationships between the pluton and megascopic phase 2 folds as they may have existed at the close of the second deformation. Figure 4-2 represents the present distribution of granitic gneiss resulting from the influence of later phase 3, 4 and 5 folding. The hornblende granodiorite gneiss east of Skaha Lake, a deeper level in the pluton, now has the form of a gneiss dome resulting from the interference of large phase 4 and 5 folds (northerly and westerly trends) although this is not obvious from the map-pattern (Little 1961) because of local topography.

Age

Little (1961), based on his experience with granitic rocks in southern parts of the Shuswap terrane and further east, considered the older granitic gneisses found in the Southern Okanagan region to be roughly equivalent in age to the Jurassic Nelson Plutonic Rocks. The Nelson Batholith and similar nearby plutons have since been shown to be of late and post-kinematic types at the eastern margin of the Shuswap Complex (Ross 1968, Hyndman 1971, Read 1971). Late and post-kinematic plutons (Unit B), in Vaseaux Lake area, are associated with phase 3 deformation which is of Jurassic or older age (this study), and these younger granitic rocks cut the granitic gneiss (Unit A). For the above reason, and because the granitic gneisses are associated with an older phase of deformation (phase 2), they are considered to be older, and perhaps are much older than Jurassic.

UNIT B

LATE-KINEMATIC GRANODIORITE-QUARTZ MONZONITE

The metamorphic rocks of Vaseaux Lake area are bounded on the south and east by a westerly extension of a batholithic complex which underlies much of Okanagan Highland further east. Within the map-area these rocks are granodiorites and quartz monzonites characterized by well developed marginal foliations in the vicinity of their contacts, and a less conspicuous but penetrative regional foliation F_3 (plate 4-3). Commonly these rocks contain poikilitic orthoclase megacrysts which are typically much larger than associated quartz and plagioclase (plate 4-4). Related dykes, sills and pegmatite cut the succession and are foliated parallel to F_3, but like the pluton are only involved in the latest part of phase 3 deformation, and do not, themselves, outline phase 3 folds. A small stock exposed east of Vaseaux Lake is of similar composition but is not foliated parallel to F_3. It is thought to be a post-kinematic phase of Unit B, and in some ways resembles the Oliver Quartz Monzonite which is exposed southwest of the map-area.

Lithology

Unit B consists principally of biotite granodiorite but grades eastward to biotite quartz monzonite as orthoclase megacrysts become larger and more abundant. No contact was observed between these two rock types and mapping is not sufficiently detailed to be assured that they are not separate phases.

Estimated modal abundances of the primary minerals range as

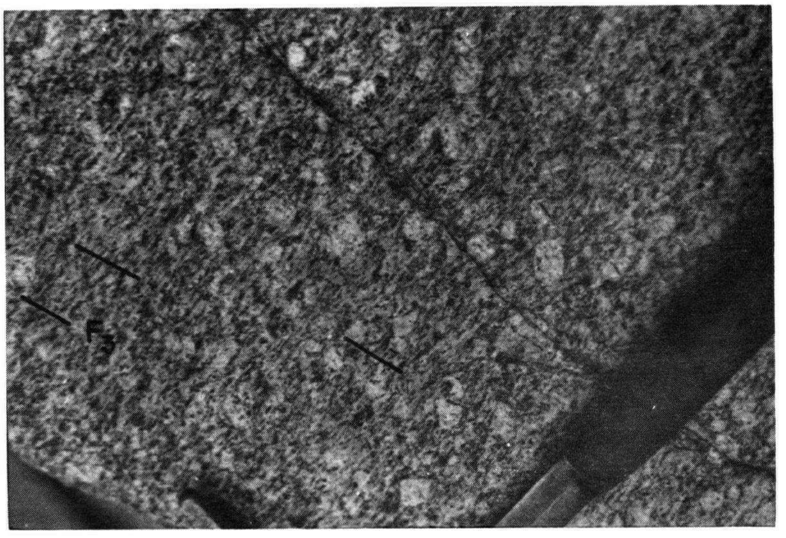


Plate 4-3 Poikilitic orthoclase megacrysts in foliated border phase of Unit B. Weaker F_3 cleavage crosses obliquely.

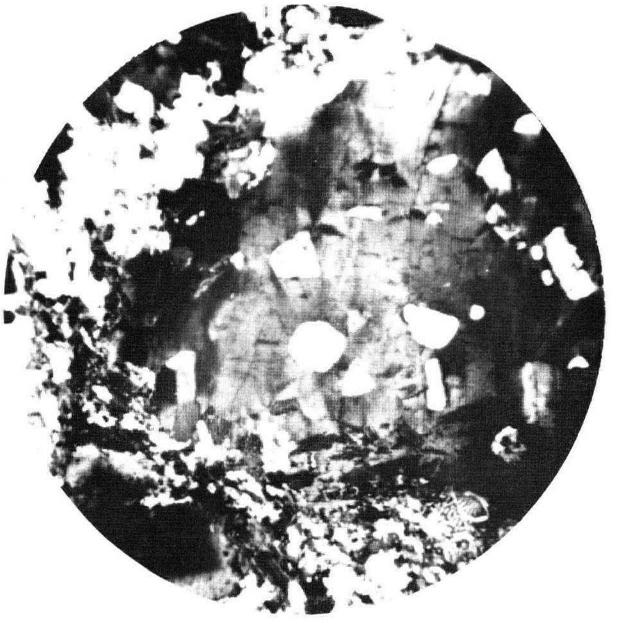


Plate 4-4 Poikilitic habit of orthoclase in granodiorites of Unit B. Crossed polarizers. Field 4.7 mm.

follows; plagioclase (36-60%), quartz (16-30%), orthoclase (13-32%), biotite (4-15%), hornblende (0-2%). Accessories are apatite, sphene, zircon and opaques. In thin-section cataclastic textures are dominant but quartz forms a matrix which has undergone ductile flow. Mortar structure is developed along feldspar boundaries, and biotite is shredded and bent around the feldspar grains. In contact with quartz, biotite is sub-parallel to F_3, and partially defines this planar structure.

Plagioclase (An 18-35) exhibits complex zoning (plate 4-5), a relict of an original igneous texture. Its margins are embayed but this may be the result of deformation rather than a magmatic reaction.

Orthoclase occurs in all grain sizes from microscopic specs in the matrix to inch long megacrysts, and larger grains typically contain inclusions of plagioclase and quartz (plate 4-4). These inclusions are always much smaller than grains of the same minerals outside the orthoclase, and may have been reduced in size by participation in the reaction which gave rise to these large crystals. Optically continuous inclusions of plagioclase found in one thin-section support this hypothesis.

Crystallization of orthoclase may have consumed most of the remaining liquid phase in these rocks, and small intergrowths of myrmekite found along its margins could represent crystallization of the final liquids (plate 4-4). Typically larger crystals of orthoclase, near extinction positions, exhibit striking internal strain patterns as shown on plate (4-4).

Contact Relations

Contacts between the metamorphic rocks, and the westerly

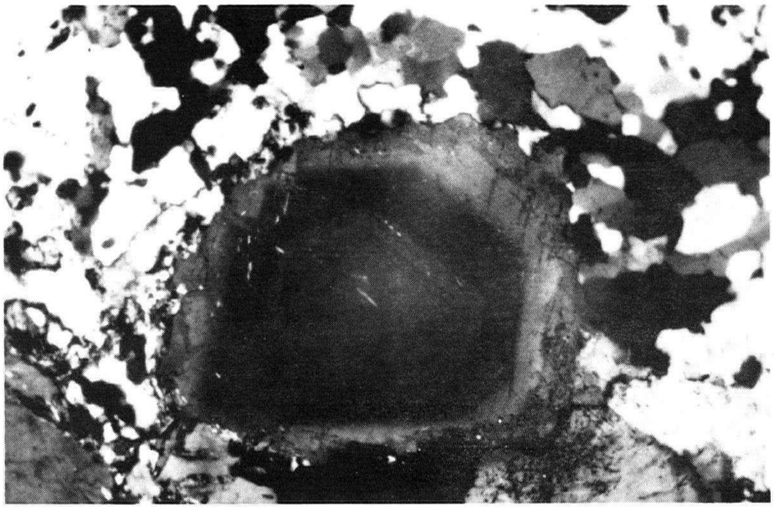


Plate 4-5 Oscillatory zoned plagioclase in granodiorite of Unit B. Crossed polarizers. Field approximately 1.6 mm.

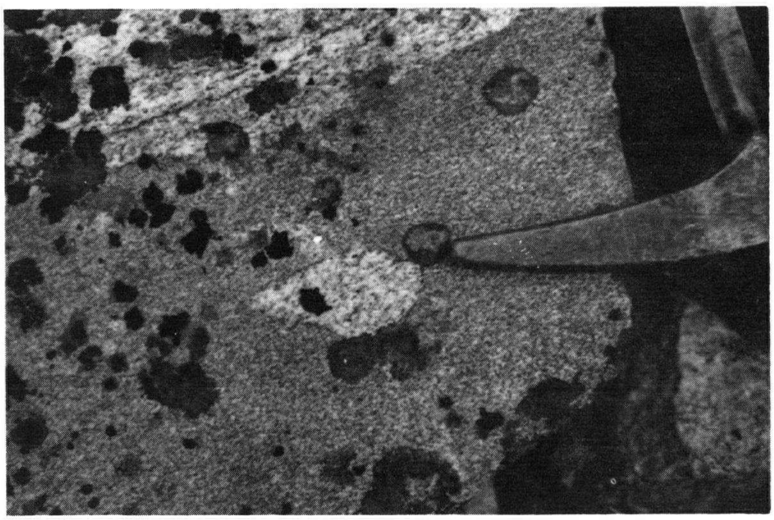


Plate 4-6 Xenolith of granite gneiss (Unit A) within granodiorite dyke-rock of Unit B as seen in coarse float at the contact between the two units.

extension of the batholith complex (the pluton), are anomalous and interesting. The walls of the pluton dip moderately south and east away from the metamorphic complex such that the metamorphic rocks form a somewhat irregular footwall against which the pluton rests. Further, the contact crosscuts all of the lithologic units suggesting that lithologic control has had little influence on the localization and emplacement of the pluton, and is not responsible for the observed shallow dips of the plutons' walls. Although some randomly orientated xenoliths occur within the pluton near its margins, the walls tend to be smooth, and stoping may not have been important in the emplacement process. Border phases are strongly foliated parallel to the walls, and forceful shouldering aside of the wall-rocks may have played a much larger role in the emplacement process than might be suspected in view of the discordant contact relationships.

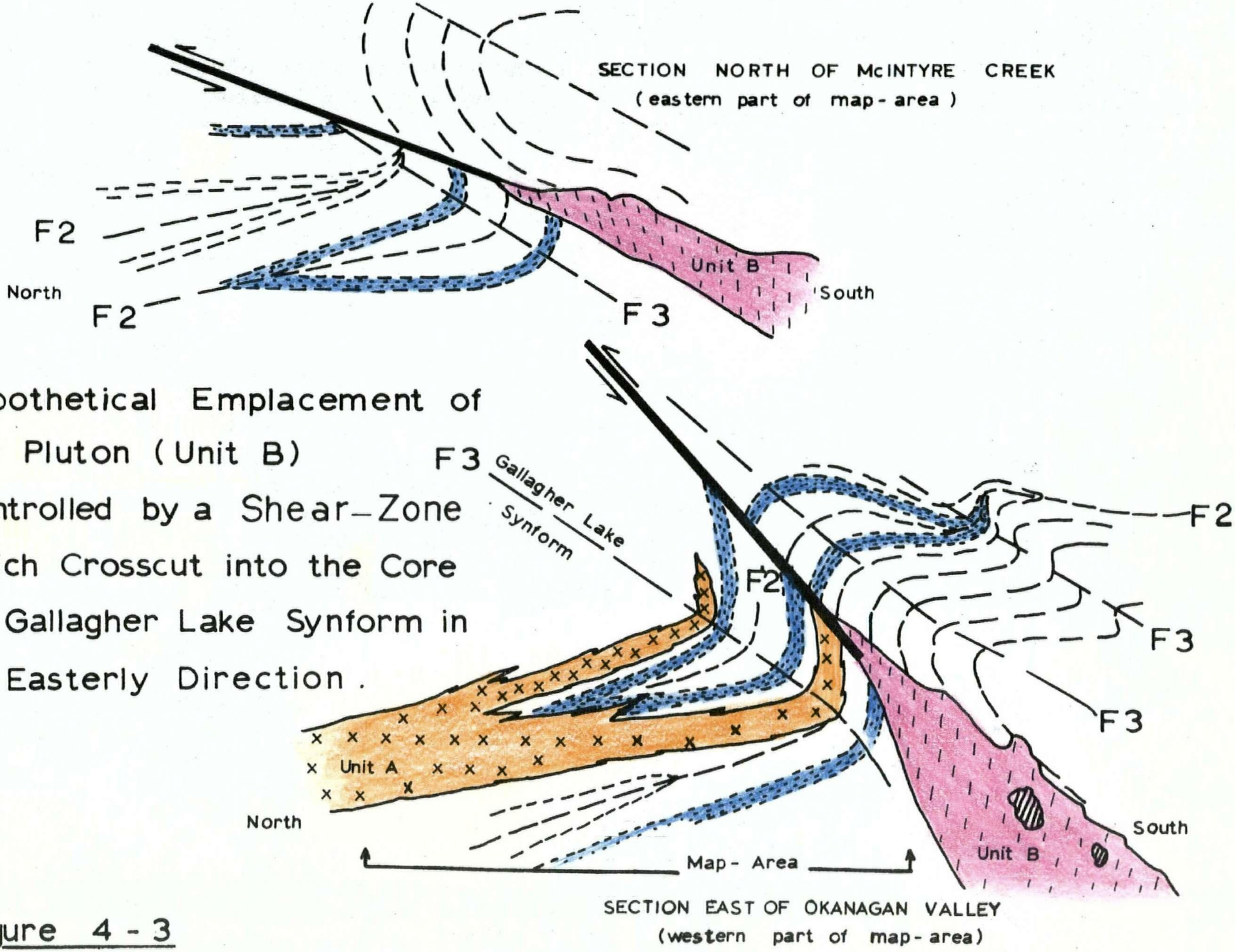
The thermal aureole which must have surrounded this pluton did not cause striking mineralogical changes in the pre-existing amphibolite facies assemblages of the wall-rocks, and metasomatism has been limited to a narrow zone (several hundred feet) adjacent to the contact. Semi-pelitic granulites have been metasomatized to the greatest extent. They form gradational contacts with the pluton and are greatly enriched in potassium feldspar. Schists and calc-silicates are also enriched in orthoclase. Samples of muscovite-biotite schist, quartz-calcite marble and calc-silicate taken further from the contact in zones impregnated with sills and pegmatite, do not appear to have developed new mineral assemblages, although they are intensely deformed. Again, the immediate contact zone has not been studied in sufficient detail to be absolutely certain that new mineral assemblages do not occur in some rocks, right at the contact.

The narrowness of the obvious metasomatic zone adjacent to the pluton might be explained in terms of the footwall position that Vaseaux Lake area rocks occupied with respect to the pluton. Volatile phases would presumably tend to move towards an upward facing wall or a higher level, where they might escape more easily.

Emplacement and Relation to Structure

Although structure and contact relationships are largely unknown for the entire batholith complex to the east, that part of it seen in Vaseaux Lake area is clearly related to phase 3 deformation, and may be in part responsible for that deformation. At the Okanagan Valley the pluton appears to have come up along the inverted limb of the megascopic phase 3 structure, Gallagher Lake Synform. Yet in an easterly direction it truncates this structure and reaches its hinge north of McIntyre Creek. Assuming that stoping did not play an increasingly important role in the emplacement process in an easterly direction, the limb of the Synform may not alone have localized the intrusion, although the inverted limb would have been thinning and highly strained during late phase 3.

An alternate hypothesis, preferred by the writer, is that the pluton rose along a phase 3 structure that cross-cut the inverted limb something like the shear zone hypothetically illustrated on figure 4-3. Such a structure might have developed during phase 3 deformation as a result of the anisotropy imposed by the limbs of megascopic phase 2 folds, which at this stage, were being re-folded by a mechanism of flexure strongly influenced by the more competent lithologies.



Hypothetical Emplacement of the Pluton (Unit B) Controlled by a Shear–Zone which Crosscut into the Core of Gallagher Lake Synform in an Easterly Direction.

Figure 4 - 3

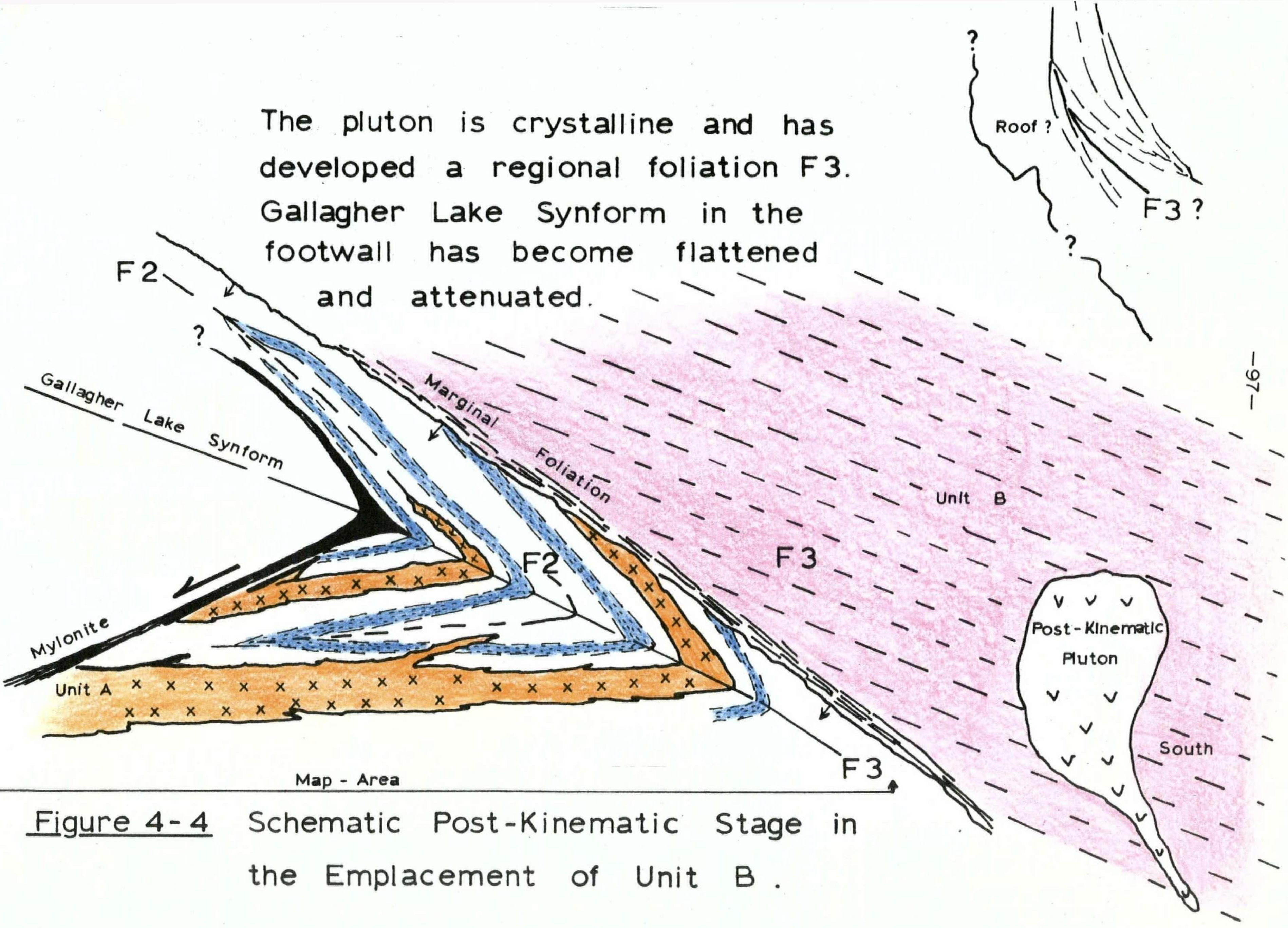


Figure 4-4 Schematic Post-Kinematic Stage in the Emplacement of Unit B.

The pluton may have worked its way up such a zone of weakness by slowly shouldering the walls aside. By adding heat to the wall-rock, it may have brought about a change in the style of deformation from a brittle to a more ductile type. The wall-rocks might then have more easily responded by moving outward, absorbing some of the shouldering stresses, but the advancing pluton may also have begun to lift its' roof.

In Vaseaux Lake area, rocks which comprise the footwall of the pluton probably responded to the shouldering effects of intrusion by renewed closure (and flattening) of phase 3 and earlier folds. The slide and mylonite found in the northern part of the map-area, associated with outward (northerly) movement of a segment in the core of Gallagher Lake Synform, may have developed to alleviate a room problem in the core of the Synform brought on by further closure. Emplacement of the pluton might also be responsible in large part for the flatness of dip, and the attenuation of Gallagher Lake Synform and parasitic structures.

Age and Significance

The rocks of Unit B cannot be directly dated on geological grounds, and no radiometric ages are available within the map-area. They are however, lithologically very similar to the intermediate phase of the composite Oliver stock, a biotite quartz monzonite characterized by up to inch long poikilitic microcline "phenocrysts" (Richards, 1968). The Oliver stock lies just beyond the south-west corner of the map-area, on strike with Unit B, and has been dated at 136-144$\pm$6 million years by the K/Ar method (White, et al, 1967, and White, et al, 1968).

Structurally, the Oliver stock is marginally foliated, but has no penetrative regional foliation parallel to F_3, and is more like the small stock east of Vaseaux Lake than other parts of Unit B. These stocks are thought to be the latest post-kinematic phases of Unit B, and the radiometric age 144 ± 6 million years is therefore considered to represent a minimum age for phase 3 deformation.

METAMORPHOSED INTERMEDIATE TO BASIC DYKES

A few fine grained dykes composed principally of biotite, hornblende and andesine with minor quartz, potassium feldspar, epidote, sphene and apatite are found in Vaseaux Lake map-area. With respect to deformation and metamorphism these are dated as post-phase 2 and pre- or syn- phase 3 on the basis of their contact relationships and internal structure. They may or may not all be of identical age, but they have in common well developed marginal, and secondary foliations parallel to F_3.

At Shuttleworth Canyon one such dyke crosscuts a major sheet of phase 2 granitic gneiss (Unit A), but is deformed with the gneiss into open phase 3 folds, clearly dating the relative time of dyke emplacement. These dykes are significant in that they suggest phases 2 and 3 were separated by some interval of time in which the rocks became cool and fractured. The two phases of deformation may not have evolved from a single continuous dynamothermal event as might be suggested by the almost co-axial phase 2 and phase 3 fold sets.

ULTRA-BASIC ROCKS AND AMPHIBOLITES

Elongate lenticular bodies and sheets of basic to ultra-basic rock with thicknesses to several hundred feet, lie parallel to compositional layering in the northeastern part of the map-area.

These rocks are coarse grained biotite calcic plagioclase amphibolites, calcic plagioclase clino-pyroxenites and clino-pyroxene dunites. Their age and origin is uncertain, but their present form and mineralogy is probably the result of a long and complex history of deformation and metasomatism.

The age of the ultra-basic rocks is clearly greater than Unit B, as they are crosscut at many localities by weakly foliated dykes and simple pegmatites related to Unit B. At one locality a small body of coarse grained amphibolite is cut and veined by granitic gneiss (Unit A), and it is therefore possible that all of the ultra-basic rocks date back to an early stage of the second or even the first deformation. They may be fragments of some early ultra-basic mass which became "sliced-up" and tectonically emplaced during an early phase of deformation. They might equally well be parts of an oceanic lithospheric plate perhaps related to a continental collision which gave rise to phase 1 folds?

Extensive metasomatism which accompanied the emplacement of granitic gneiss (Unit A) in a middle amphibolite facies environment, may have drastically altered these rocks and established their present mineralogy. At one locality olivine clino-pyroxenite is partially altered to biotite amphibolite suggesting that the amphibolite may have been a final stable assemblage. The pyroxenite however, may itself be a metasomatic rock as the coarse diopsidic pyroxene is extremely poikilitic with respect to fine grained anhedral magnetite, which may be relicts from some earlier (serpentinite ?) stage. Inclusions of magnetite persist in the replacing amphibole, and are characteristic of the coarse grained amphibolites found elsewhere.

Partial serpentinization of dunite and pyroxenite may have occurred during phase 3 deformation or earlier. Evidence for this may be seen where dykes of Unit B cut the pyroxenites, and metasomatic chrysotile, phlogophite tremolite-actinolite assemblages have been produced in the wall-rocks adjacent to the dykes and pass outwards to partially serpentinized rock. These minerals also occur along fractures throughout partially serpentinized pyroxenites, and with talc and carbonate in small zones of hydrothermal alteration not related to dykes.

TERTIARY DYKES

A few dykes and sills of probable Early Tertiary age cut the metamorphic complex. These have compositions similar to volcanic rocks of the Marron Formation found northwest of the map-area (Church 1967), with which they are probably contemporaneous. Unlike their volcanic equivalents, these dykes are strongly foliated and weakly metamorphosed, as a result of phase 4 deformation, and are therefore useful in dating the later phases of deformation in Vaseaux Lake area.

Anorthoclase bearing rhomb-porphyry sills and irregular dykes found in the map-area, are similar to rocks of the basal Yellow Lake Porphyry Member of the Marron Formation. These have narrow chill zones at their contacts, and sills in particular have developed penetrative foliations parallel to their margins. Deformation of these rocks may have commenced before they were completely solid, and probably continued as they cooled. Their metamorphic features such as the replacement of clinopyroxene by biotite and hornblende, and the unmixing of two feldspars from anorthoclase may be related to simultaneous hydrothermal activity and shearing, as these sills cooled.

Other dykes, fine grained light to dark coloured rocks, may be equivalent to some of the younger Marron Lavas. Unlike the rhomb porphyry sills, their emplacement was strongly controlled by the northerly trending J_1 fracture set, and they are themselves foliated parallel to the fractures in which they lie. Their margins are distinctly chilled, and in thin-section contain zoned plagioclase microlites in an extremely fine grained matrix.

With respect to dating the later phases of deformation, development of J_1 fractures, a late-stage phase 4 event (Chapter 3), would appear to coincide in time with volcanism which gave rise to the younger parts of the Marron Formation. Emplacement of rhomb porphyry sills and shearing in the plane of compositional layering, which are perhaps expressions of the earlier flexural-slip folding aspect of phase 4 deformation, may have been in progress at the time Yellow Lake Porphyry lavas reached surface in the Early Eocene.

CHAPTER FIVE

METAMORPHISM

INTRODUCTION

Study of the metamorphism in Vaseaux Lake area is in many ways unrewarding. Mineral assemblages are relatively simple, and are not themselves diagnostic of a precise type or physical condition of metamorphism, that may be simply illustrated as a point on a P/T diagram. Further, no systematic variation of mineral assemblages occurs within rocks of similar composition, and in general there would appear to be near equality of metamorphic grade throughout the whole area.

Metamorphism, which accompanied the second phase of deformation gave rise to the amphibolite facies mineral assemblages now found in Vaseaux Lake area. The nature of this metamorphism, and time relationships between metamorphic recrystallization and deformation are no longer easily recognized. They have been complicated by metasomatic and thermal conditions imposed by invading granitic plutons of two ages, cataclasis associated with three later phases of deformation, and widespread hydrothermal alteration which accompanied the latest of these.

EARLY METAMORPHISM

While two early phases of deformation (phases 1 and 2) have been recognized, accompanying metamorphism was of a progressive nature. It appears to have reached middle to upper greenschist facies during phase 1, and gone on to amphibolite facies during phase 2, and no evidence was found to suggest whether or not a long period of time intervened. Conceivably, phase 1 and phase 2 folds may have been successively formed under the continued influence of a broad phase of progressive regional metamorphism, which culminated with plutonism and metasomatism during the second deformation, and gave rise to the present mineral assemblages. Later deformation, metamorphism and alteration has had the effect of mechanically re-arranging and partially re-crystallizing these assemblages, but only locally have they been drastically changed or completely obliterated.

Mineral assemblages found within the succession, and thought to be representative of the early metamorphism are listed on table 5-1, where they are grouped on the basis of rock type. These assemblages, on the basis of plagioclase compositions, the presence of diopside in amphibolites and calc-silicates, and garnet in most assemblages, are assigned to the lower or middle part of the amphibolite facies of Turner (1968) (almandine amphibolite facies of Winkler 1965 - Turner and Verhoogen 1960). Index minerals, such as staurolite, andalusite, kyanite etc., necessary to classify the metamorphism more specifically, are not found. Pelitic rocks must have been originally somewhat impoverished in alumina such that micas, feldspars and garnet, trapped alumina in their structures as it became available, and the more aluminas index minerals could not form.

Temperatures corresponding to the highest part of the amphibolite facies (Sillimanite-almandine-orthoclase subfacies), characterized by the breakdown of muscovite in favour of sillimanite and K-feldspar, were not attained. Muscovite is a stable part of most pelitic assemblages, and those assemblages which contain a single mica (biotite) lack sillimanite. Further, epidote persists

TABLE 5-1

MINERAL ASSEMBLAGES FORMED DURING EARLY METAMORPHISM (PHASE 2)

ROCK TYPE AND LITHOLOGIC UNIT	NUMBER OF OCCURRENCES IN THIN-SECTION	ASSEMBLAGE	
SCHISTS UNITS 2, 4	5	Qtz, Plag (An$_{28-35}$), Biot, K-Felds.	± sphene apatite zircon opaques
	3	Qtz, Plag (An$_{30-89}$), Biot, Garn.	
	3	Qtz, Plag (An$_{21-29}$), Biot, Musc.	
	5	Qtz, Plag (An$_{18-30}$), Biot, Musc, K-Felds.	
	8	Qtz, Plag (An$_{28-40}$), Biot, Musc, Garn.	
	1	Qtz, Plag (An$_{30}$), Biot, Musc, K-felds, Sill, (local Garn.).	
IMPURE QUARTZITES UNITS 2, 4	1	Qtz, Biot, Musc.	± zircon apatites opaques
	2	Qtz, Biot, Musc, Plag (An$_{26-38}$).	
	2	Qtz, Biot, Musc, Plag (An$_{40-42}$), Garn.	
	1	Qtz, Biot, Musc, K-felds.	
	2	Cal.	
	1	Cal, Qtz, Diop, Epid.	
	1	Cal, Qtz, Diop, Epid, Scap.	

Cont'd..

ROCK TYPE AND LITHOLOGIC UNIT	NUMBER OF OCCURRENCES IN THIN-SECTION	ASSEMBLAGE	
Cont'd..	3	Cal, Qtz, Diop, Epid, Scap, Gros.	
	1	Cal, Qtz, Diop, Epid, Scap, Gros, Plag (calcic).	
CARBONATES	3	Cal, Qtz, Diop, Epid, Scap, Plag (An_{68-74}), K-Felds.	musc
CALC-SILICATES	1	Cal, Qtz, Scap, K-Felds.	sphene zircon ± phlogophite zircon opaques
UNITS 2, 4	1	Diop, Epid, Qtz, Scap, K-Felds.	
	1	Biot, Epid, Qtz, Gros, Plag (An_{38}), K-Felds.	
	1	Biot, Hb, Qtz, Gros, Plag (An_{38}).	
	1	Qtz, Plag (An_{32}), Biot, Hb.	
GRANULITES AND	2	Qtz, Plag (An_{29-30}), Biot, Hb, K-Felds.	
SEMI-PELITIC	4	Qtz, Plag (An_{30-37}), Biot, Hb, K-Felds, Epid.	sphene zircon ± apatite allanite opaques
GRANULITES	4	Qtz, Plag (An_{31-39}), Biot, Hb, Epid, Garn.	
UNITS 1-5	1	Qtz, Plag (An_{73}), Biot, Hb, Epid, Garn, Diop.	
	1	Hb, Plag (An_{32}).	
	2	Hb, Plag (An_{48-74}), Diop.	

Cont'd..

ROCK TYPE AND LITHOLOGIC UNIT	NUMBER OF OCCURRENCES IN THIN-SECTION	ASSEMBLAGE	
Cont'd..	2	Hb, Plag (calcic), Diop, Biot, Epid.	
AMPHIBOLITES UNIT 4	2	Hb, Plag (An_{32-41}), Biot, Epid, Garn.	± sphene apatite zircon opaques
	3	Hb, Plag (An_{40-42}), Biot, Epid, Garn, Qtz.	

Abbreviations:

Qtz.	-	quartz	Sill.	-	sillimanite
Plag.	-	plagioclase	Cal.	-	calcite
K-Felds.	-	K-Feldspar	Diop.	-	diopside
Biot.	-	biotite	Epid.	-	epidote
Musc.	-	muscovite	Scap	-	scapolite
Garn.	-	garnet	Gros.	-	grossularite

Hb. - hornblende

in many quartz bearing assemblages, but should have been eliminated had conditions of the highest amphibolite subfacies prevailed (Winkler 1965).

Regional metamorphism in Vaseaux Lake area cannot be entirely separated from synkinematic plutonism (granitic gneisses of Unit A) and associated metasomatism. Potash metasomatism, in particular, has given rise to orthoclase in assemblages which otherwise might not include K-feldspar. Rocks such as the semi-pelitic granulite, shown on plate 5-1, usually contain biotite, hornblende, quartz, plagioclase and possibly epidote and garnet. In this instance large porphyroblasts of orthoclase, as well as matrix orthoclase are also present, and are clearly metasomatic. At the locality shown on plate 5-1, the metasomatic zone is several hundred feet thick and lies above a major sheet of granitic gneiss. Here the metasomatism was a late phase 2 event, as porphyroblasts have grown across phase 2 structures on the hinges and in the cores of phase 2 minor folds, and are themselves but weakly deformed.

In rocks such as schist, which have undergone considerably more deformation since the emplacement of granitic gneiss, metasomatic K-feldspar is difficult to recognize. Where the K-feldspar is restricted to pegmatitic and quartzo-feldspathic layers, a more normal situation, it is easily attributed to the metasomatism. Where it forms part of a fine grained matrix, such as in the K-feldspar bearing assemblages reported on table 5-1, its origin is less certain. In these rocks the K-feldspar may be part of the original assemblage, as it is not found in contact with garnet and rarely occurs in layers containing garnet. Biotite or muscovite would be expected to form rather than K-feldspar, if excess K_2O were available in an almandine bearing assemblage metamorphosed

Plate 5-1 Metasomatic orthoclase porphyroblasts in semi-pelitic granulite above a major sheet of granitic gneiss.

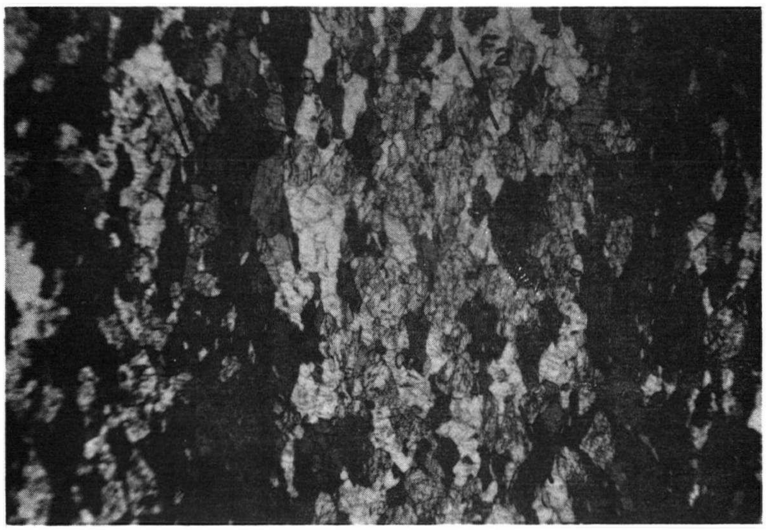


Plate 5-2 Laminated plagioclase diopside amphibolite displaying weakly developed cleavage F_2. Plane polarized light. Field approximately 4.7 mm.

in the lower part of the amphibolite facies (Winkler 1965).

Time relationships between deformation, crystallization of the various minerals, plutonism and metasomatism are not entirely clear. The highest temperature assemblage recorded (sillimanite after muscovite) occurs at the contact of a major sheet of granitic gneiss, but metamorphism probably reached amphibolite facies before granitic magmas were emplaced. Whether metasomatic fluids, in advance of the rising magmas, carried heat upwards and caused metamorphism to reach the amphibolite facies, or whether the metamorphism is part of broader high grade regional metamorphic picture, cannot readily be said because of the smallness of the map-area.

The principal reason for associating the culmination of metamorphism with phase 2 deformation is the strong preferred orientation of hornblende parallel to L_2, but hornblende appears to have formed at an early syn-kinematic stage. Hornblende, once formed, became affected in various ways by later parts of the same deformation. In quartz rich semi-pelitic granulites for example, hornblende became subject to a high degree of cataclasis as a result of the internal deformation and flow of quartz. In quartz deficient amphibolites, cataclasis was less significant. Hornblende, diopside, plagioclase assemblages had greater strength, and did not deform so much internally by a flow mechanism, (plate 5-2). Cataclasis was restricted to discrete shears developed parallel to F_2 and to the hinges of phase 2 folds.

The orientation of hornblende prisms may have been governed by mimetic crystallization along foliation intersections, because it has also grown parallel to L_1, most notably on the hinges of relict phase 1 folds. Otherwise two generations of hornblende, and area-wide recrystallization of hornblende during phase 2 deformation, are implied. There seems to be no reason to expect such widespread recrystallization if the metamorphism were of a progressive nature. Evidence for late- or post-kinematic growth of other minerals is also hard to find, although the true relationships are obscured by phase 3 and later deformation. In schists where F_2 is a transposition structure, criss-crossing and intergrown micas suggest more than one period of growth before phase 3, but it is impossible to relate the growth of micas to any particular part of phase 2 deformation. In some less deformed rocks, quartz rich semi-pelitic granulites in particular, micas exhibit relationships suggesting pre- or early phase 2 growth, followed by rotation into attitudes sub-parallel to F_2, later in phase 2 deformation. For example plates 5-3 and 5-4 show the hinge of a minor phase 2 fold outlined by layers rich in biotite, as they appear in thin-section. Rather than sweeping smoothly around the hinges, many individual micas appear to have been rotated away from the plane F_o/F_1 and now lie sub-parallel to F_2. Their new attitudes, as seen with crossed polarizers, are governed by grain boundaries of quartz, which as a result of flattening have become elongate parallel to F_2. Micas trapped between flattening grains of quartz appear to have become well orientated, while those bounding on feldspar are not so well orientated and are often bent or broken. Although some growth of biotite parallel to F_2 may have occurred, the main period of mica growth preceded at least the final movements on F_2, and may date back to an earlier stage in the second or even the first deformation.

The conditions of metamorphism that may have prevailed during phase 1 deformation are part of the same perplexing problem.

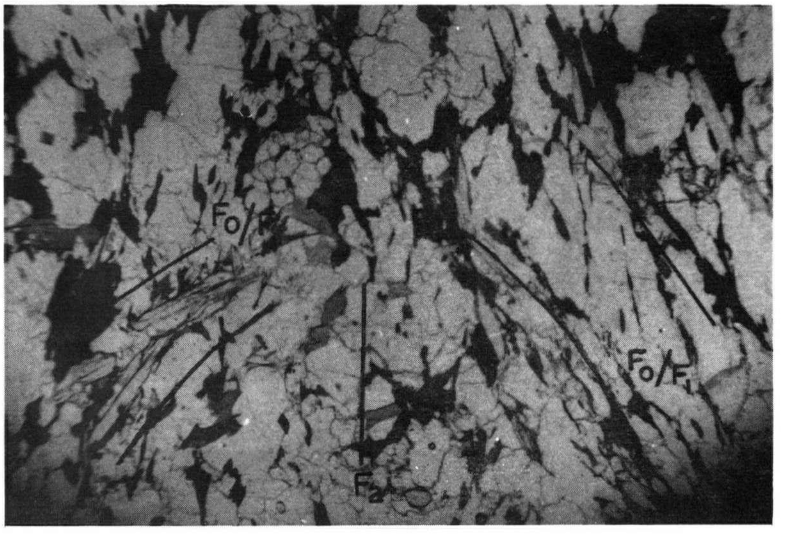


Plate 5-3 Phase 2 minor fold hinge displaying micas parallel and sub-parallel to F_o/F_1 and F_2. Plane polarized light. Field approximately 4.7 mm.

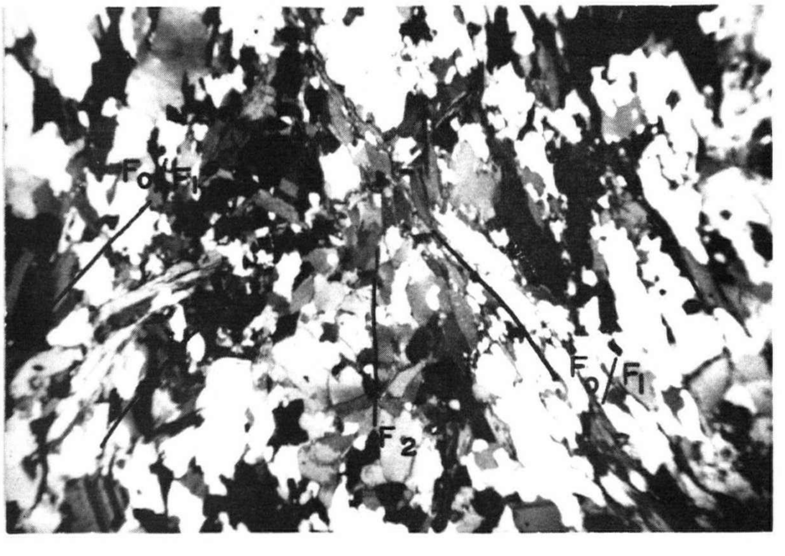


Plate 5-4 Same field as above but with polarizers crossed to illustrate strain pattern in quartz. See text.

Quartz-feldspar (largely plagioclase) segregation layers and lamellae are the obvious fabric elements developed during the first phase of deformation and metamorphism. Where relict phase 1 folds are found, segregation layers are deformed on the hinges (plates 3-1 to 3-8), but are also developed to a lesser degree parallel to F_1. It therefore appears, that the development of segregation layering preceded and overlapped the development of F_1, and that segregation was controlled by an earlier foliation, perhaps parallel to bedding.

Segregation layering is known to be well developed in rocks deformed and metamorphosed in the upper greenschist facies, such as in the Otago schists of New Zealand (Turner, 1968). By analogy, and lacking any evidence to suggest otherwise, conditions of at least middle to upper greenschist facies are therefore suggested for the first deformation in Vaseaux Lake area. During this metamorphism, the development of segregation layering might relate in time to gross chemical re-arrangement and dehydration associated with the breakdown of clays and chlorites, and the formation of micas. Released water may have migrated along shear planes and given rise to segregation layering by a solution-nucleation process.

The degree of development of the axial foliation F_1, during early deformation is not known, and whether it was originally a strain-slip structure or a flow-type cleavage cannot be said with certainty. Where possible vestiges of this early cleavage are seen in thin-section, such as within the impure quartzite shown on plates 5-5 and 5-6, F_1 is outlined by flattened quartz and biotite. The mode of occurrence of these minerals suggest that ductile flow parallel to F_1 was at least a contributing factor in the early

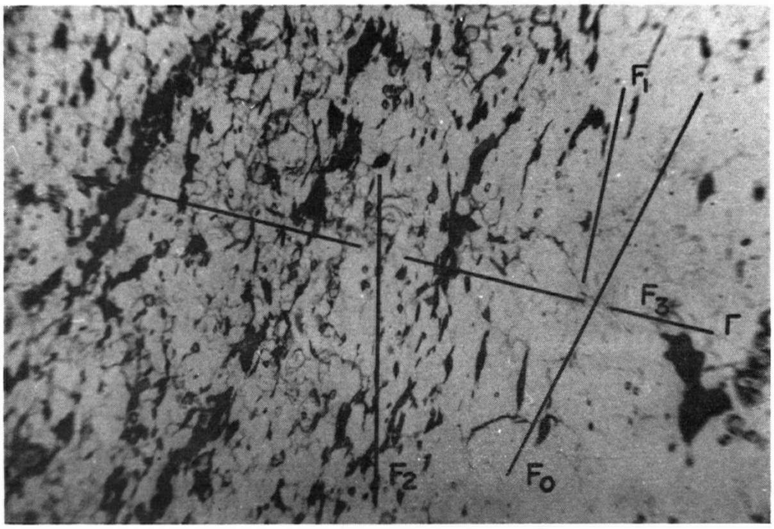


Plate 5-5 Penetrative foliations F_1? and F_2 and bedding F_o in garnet plagioclase (An_{38}) biotite quartzite from Unit 4a. Plane polarized light. Field approximately 4.7 mm.

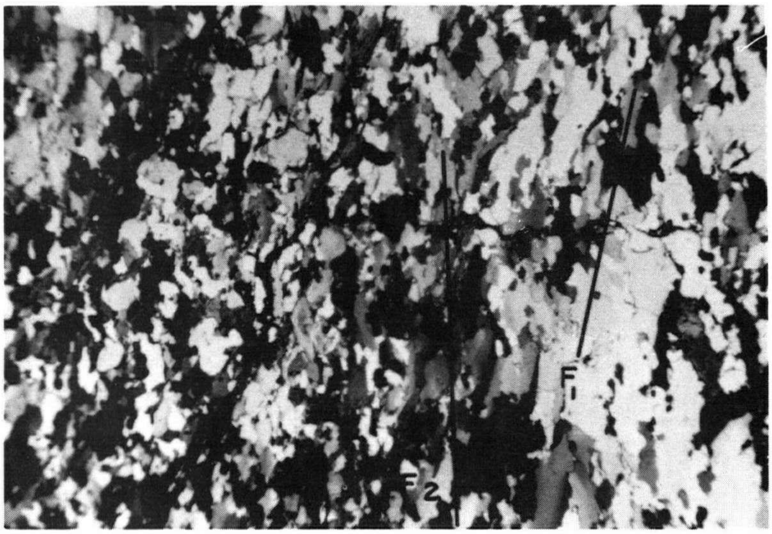


Plate 5-6 Same field as above but with polarizers crossed to illustrate strain patterns in quartz. See text.

deformation, and that synkinematic biotite may have formed and become coarse grained. Neither segregation layering nor F_3 are well developed in plates 5-5 and 5-6, and the observed compositional layering may be bedding (F_o). Biotite lies parallel to F_o and F_1, and both are planes of flattening, in which quartz grains have elongate shapes. The penetrative foliation F_2, also outlined by quartz and biotite, cuts obliquely across both of these earlier structures.

Conclusions:

It would appear that metamorphism accompanying phase 1 deformation in Vaseaux Lake area reached, at least, upper greenschist facies and gave rise to mica bearing assemblages and primitive segregation layering. At some later time, during phase 2 deformation, metamorphism progressed to the amphibolite facies, and synkinematic crystallization resulted in hornblende aligned parallel to L_2, and mimetically along vestiges of the earlier linear structure L_1. Micas probably continued to increase in size in the planes F_o/F_1 and new micas may have grown parallel to F_2. Some mica bounding on quartz as the result of flattening and ductile flow of quartz appears to have been rotated into attitudes sub-parallel to F_2.

Later, probably at the thermal culmination associated with phase 2 deformation, the succession was extensively metasomatized and veined with pegmatite, in advance of a rising pluton (Unit A). Maximum grain size was probably attained as thick granitic sheets were emplaced producing local higher temperature sillimanite bearing assemblages at their immediate contacts.

With waning temperature, phase 2 deformation appears to have continued to affect the succession, but was of a more brittle character. Alternatively brittle deformation parallel to F_2 may be almost entirely the result of renewed closure of phase 2 folds during phase 3 or later deformations, as will be seen in the following sections.

PHASE 3 METAMORPHISM

In Chapters 3 and 4 it has been suggested that phase 3 deformation progressed with increasing temperature from flexural-slip folding, to a more ductile type of deformation, as late-kinematic granitic plutons (Unit B) were emplaced. Emplacement of the main granitic mass may be responsible for the later more extreme part of the deformation. It appears to have made room for itself by flattening and tightening Gallagher Lake Synform and some earlier folds. Emplacement of Unit B probably also marked a local thermal high associated with phase 3 deformation, and may in a general way be considered the cause of metamorphism.

Mineralogically, phase 3 was by nature, a physically destructive event characterized by recrystallization pre-existing amphibolite facies mineral assemblages. New mineral assemblages, either prograde or retrograde, did not form, and new minerals grown from comminuted materials are those present in the original assemblages. Deformation and metamorphism are therefore thought to have culminated at temperatures and pressures that were neither much greater or less than those that produced the middle amphibolite facies assemblages during phase 2 deformation. Although temperatures probably decreased with distance from Unit B, conditions of at least lowest amphibolite facies are implied throughout the area at the culmination phase 3.

Direct evidence of metamorphism in the lower amphibolite facies comes from a few basic and intermediate dykes which were metamorphosed for the first time during phase 3 (Chapter 4). Mineral assemblages in these rocks consist principally of andesine, biotite and hornblende with minor quartz, K-feldspar, epidote, sphene, opaques.

In previously metamorphosed rocks, growth of a new generation of biotite parallel to F_3, such as shown on plate 5-7, is not inconsistent with lower amphibolite facies metamorphism. Biotite, is the only mineral that can be definitely shown to have grown during phase 3, although in some schists tiny euhedral garnets in association with large flattened garnets also may have grown during phase 3.

Pyroxenites and dunites, as indicated in Chapter 4, may have been partially serpentinized during phase 3, suggesting an upper temperature limit of about 500°C (Turner, 1968) within the limited area that such rocks are found. Metamorphism would then be restricted to the lowermost amphibolite facies, but there is unfortunately no way to exactly date the time of serpentinization, and it could, for example, be a very late phase 3 phenomenon, accomplished as temperatures waned.

Although the rocks were not chemically responsive to temperatures and pressures prevailing during phase 3, they responded physically by deforming. Again various minerals present participated in different ways and responded differently depending on their structural position, and the mineralogical composition of the rock in which they occur. Quartz, for example, in weakly deformed semi-pelitic granulites such as shown on plate 5-8, deformed by ductile flow parallel to F_3 and developed pronounced strain

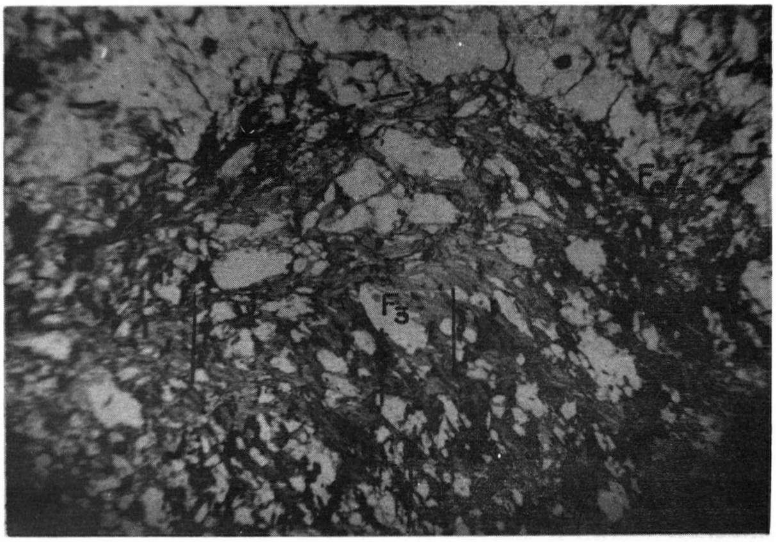


Plate 5-7 Phase 3 biotite aligned parallel to the axial plane F_3 of a minor fold. Plane polarized light. Field approximately 4.7 mm.

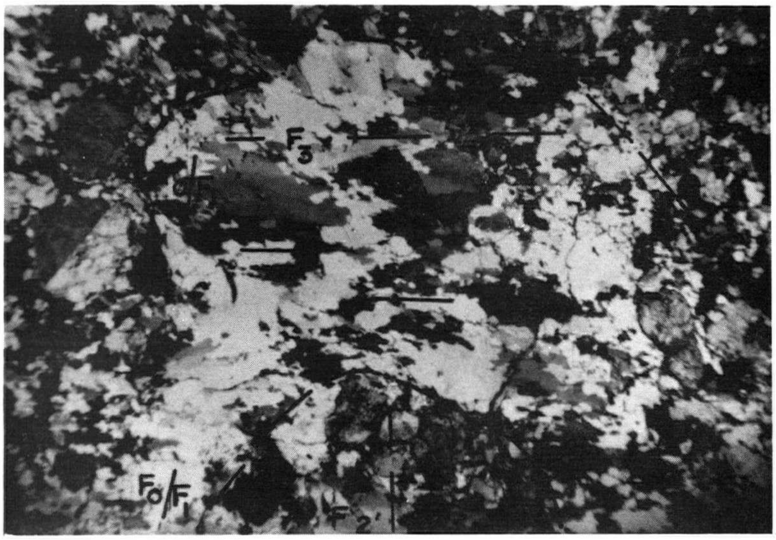


Plate 5-8 Strain pattern in quartz outlining the foliation F_3 across the hinge and limbs of a minor phase 2 fold. Plane polarized light. Field approximately 4.7 mm.

patterns (deformation bands of Carter et al 1964). More brittle minerals such as feldspars, amphibolites and micas were mechanically abraded and sometimes marginally recrystallized.

Extreme deformation related to phase 3 was highly localized by lithology (schist), pre-existing structure (phase 2 folds) and newly developed mylonitic zones of which the slide in the northern map-area is a large-scale example. Some similarities in the sequence of events comprising phase 3 deformation, may be seen in these intensely deformed rocks.

Within schists, large garnets have been flattened in the plane of F_2, but are also slightly to conspicuously elongate parallel or sub-parallel to L_3, which suggests that their deformation must be a phase 3 feature. Just how they attained such shapes during phase 3 is a matter involving some speculation.

Many of these garnets, as indicated by obliquely orientated inclusions of mica, have been rotated at some stage in their history (plate 5-9). Whether rotation accompanied growth during phase 2, or occurred later, cannot be exactly said, but it is thought likely that at least some of the rotation occurred during phase 3, and might be the reason for elongation parallel to L_3.

It is argued that at some early stage in phase 3 deformation, flattening and rotational shear acted simultaneously in the plane of F_2 such that garnets were rolled into "spindle-shapes", elongate approximately parallel to L_3. At a later stage, an episode of non-rotational flattening in the plane of F_2 commenced, and garnets continued to flatten, but retained, to various degrees, elements of their original elongation parallel to L_3. The non-rotational episode of flattening is thought to coincide in time with the late development of strain-slip cleavage F_{3a} (plate 5-10)

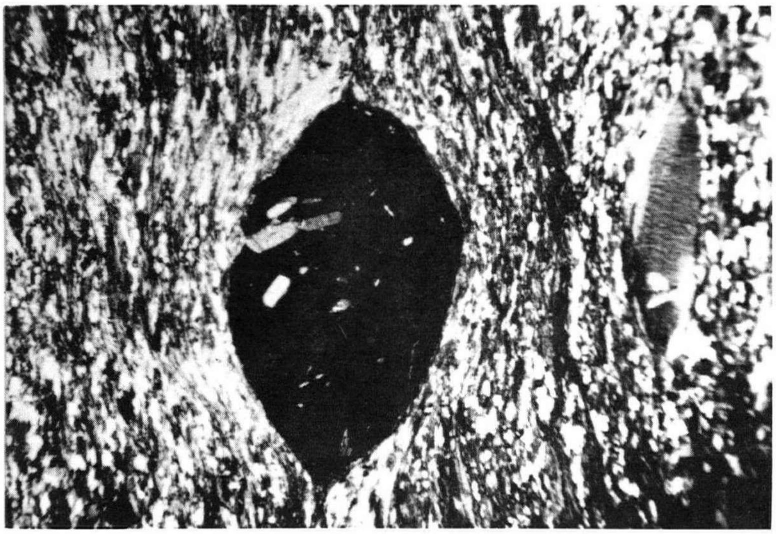


Plate 5-9 Flattened garnet bearing oblique inclusions of mica. Crossed polarizers. Field approximately 4.7 mm.

Plate 5-10 Flattened garnet lying parallel to F_2. Late strain-slip cleavage F_{3a} crosses obliquely. Plane polarized light. Field approximately 4.7 mm.

which took up the shear component previously operating parallel to F_2.

Where garnets are not seen in schists, similar histories may be sometimes inferred from minor folds. For example, in plate 5-11, an isoclinal phase 2 structure has developed in pegmatite veined schist under the influence of flattening and rotational shear (rotated porphyroblasts). Resulting transposed layering is crossed by a later oblique cleavage F_{3a} (plate 5-12) which is best developed in zones of incipient phase 3 folding.

In mylonites where phase 3 deformation is even more intense, and transposition and recrystallization are almost complete, F_{3a} is also a late formed cleavage. Rocks from the northern mylonitic zone, in thin-section, display a well developed cleavage F_{3a} outlined by new biotite, grown from comminuted materials in the matrix (plate 5-13). Here F_{3a} formed after movements parallel to the transposed internal layering had ceased, at a time when shallow phase 3 folds were developed across the mylonites.

The sequence of events inferred from rocks which became highly deformed during phase 3, is consistent with an overall picture of phase 3 deformation. At an early stage rotational shear would be expected on the limbs of the megascopic phase 3 structure (Gallagher Lake Synform) which was developing by a mechanism of flexural-slip. Flattening, at the same time, must have been important, because of renewed closure of phase 2 folds as a result of re-folding.

As temperatures rose and phase 3 deformation was intensified in response to the emplacement of Unit B, rotational shear and flattening within the planes of pre-existing foliations continued until interrupted by the development of phase 3 planar structures.

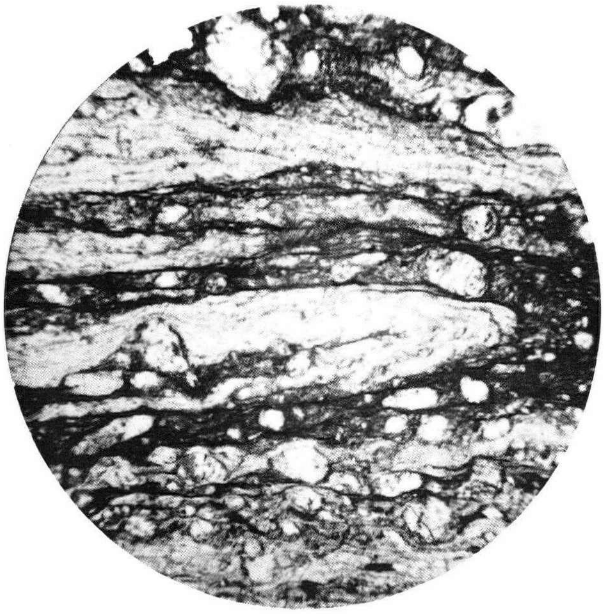


Plate 5-11 Isoclinal phase 2 structure in pegmatite veined schist. Plane polarized light. Field approximately 4.7 mm.

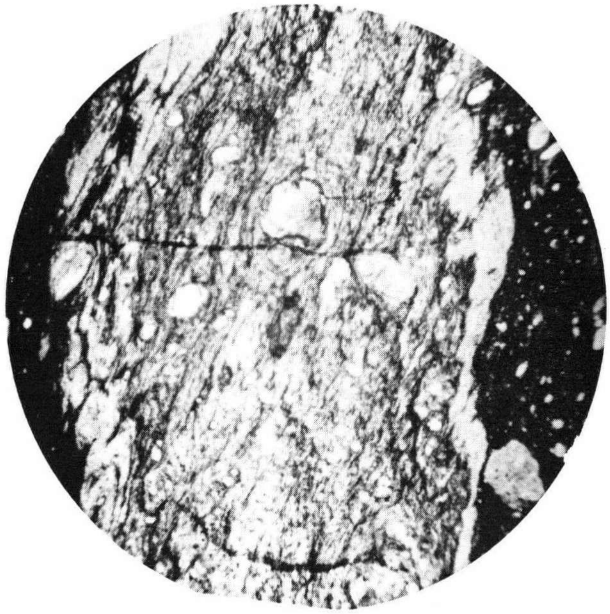


Plate 5-12 Oblique phase 3 structure developed across transposed pegmatitic layering in schist. Plane polarized light. Field approximately 4.7 mm.

This stage was reached when Gallagher Lake Synform became so tightly appressed that it could close no further by a flexural mechanism. A large segment within the core of the Synform, now bounded by the mylonitic zone in the northern map-area, was forced outwards as further closure became difficult, at some transitional stage.

Finally, the penetrative cleavage F_{3a}, a strain-slip structure as well as a plane of flattening, developed and began to take up the shear component previously operating in the planes of earlier foliations. As the Synform continued to close, earlier foliations as well as F_3 planar structures continued to act as planes of flattening.

TERTIARY THERMAL EVENT

Structural and petrographic evidence of an Early Tertiary thermal-hydrothermal event is found in the rocks of Vaseaux Lake area, and probably coincides approximately in time with volcanism in nearby areas. With respect to the development of structure, the thermal event overlapped phases 4 and 5 of deformation, both of which include episodes of open folding and fracturing.

Rhomb porphyry sills and dykes, equivalent in age to the basal Marron lavas, were emplaced during the fourth phase of folding, and developed strong foliations parallel to their margins (Chapter 4). Their margins are but weakly chilled, and it is thought that the wall-rocks may have been warm at the time they were emplaced, and that cooling may have been somewhat inhibited. Slow cooling is further implied by the unmixing of two feldspars in anorthoclase (plate 5-14) although exsolution was probably facilitated by simultaneous shearing, as it is best developed in more highly

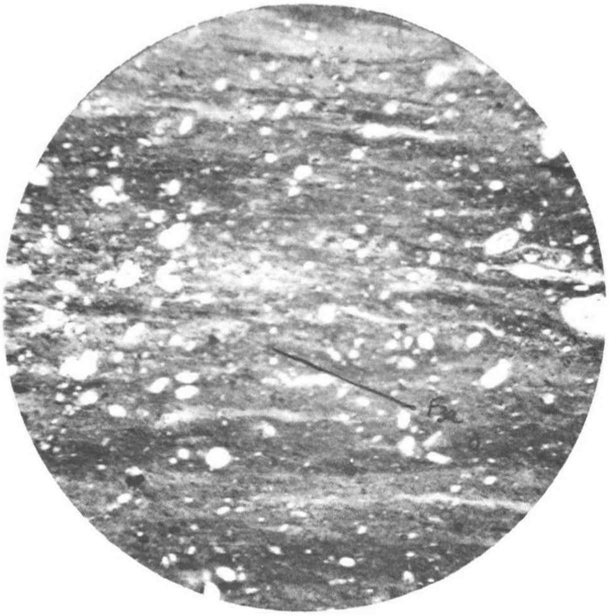


Plate 5-13 Late cleavage F_{3a} outlined by new biotite across transposed layering in mylonite. Plane polarized light. Field approximately 4.7 mm.

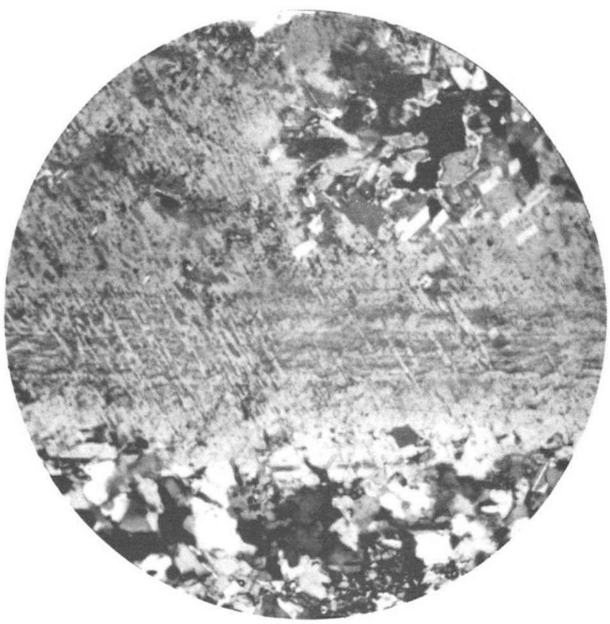


Plate 5-14 Exsolution textures and relict zoning at the margin of a rhomb shaped pseudo-anothoclase phenocryst. Crossed polarizers. Field approximately 4.7 mm.

sheared rocks.

Another feature of highly sheared rhomb porphyries are pseudomorphs of hornblende rimed by biotite, after phenocrysts of clinopyroxene. It is thought that such hornblende and biotite may have formed by a late hydrothermal reaction aided by shearing as the rhomb porphyry bodies cooled, rather than by a reaction induced by a regional P/T environment approaching amphibolite facies.

Evidence of widespread hydrothermal activity, also of probable Early Tertiary age is found throughout Vaseaux Lake map-area. Intense hydrothermal alteration is restricted to two large areas, near the southern and northern boundaries of the map-area (plate 5-pocket), but incipient to weak replacement of biotite and hornblende by chlorite, epidote-chlorite veining, and weak sericitization of feldspar is often found elsewhere.

Most highly altered rocks within the large zones of intense alteration, are bleached white to grey derivatives of metamorphic and granitic rock, veined and impregnated with clay minerals. Feldspars are replaced by clays and sericite, ferromagnesian minerals are not to be found, and textures are strikingly cataclastic (plate 5-15). Outward through a broad zone, chlorite and epidote became progressively more abundant, and relicts of original fabric and texture may be recognized. Sericite persists in plagioclase, but saussurite becomes the dominant alteration product, and small amounts of secondary carbonate and pyrite are found along fractures. At greater distance from the centers, beyond the zones shown on plate 5, the alteration slowly diminishes to an incipient level, and is not seen at all in some distant areas.

Zones of most intense alteration appear to be structurally

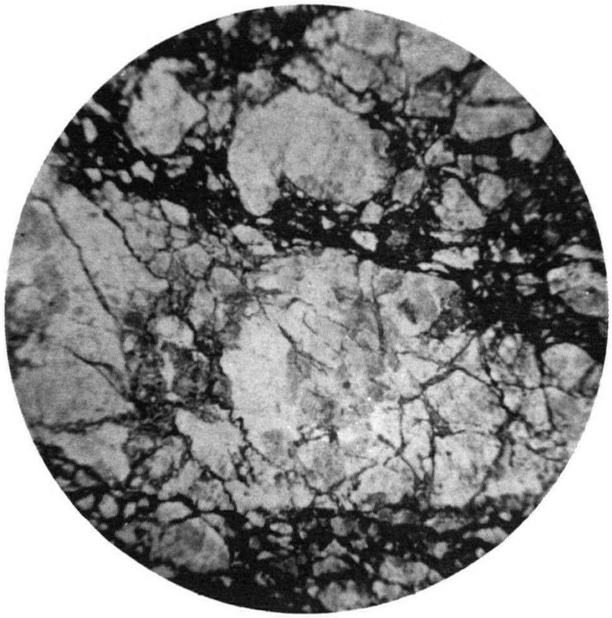


Plate 5-15 Cataclastic texture in bleached granodiorite from the southern zone of argillic alteration. Plane polarized light. Field approximately 4.7 mm.

controlled and are not, in any way, directly related to exposed igneous bodies. At the southern occurrence, most intense alteration is clearly related to faults which bound an internally fractured granitic block (Unit B) on the north and east. In the north, the zone lies roughly along the axial trace of Okanagan Falls Syncline (Church, 1967), a major phase 5 fold containing volcanics and sediments of the Early Tertiary Marmara and White Lake Formations in its core. Elsewhere, where alteration is less extreme, J_1 fractures have strongly bleached walls and contain chlorite, epidote, and sericite. J_2 fractures may or may not be altered, and younger fracture sets J_3 and J_4 are entirely younger than the hydrothermal event. The time of alteration, from a structural point of view, would therefore be placed between late phase 4 deformation (J_1) and early phase 5 deformation (J_2) (see Chapter 3).

Relationships between Tertiary rocks in the core of Okanagan Falls Syncline, and the underlying Vaseaux Formation also provide a clue to the age of the alteration. The Tertiary rocks are, in general, unaltered with the exception of small zones that may be genetically related to volcanic rocks in the lower part of the sequence. In contrast, the underlying Vaseaux Formation within 50 feet of the contact is highly altered, and the broad zone of intense alteration within the Vaseaux Formation projects directly into the very much less altered Tertiary rocks. The drastic change in alteration intensity is difficult to explain without invoking a pre-Marmara and White Lake age for the alteration despite the fact that the unconformity is not exposed, and the contact may or may not be, in part, a fault (Little, 1961).

The observed relationships suggest that phase 5 folding commenced (Okanagan Falls Syncline began to form) and fractures were opened along its hinge localizing the most intense hydrothermal activity. Locally altered Marmara volcanics and pyroclastics in the lower part of the Tertiary pile may have accompanied or closely followed the period of most intense alteration, but overlying White Lake sediments were deposited later. Perhaps Okanagan Falls Syncline continued to grow and formed the basin of deposition in which the White Lake sediments accumulated, and in which they were ultimately deformed.

Although intense alteration in the Vaseaux Formation does not directly coincide in space with centers of Tertiary volcanism, both are related in time, and are therefore considered to be related phenomena. In its broadest aspects (detailed clay mineralogy not available), the alteration is similar to that affecting granitic and volcanic rocks beneath presently active hot-springs such as Sulphur Bark and Steamboat Springs (Dickson and Tenell, 1967). Hot-springs therefore may have existed near the northern and southern boundaries of the map-area in the Early Tertiary. These became extinct before White Lake sediments were deposited in Okanagan Falls Syncline, and thus might relate in time to either the Marron volcanics or the somewhat younger Marmara volcanics.

CHAPTER SIX

CONCLUSIONS

SUMMARY OF GEOLOGIC HISTORY (Contributions)

Within the Vaseaux Formation of the present map area a local structural succession comprised of 5 lithologic units exceeding 4000 feet in total present thickness has been established. These lithologic map-units consist of high grade metamorphic rocks that were probably derived from turbidite sandstones, shales and basic volcanic rocks deposited and interbedded with minor carbonate and quartzite in a near shore environment. Subsequently the Vaseaux Formation has undergone a complex history of polyphase deformation, metamorphism and igneous intrusion as summarized below.

1. Phase 1 folding, similar in style and along northerly trends, gave rise to McIntyre Bluff Fold and minor structures. These folds may have been originally recumbent, and associated tectonic slides which developed probably continued to be active at various times during later deformation.

Metamorphism which accompanied phase 1 deformation appears to have reached at least upper greenschist facies, and gave rise to primitive segregation layering. Minor sheets of quartz monzonite were emplaced into the succession before or during phase 1 deformation.

2. Phase 2 folding, also similar in style but along northwesterly trends re-folded and tightened the earlier recumbent structures. Major folds formed during phase 2 are Vaseaux Lake Antiform, Shuttleworth Creek Synform, and other unnamed structures,

and congruent minor folds are abundant in association with these. Axial planes of phase 2 folds were originally inclined at some moderate angle to the northeast and their axes were almost horizontal.

Metamorphism in the amphibolite facies and ubictuous synkinematic recrystallization accompanied phase 2 deformation, and the metamorphism may or may not have been a continuation and culmination of that associated with phase 1. At the thermal culmination associated with phase 2, the succession was extensively metasomatized and veined with pegmatite in advance of a rising pluton (Unit A). A thick sheet of synkinematic granitic gneiss with several crosscutting apophyses was then emplaced along the limbs and axial planes of phase 2 folds. These granitic rocks together form the differentiated top of a somewhat more mafic pluton (Unit A) which became frozen at the observed level at a late stage in phase 2 deformation.

Small lenses and sheets of ultra basic rock may have been tectonically emplaced at an early stage in the second or during the first phase of deformation. Their origin is unknown.

3. Phase 3 deformation commenced with flexural-slip folding along westnorthwesterly trends but progressed to a more ductile type of deformation (similar folding) as granitic rocks of Unit B were emplaced. Callagher Lake Synform and congruent minor folds were formed early about southwesterly dipping axial planes and near horizontal axes and continued development about the same directions throughout the latter part of phase 3 deformation. As Gallagher Lake Synform continued to close in response to forceful emplacement of a sub-concordent pluton (Unit B) a slide

developed, and gave rise to mylonite, and local minor folds of diverse trend. Earlier formed phase 1 and 2 structures were re-folded, tightened and variously re-orientated throughout phase 3.

Narrow basic to intermediate dykes intruded the succession at some time between phase 2 and phase 3 deformation. Their emplacement along steep fractures indicates that development of phase 2 and phase 3 folds along almost co-axial trends are not a result of a single long-continued dynamothermal event. Rather phases 2 and 3 were separated by a period of time of unknown duration when the rocks were cool and brittle.

Later metamorphism, which accompanied phase 3, reached at least lower amphibolite facies, possibly at about the time granitic rocks of Unit B were emplaced. New mineral assemblages were formed in the above mentioned dykes, while pre-existing phase 2 assemblages remained unchanged. Minerals newly crystallized from comminuted materials in the matrix were oriented along phase 3 directions.

The minimum age of phase 3 deformation has been set at 140 m.y. (Upper Jurassic) by K/Ar dates on the post-phase 3 Oliver stock.

4. Phase 4 folding, flexural-slip in style, gave rise to a major northerly trending antiform with a steeply dipping axial plane and gently plunging axis. Earlier structures were slightly re-orientated on the limbs of this large antiform, and slip within the planes of pre-existing foliations gave local discontinuities along which thin zones of mylonite were developed. Fracturing along steeply dipping northnortheasterly trending surfaces accompanied and/or followed phase 4 folding.

Phase 4 is dated with respect to nearby early Tertiary rocks by anorthoclase bearing rhomb porphyry dykes involved in the deformation. These are equivalent in age to anorthoclase bearing lavas of the basal Marron Formation and their age and the age of deformation has been set at 44 m.y. B.P. by K/Ar dating (Ross and Barnes 1972).

Widespread hydrothermal alteration, probably associated in space and time with rising early Tertiary Marron lavas, and possibly related to hot-spring systems, affected the succession during phase 4 and overlapped the incipient stages of phase 5 deformation.

5. Phase 5 folding, also flexural-slip in style, produced open all scale northwesterly trending folds with steeply dipping axial planes and shallowly plunging axes. These folds have resulted in further re-orientation of the earlier structures, and a large antiform intersects the earlier phase 4 anitform to give a broad domal structure near the centre of the map-area. Phase 5 folding was accompanied by extensive fracturing and faulting and was accomplished primarily by buckling of independent fault bounded blocks.

Phase 5 may have followed continuously from, or shortly after, phase 4 deformation but was by character a more brittle (cooler) deformation. The hydrothermal event associated with phase 4 clearly pre-dates deposition of White Lake sediments which now occupy the core of phase 5 Okanagan Falls Syncline. A minimum age of phase 5 deformation is set at pre-Miocene by which time the late mature erosion surface preserved in the district had developed.

INTERPRETATION

The age of the Vaseaux Formation and 5 later phases of deformation cannot all be determined by observation of relationships withir the area mapped or within nearby areas. Ages of phases 4 and 5 of deformation are best known and may be set at 44 m.y.B.P. and post 44 m.y.B.P. - pre 25 m.y.B.P. respectively on the basis of K/Ar dating of Marron Rhomb porphyry dykes which were deformed during phase 4 (Ross and Barnes 1972). Involvement of White Lake sediments in only phase 5 folding and the development of a later mature erosion surface prior to the Miocene (Church 1967) place limits on phase 5.

A minimum 140 m.y.B.P. (Upper Jurassic) age for phase 3 deformation has been suggested previously on the basis of the K/Ar age (White et al.) of the post-phase 3 Oliver stock. Recent work west of the map-area (Ross and Barnes 1972), to the contrary has shown that phase 3 deformation is pre-late Mississippian in age. The evidence for the foregoing statement is found near Olalla and at Blind Creek where undeformed fossiliferous limestones of late Mississippian or early Pennsylvanian age overlie highly deformed rocks of the Old Tom and Shoemaker Formations in which structures equivalent to phases 2 and 3 in the Vaseaux Formation are present.

The Upper Jurassic minimum age for phase 3 deformation suggested by the Oliver stock would, therefore, seem to be erroneous, at least superficially. Further the synkinematic phase 3 pluton Unit B, despite its lithologic similarity with parts of the Oliver stock, would seem to be much older and totally unrelated.

In explanation, an alternate hypothesis is offered that seems more consistent with the history of phase 3 deformation and the implied synkinematic intrusion of Unit B. That is, phase 3 structures which formed originally during a Paleozoic orogeny were reactivated during the Upper Jurassic at the time of intrusion of granitic magmas and Unit B. As previously shown, Unit B was emplaced along pre-existing phase 3 structures (Figures 4-3 and 4-4) but no evidence was found to suggest that the intrusion had to be closely associated in time with the first development of that structure. Factual evidence only supports an argument that the penetrative foliation F3 remained active subsequent to emplacement of Unit B and, reactivation is a possible explanation.

If the above hypothesis were true, phase 3 could no longer be regarded as a single, continuous dynamothermal event culminating with the emplacement of granitic magmas. An extended interval of time between late Mississippian and Upper Jurassic, when the rocks remained undeformed, would then separate the first and last movements associated with phase 3. First movements might correspond to part of the Lower Mississippian Caribooan Orogeny (Douglas et al., 1968) with the later reactivation of phase 3 structures in response to the Upper Jurassic - Cretaceous Columbian Orogeny.

The age of phase 1 and phase 2 deformation in the Vaseaux Formation are not known other than by generalization that they must be older than the pre-late Upper Mississippian phase 3 event. It seems conceivable that both might have originated during some early phase of the Lower Mississippian Caribooan Orogeny, but one or both might relate to some yet earlier event.

Structures equivalent to phase 2 in the Vaseaux Formation have been recognized and correlated in both the Kobau Group (Okulitch, 1969) and the Old Tom and Shoemaker Formations (Ross and Barnes 1972) and presumably all of the above rocks are of about the same age. Okulitch,1969, suggested that the Kobau sediments were derived in part from rising nappe structures developed during phase 1 folding of the Vaseaux Formation, and soon became involved in the phase 2 re-folding of these nappes. If Okulitch is correct, phases 1 to 3 of deformation may all relate in time to the Cariboоan Orogeny, and the later phase 2 and 3 folds might be locally developed accommodations rather than regionally developed fold sets. For that reason correlations of fold sets across great distances within the Shuswap complex, without the benefit of detailed knowledge of intervening areas, could be very misleading and is not warranted at this time.

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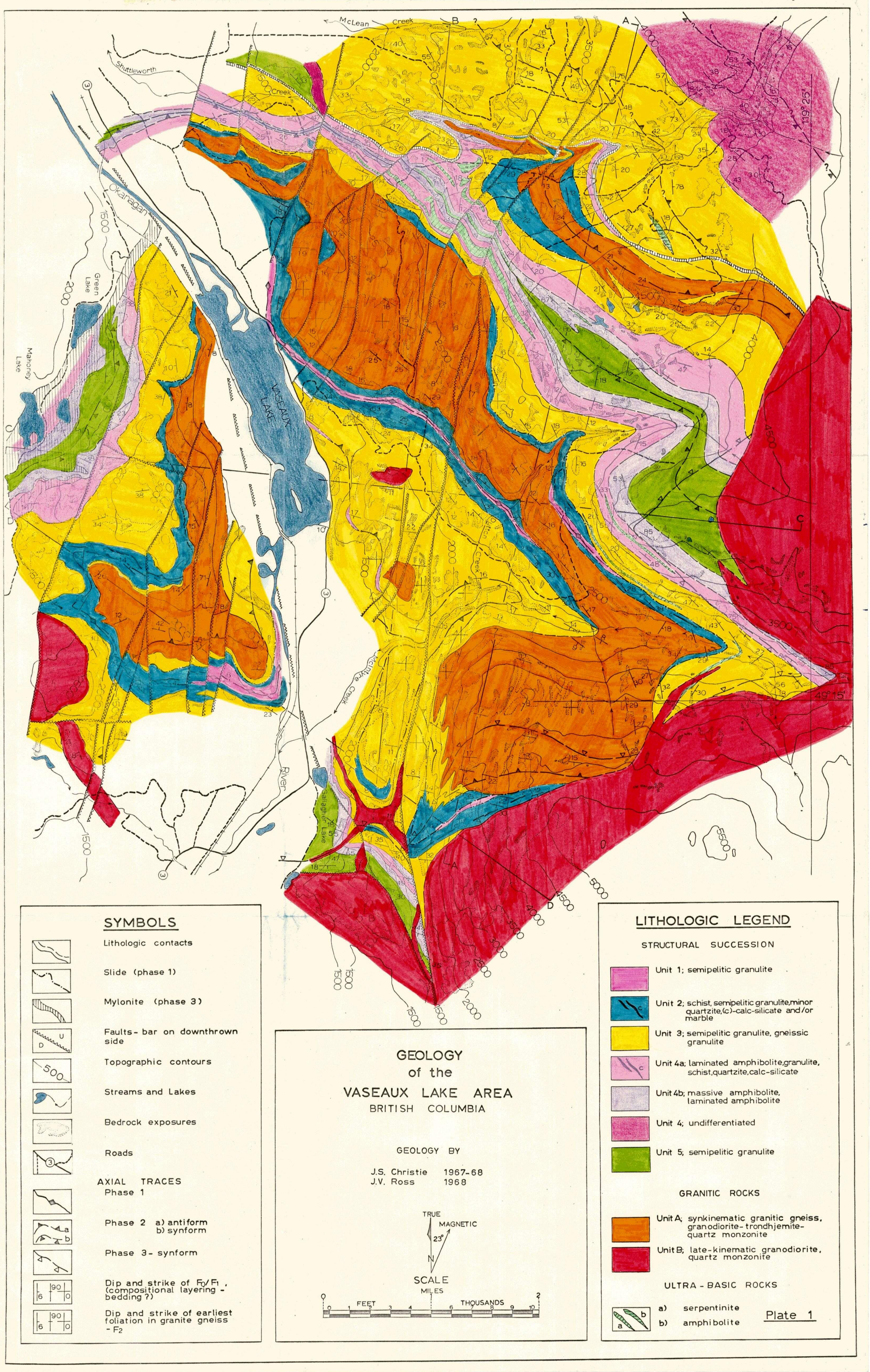
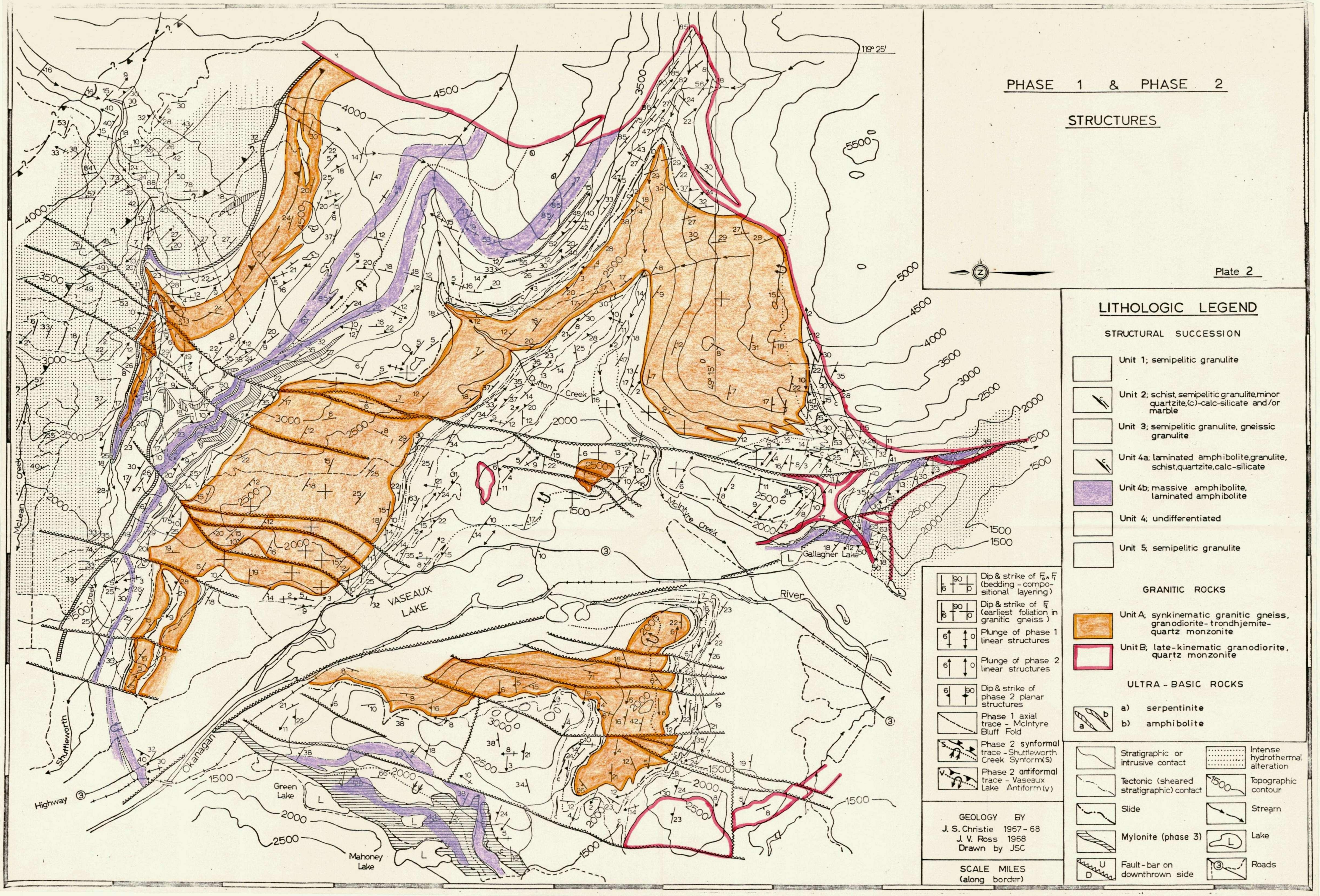
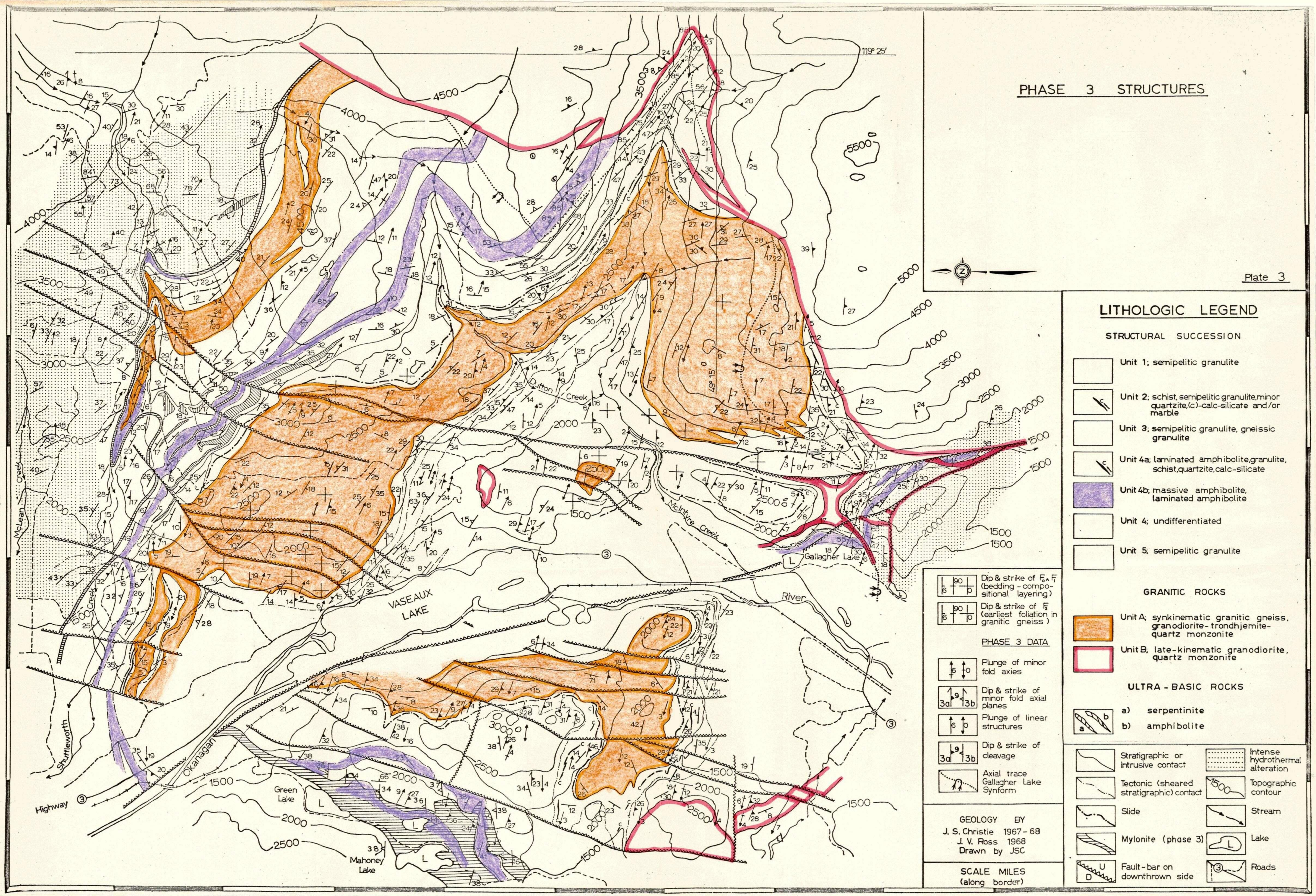
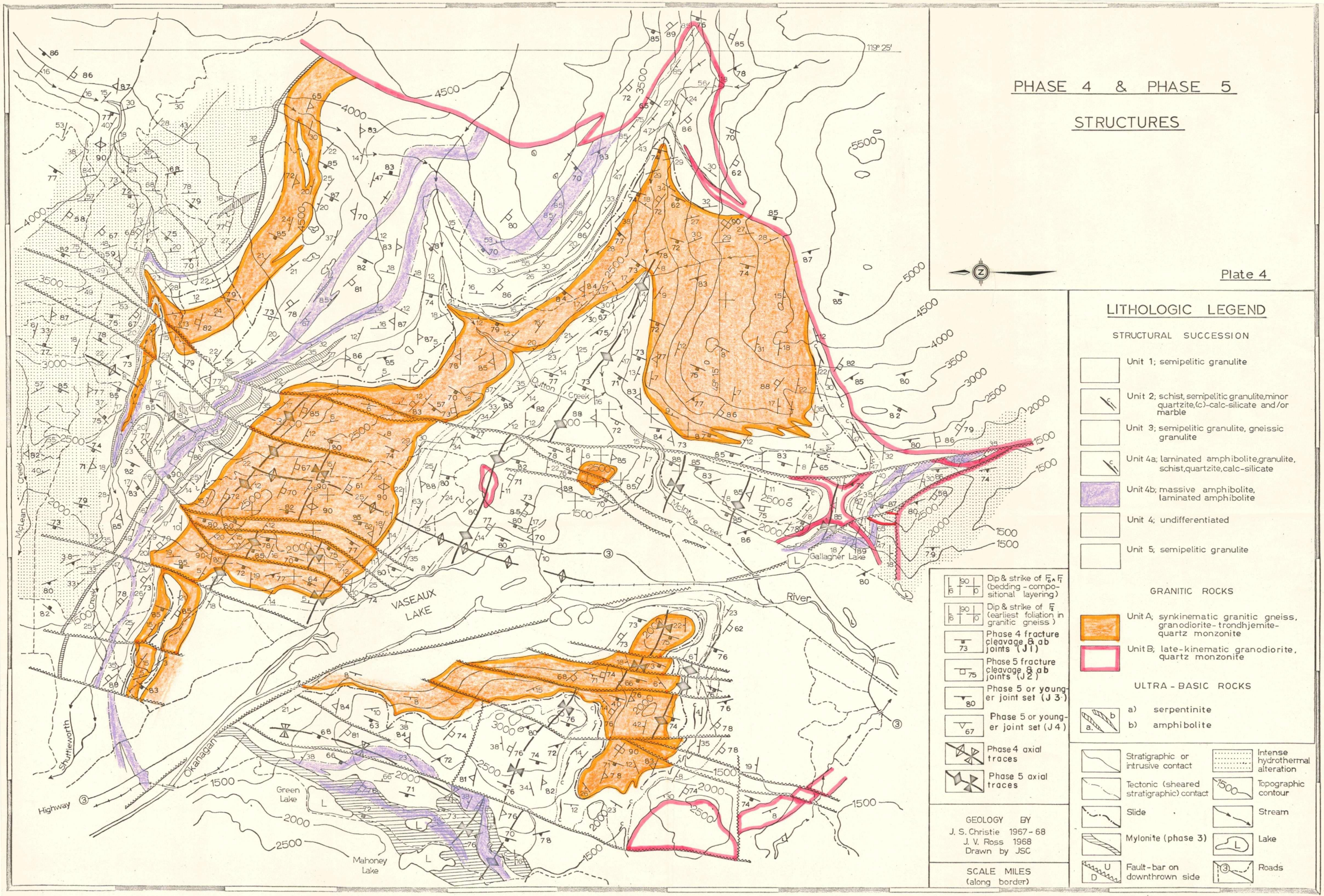

McLean Creek
Shuttleworth Creek
Okanagan
Green Lake
Mahoney Lake
VASEAUX LAKE
McIntyre Creek
River
Gallagher Lake
119°25'
49°15'
SYMBOLS
Lithologic contacts
Slide (phase 1)
Mylonite (phase 3)
Faults- bar on downthrown side
Topographic contours
Streams and Lakes
Bedrock exposures
Roads
AXIAL TRACES
Phase 1
Phase 2 a) antiform
b) synform
Phase 3- synform
Dip and strike of F0/F1 (compositional layering - bedding ?)
Dip and strike of earliest foliation in granite gneiss - F2
GEOLOGY
of the
VASEAUX LAKE AREA
BRITISH COLUMBIA
GEOLOGY BY
J.S. Christie 1967-68
J.V. Ross 1968
TRUE
MAGNETIC
23°
N
SCALE
MILES
FEET
THOUSANDS
LITHOLOGIC LEGEND
STRUCTURAL SUCCESSION
Unit 1; semipelitic granulite
Unit 2; schist, semipelitic granulite, minor quartzite, (c)-calc-silicate and/or marble
Unit 3; semipelitic granulite, gneissic granulite
Unit 4a; laminated amphibolite, granulite, schist, quartzite, calc-silicate
Unit 4b; massive amphibolite, laminated amphibolite
Unit 4; undifferentiated
Unit 5; semipelitic granulite
GRANITIC ROCKS
Unit A; synkinematic granitic gneiss, granodiorite-trondhjemite-quartz monzonite
Unit B; late-kinematic granodiorite, quartz monzonite
ULTRA-BASIC ROCKS
a) serpentinite
b) amphibolite
Plate 1


PHASE 1 & PHASE 2
STRUCTURES
Plate 2
LITHOLOGIC LEGEND
STRUCTURAL SUCCESSION
Unit 1; semipelitic granulite
Unit 2; schist, semipelitic granulite, minor quartzite, (c)-calc-silicate and/or marble
Unit 3; semipelitic granulite, gneissic granulite
Unit 4a; laminated amphibolite, granulite, schist, quartzite, calc-silicate
Unit 4b; massive amphibolite, laminated amphibolite
Unit 4; undifferentiated
Unit 5; semipelitic granulite
GRANITIC ROCKS
Unit A; synkinematic granitic gneiss, granodiorite-trondhjemite-quartz monzonite
Unit B; late-kinematic granodiorite, quartz monzonite
ULTRA-BASIC ROCKS
a) serpentinite
b) amphibolite
Stratigraphic or intrusive contact
Intense hydrothermal alteration
Tectonic (sheared stratigraphic) contact
Topographic contour
Slide
Stream
Mylonite (phase 3)
Lake
Fault-bar on downthrown side
Roads
Dip & strike of F_0 & F_1 (bedding - compositional layering)
Dip & strike of F_1 (earliest foliation in granitic gneiss)
Plunge of phase 1 linear structures
Plunge of phase 2 linear structures
Dip & strike of phase 2 planar structures
Phase 1 axial trace - McIntyre Bluff Fold
Phase 2 synformal trace - Shuttleworth Creek Synform(S)
Phase 2 antiformal trace - Vaseaux Lake Antiform (v)
GEOLOGY BY
J. S. Christie 1967-68
J. V. Ross 1968
Drawn by JSC
SCALE MILES
(along border)
119° 25'
VASEAUX LAKE
Okanagan River
Gallagher Lake
Green Lake
Mahoney Lake
Dutton Creek
McIntyre Creek
McLean Creek
Shuttleworth Creek
Highway 3



PHASE 3 STRUCTURES
Plate 3
LITHOLOGIC LEGEND
STRUCTURAL SUCCESSION
Unit 1; semipelitic granulite
Unit 2; schist, semipelitic granulite, minor quartzite, (c)-calc-silicate and/or marble
Unit 3; semipelitic granulite, gneissic granulite
Unit 4a; laminated amphibolite, granulite, schist, quartzite, calc-silicate
Unit 4b; massive amphibolite, laminated amphibolite
Unit 4; undifferentiated
Unit 5; semipelitic granulite
GRANITIC ROCKS
Unit A; synkinematic granitic gneiss, granodiorite-trondhjemite-quartz monzonite
Unit B; late-kinematic granodiorite, quartz monzonite
ULTRA-BASIC ROCKS
a) serpentinite
b) amphibolite
Dip & strike of F₀∧F₁ (bedding - compositional layering)
Dip & strike of F₁ (earliest foliation in granitic gneiss)
PHASE 3 DATA
Plunge of minor fold axies
Dip & strike of minor fold axial planes
Plunge of linear structures
Dip & strike of cleavage
Axial trace Gallagher Lake Synform
Stratigraphic or intrusive contact
Tectonic (sheared stratigraphic) contact
Slide
Mylonite (phase 3)
Fault-bar on downthrown side
Intense hydrothermal alteration
Topographic contour
Stream
Lake
Roads
GEOLOGY BY
J. S. Christie 1967-68
J. V. Ross 1968
Drawn by JSC
SCALE MILES
(along border)
VASEAUX LAKE
Gallagher Lake
Green Lake
Mahoney Lake
Dutton Creek
McIntyre Creek
McLean Creek
Shuttleworth Creek
Okanagan River
Highway
119° 25'


PHASE 4 & PHASE 5
STRUCTURES
Plate 4
LITHOLOGIC LEGEND
STRUCTURAL SUCCESSION
Unit 1; semipelitic granulite
Unit 2; schist, semipelitic granulite, minor quartzite, (c)-calc-silicate and/or marble
Unit 3; semipelitic granulite, gneissic granulite
Unit 4a; laminated amphibolite, granulite, schist, quartzite, calc-silicate
Unit 4b; massive amphibolite, laminated amphibolite
Unit 4; undifferentiated
Unit 5, semipelitic granulite
GRANITIC ROCKS
Unit A, synkinematic granitic gneiss, granodiorite-trondhjemite-quartz monzonite
Unit B, late-kinematic granodiorite, quartz monzonite
ULTRA-BASIC ROCKS
a) serpentinite
b) amphibolite
Stratigraphic or intrusive contact
Intense hydrothermal alteration
Tectonic (sheared stratigraphic) contact
Topographic contour
Slide
Stream
Mylonite (phase 3)
Lake
Fault-bar on downthrown side
Roads
Dip & strike of $F_0 \wedge F_1$ (bedding - compositional layering)
Dip & strike of F_1 (earliest foliation in granitic gneiss)
Phase 4 fracture cleavage & ab joints (J1)
Phase 5 fracture cleavage & ab joints (J2)
Phase 5 or younger joint set (J3)
Phase 5 or younger joint set (J4)
Phase 4 axial traces
Phase 5 axial traces
GEOLOGY BY
J. S. Christie 1967-68
J. V. Ross 1968
Drawn by JSC
SCALE MILES
(along border)
119° 25'
VASEAUX LAKE
River
Okanagan
Highway 3
Dutton Creek
McIntyre Creek
Gallagher Lake
McLean Creek
Shuttleworth Creek
Green Lake
Mahoney Lake

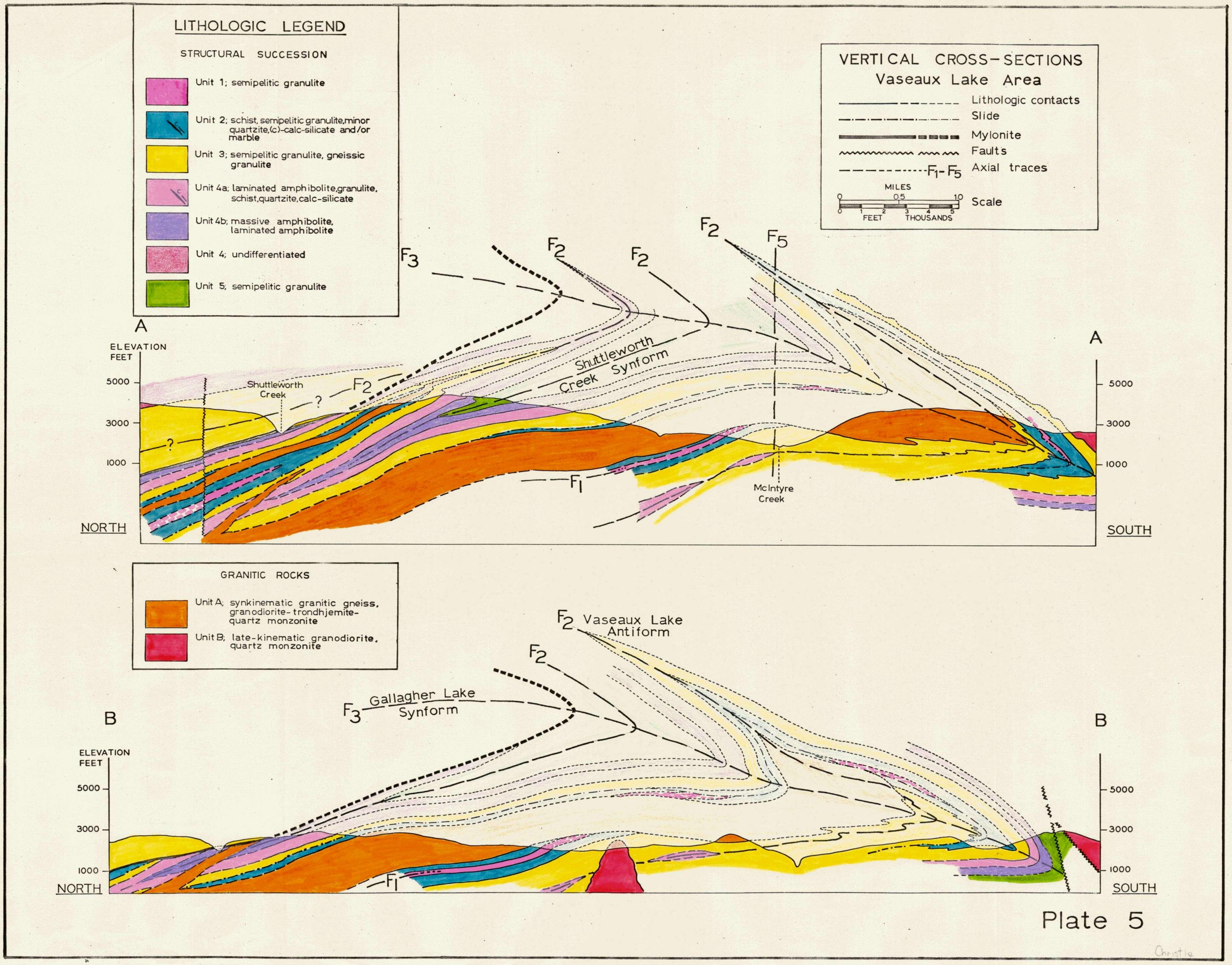


Plate 5

Christie

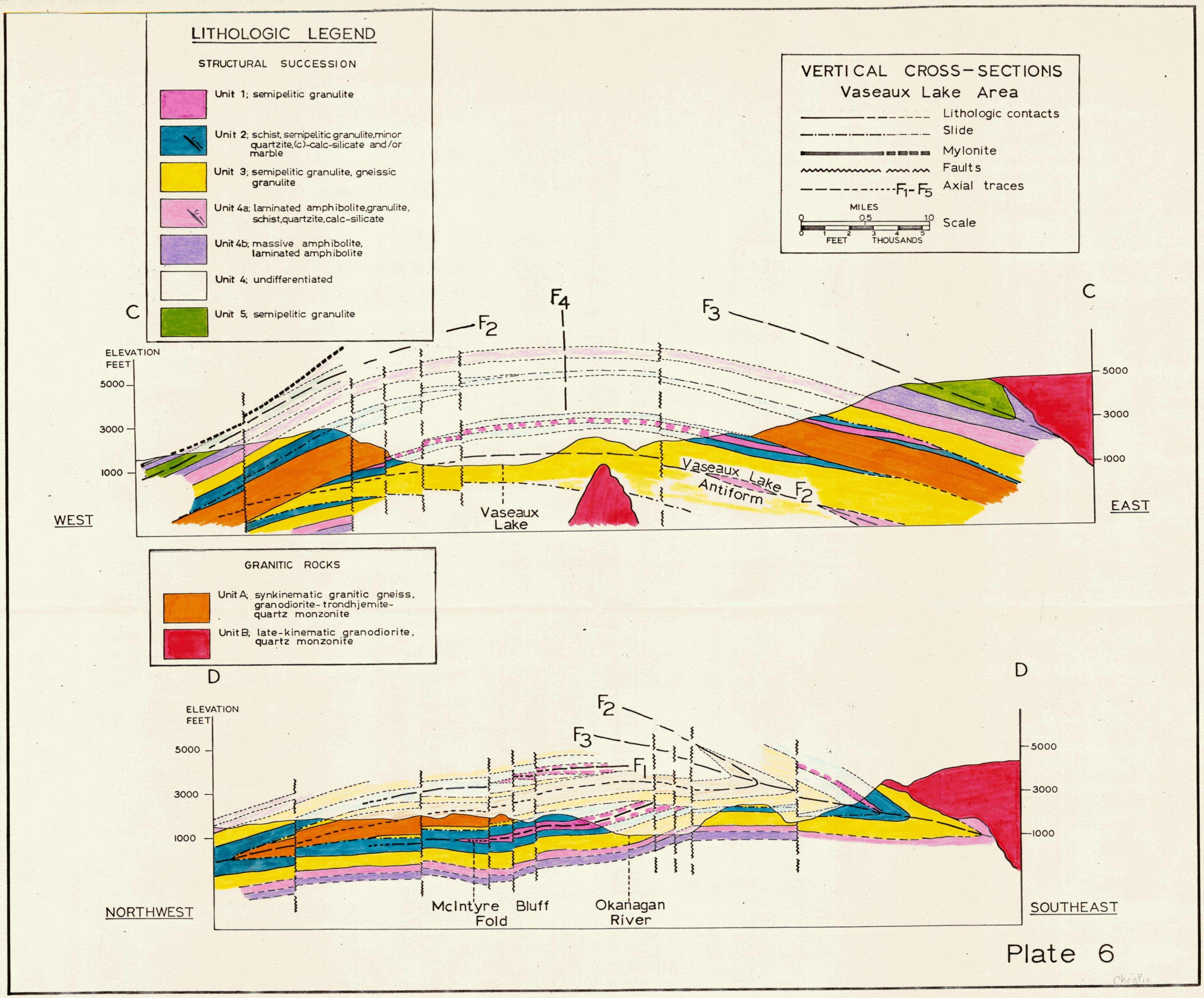

LITHOLOGIC LEGEND
STRUCTURAL SUCCESSION
Unit 1; semipelitic granulite
Unit 2; schist, semipelitic granulite, minor quartzite, (c)-calc-silicate and/or marble
Unit 3; semipelitic granulite, gneissic granulite
Unit 4a; laminated amphibolite, granulite, schist, quartzite, calc-silicate
Unit 4b; massive amphibolite, laminated amphibolite
Unit 4; undifferentiated
Unit 5; semipelitic granulite
VERTICAL CROSS-SECTIONS
Vaseaux Lake Area
Lithologic contacts
Slide
Mylonite
Faults
F1-F5 Axial traces
MILES
0 0.5 1.0
0 1 2 3 4 5
FEET THOUSANDS
Scale
C
C
F4
F3
F2
ELEVATION FEET
5000
3000
1000
WEST
EAST
Vaseaux Lake
Vaseaux Lake F2 Antiform
GRANITIC ROCKS
Unit A; synkinematic granitic gneiss, granodiorite-trondhjemite-quartz monzonite
Unit B; late-kinematic granodiorite, quartz monzonite
D
D
F2
F3
F1
ELEVATION FEET
5000
3000
1000
NORTHWEST
SOUTHEAST
McIntyre Bluff Fold
Okanagan River

Plate 6