THE UNIVERSITY OF MANITOBA

A VOLCANICLASTIC SEQUENCE ON THE FLANK OF AN EARLY PRECAMBRIAN STRATOVOLCANO LAKE OF THE WOODS, NORTHWESTERN ONTARIO

by

DWAYNE PETER CAR

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

DEPARTMENT OF EARTH SCIENCES

WINNIPEG, MANITOBA

FEBRUARY, 1980

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ABSTRACT

A 4 km thick, fragmental, intermediate to felsic, metavolcanic sequence has been examined for a strike length of 18 km in the Lake of the Woods area, Northwestern Ontario. The sequence occurs between two mafic flow formations and represents a section through the subaqueous flank of a large felsic to intermediate stratovolcano that was erupted atop a large subaqueous to locally subaerial mafic shield volcano.

The sequence comprises, in ascending stratigraphic succession, 1) a laterally limited felsic ash-flow tuff formation, 2) an extensive heterolithic felsic to intermediate breccia deposited by debris flows, 3) a lenticular monolithic granodioritic conglomerate deposited by debris flows and largely enclosed by the underlying heterolithic breccia, 4) a lenticular formation of mafic flows completely enclosed by the heterolithic breccia, 5) a second more extensive monolithic conglomerate with two heterolithic members, 6) a thick greywacke formation that contains minor heterolithic breccia units and a thin chert-magnetite iron formation, 7) a third and final monolithic conglomerate of limited lateral extent, 8) a felsic ash-flow tuff, and 9) a felsic formation consisting of several members ranging from flows to lapilli-tuff. The last two formations are coeval with the lowermost part of the overlying mafic flow formation.

All units were deposited subaqueously, but the heterolithic breccia, monolithic conglomerate, and breccia interbeds within the greywacke were derived from the subaerial portions of the stratovolcano. Only a subaerial environment is capable of providing the intense mixing of

clast types observed in these formations, and rounding of clasts in the conglomerate.

Initial fragmental volcanism consisted of felsic Plinian eruptions that produced ash-flow tuff. Subsequent intermediate Vulcanian and felsic Plinian eruptions produced material that was transported downslope by debris flows and deposited as secondary pyroclastic heterolithic breccia. The Plinian deposits were concentrated along the east flank of the volcano, probably due to prevailing wind directions.

The three monolithic conglomerate formations are submarine fans that were derived by erosion of intermittently active dacitic dome complexes that produced offshore islands on the flank of the volcano. While active, the complexes prevented topographically higher breccias from reaching the depositional sites by blocking the debris flows.

During the waning stages of volcanism at the main vent, volcanogenic greywacke was deposited by westerly derived turbidity currents. This westerly derivation indicates a possible westward shifting of vents.

Early in the eruption of the overlying mafic flow sequence, minor coeval felsic formations consisting of an ashflow unit, various tuffs, lapilli-tuff and breccia, and autoclastic flows were erupted at the main vent. These probably represent the vent's final eruptive products.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the following individuals: Dr. L. D. Ayres, whose unceasing search for a greater understanding of geology has taught me how to better interpret what I observe, Dr. W. Brisbin and Dr. M. Clutton-Brock for their critical reviews of this manuscript, B. Brown, R. Hargreaves, and P. Buck, for their helpful comments during many discussions, and R. Onotera, F. Racicot, and R. Hargreaves for their capable field assistance. Thanks are also expressed to Ms. Beverley Soutar and D. Jarvis for typing various drafts of this manuscript. This research was supported by a grant from the National Research Council of Canada to Dr. L. D. Ayres.

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INTRODUCTION

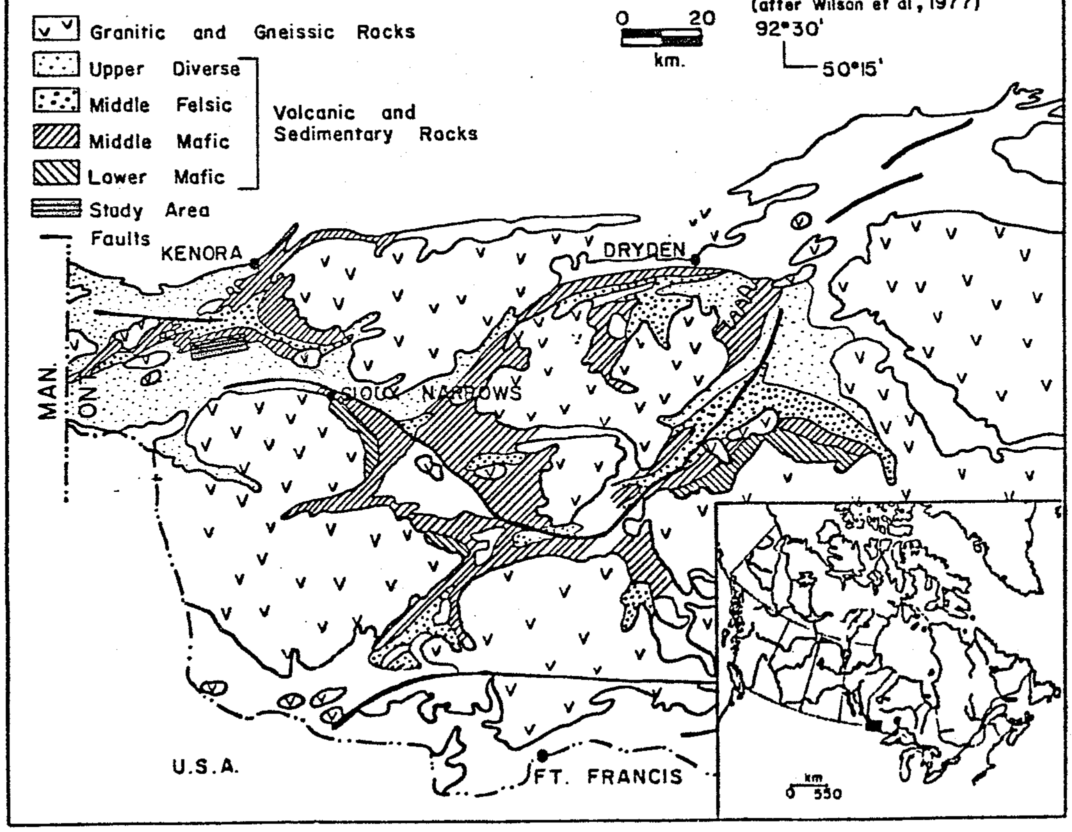
The need for a greater understanding of the physical nature and environments of early Precambrian volcanism prompted this study. Stratigraphic analysis was undertaken on an 18 km long segment of a 4 km thick fragmental sequence in the Lake of the Woods area (Fig. 1). This sequence represents a cross-section through the flank of a stratovolcano, but by analysis of the parameters present in the various formations, the nature of the volcanism can be reconstructed.

It has been oft stated that to understand the present, one must examine the past. Although this statement has been challenged by those geologists ascribing to the theory of non-uniformitarianism (e.g. Cook, 1966, p. 155), it is particularly appropriate for volcanologists.

When examining modern volcanoes, some major problems are encountered. In particular, the internal structure and interrelationship of rock units cannot be determined because the lack of dissection means that only the most recent deposits can be examined. Furthermore, if the volcanoes have a large subaqueous component, then even examination of the surface deposits becomes difficult. Thus, to compliment the study of modern volcanoes, it is necessary to examine older, more deeply dissected volcanoes such as those in the vertically-dipping early Precambrian metavolcanic sequences. Even though these sequences are deformed and metamorphosed, they provide excellent sections through ancient volcanoes.

Until recently, physical volcanology has been a neglected aspect of ancient volcanic sequences, in particular, the determination of 1) environments of volcanism and deposition, 2) the intensity, duration,

Figure 1 Areal Distribution of the Four Volcanic Stratigraphic Groups in the Lake of the Woods Area
(after Wilson et al, 1977)



and character of eruptions, and 3) the subsequent transportation and redeposition of fragmental rocks, all of which are an integral part of any reconstruction of the volcanic sequence. This neglect reflects several factors. In the first place, insufficient work has been done on fragmental rocks and their facies relationships in modern volcanoes to provide a competent basis of comparison to older rocks. Secondly, too much emphasis has been placed on chemical stratigraphy and magma evolution, to the detriment of the physical stratigraphy (Walker, 1973, Ayres, 1977).

Reconstruction of the volcano from study of its deposits involves stratigraphic analysis including both lateral and vertical facies relationships. Such analysis may be complicated by the fact that each volcanic sequence may represent one or more different depositional environments. Furthermore, facies relationships may be complicated by the presence of more than one vent supplying similar materials to an area penecontemporaneously (Dickinson, 1968) or several vents supplying materials that differ in nature and composition to the same stratigraphic unit.

Lateral facies examination involves individual stratigraphic units which can cover a large geographic area. It is useful in the reconstruction of volcanism at a given point in time. To be fully effective, this technique requires the presence of laterally extensive and correlatable units as well as three-dimensional exposures. The study of vertical facies relationships does not have as many inherent problems as lateral facies analysis because the erosional surface in most early Precambrian metavolcanic sequences is a vertical section.

Problems in Early Precambrian Volcanism

In any study of early Precambrian volcanism, there are three basic problems. Possibly the greatest of these is the determination of the original spatial distribution of the volcanoes and of individual vents within these volcanoes. When examining a metavolcanic sequence such as that in the Kenora - Dryden area (Fig. 1) which has a lateral extent of 190 km, one must know whether the products represent one large volcano or several smaller coalescing or superimposed volcanoes. If there were several volcanoes, were they coeval, or did they occur in succession? Did all volcanoes have identical eruptive sequences? If several volcanoes in a belt were active simultaneously, were the products at any given stage similar or different? Such problems can only be answered by thorough lateral and vertical stratigraphic analysis.

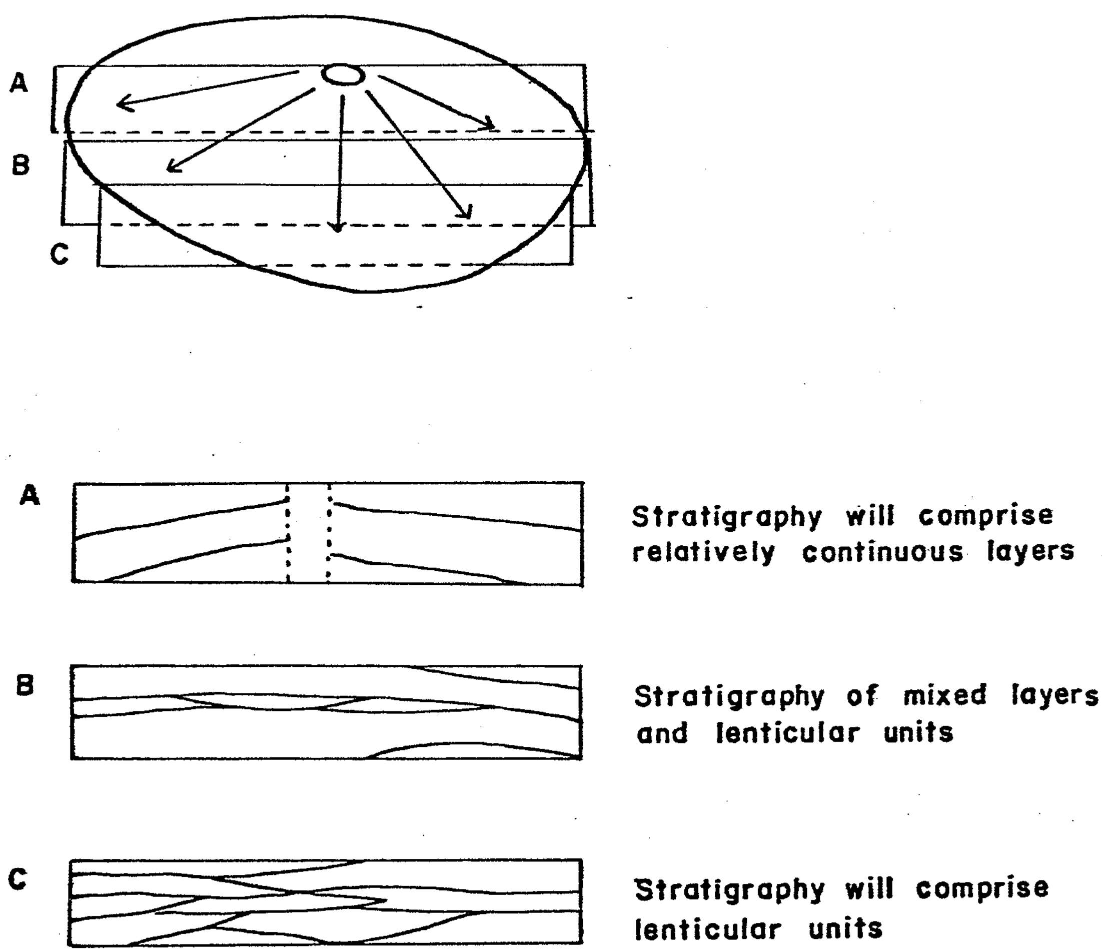
The second problem is post-depositional tectonism which may change the thickness and distribution of the volcanic units. Most units are apparently thinned during isoclinal folding and the present thickness is less than the original thickness. Furthermore, various lithologies behave differently during deformation and preferential thinning or thickening of units may drastically alter their volumetric relationships as observed in a cross-section. Erosion can alter the sequence by removing portions of units. Faults may terminate or juxtapose units, in places producing the same effect as a facies change or pre- or post-depositional erosion. In an area of scattered outcrop such as the largely island terrain in the Lake of the Woods area (Fig. 30), it cannot always be determined whether lateral lithologic changes are due to post-depositional faults, syndepositional faults, facies changes, or erosion. However, folding does give three-dimensional exposure that otherwise would be lacking.

The third problem involves transport directions in the typical isoclinally folded, vertically-dipping, early Precambrian sequences where each fold limb is a two-dimensional section through a three-dimensional sequence. In the homoclinal sequences of these fold limbs, one may be tempted to infer from lateral facies changes that the direction of transport was in the plane of observation. However, the true vector of transport can be determined only be examining the sequence on several fold limbs which provide three-dimensional control, although general transport directions may be inferred from examination of a single section. The only cross-section where transport directions would be in the plane of observation is through the centre of a volcano (Fig. 2). Most random sections will cross the volcano at some other position and transport directions which are axiomatically down slope will be at an angle to the plane of the section. Apparent transport directions can be determined in many of these sections, but the real direction will be at some angle to the section.

Volcanic Vents

Although little is known yet about the physical aspects of individual early Precambrian volcanoes, it appears that both shield volcanoes and stratovolcanoes were present: the shields were composed principally of basaltic flows, whereas the stratovolcanoes were formed from a variety of volcanic products of differing compositions (Clifford and McNutt, 1971). These volcanoes were probably produced by both central and fissure vent eruptions. The largely fragmental sequence in the study area is part of a stratovolcano that was probably erupted largely from a central

Figure 2 Directions of transport of volcanic materials in several cross-sections through a volcano



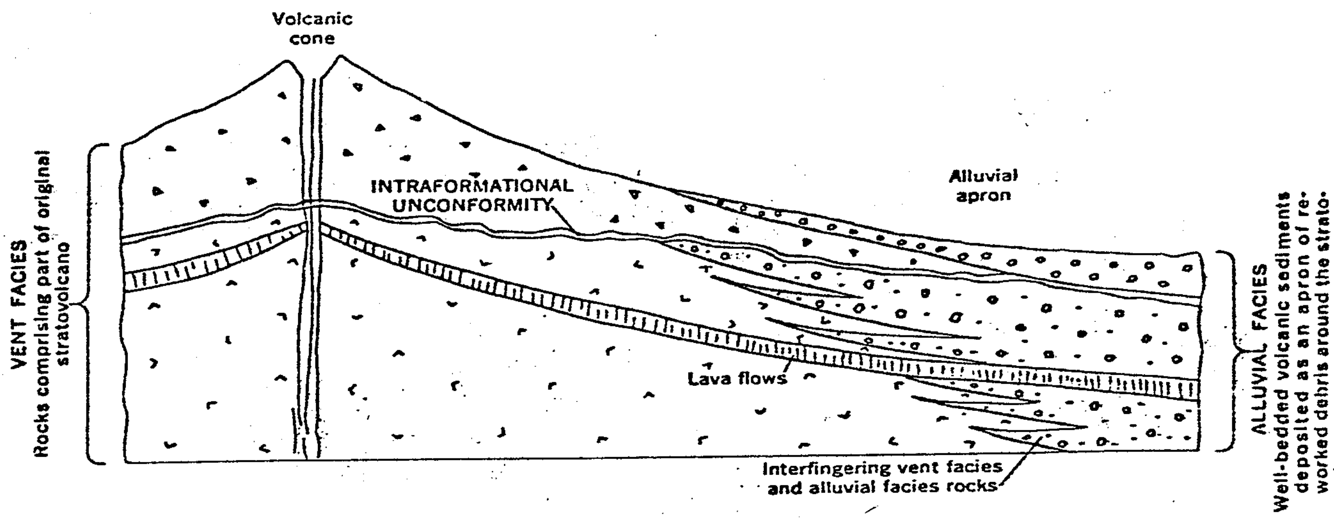
vent, with some eruptions possibly originating from subsidiary flank vents. In such volcanoes the main vent occurs at the apex of the volcano and its location is most important in volcanic reconstruction.

It must be stressed that delineation of vents is only one aspect of a much larger and more important problem, namely reconstruction of the volcanic history of an area. However, because vents are both the source and apex of the volcano, many of the problems associated with unravelling a volcanic sequence may be solved once the major vent has been located.

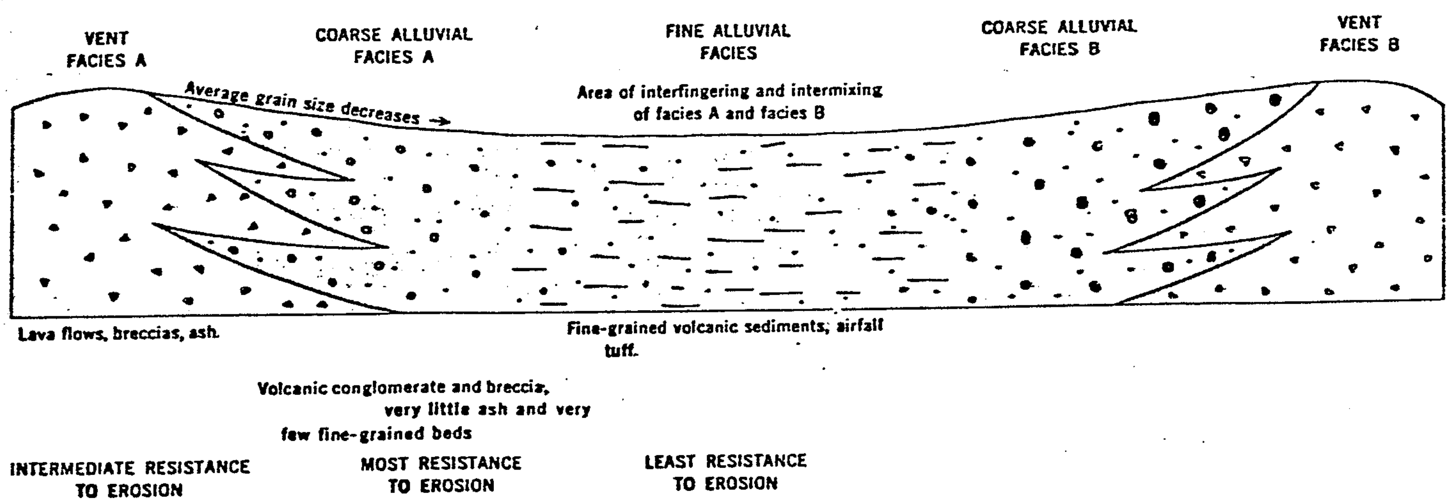
In most early Precambrian sequences, vents are not exposed, and their position must be inferred from facies relationships (Fig. 3). Briefly, the vent facies consists of all the rocks that occur at or close to the vent, whereas the alluvial facies consists of material that was transported away from the vent to be deposited on the flanks of the volcano. The outward change from the vent facies to the alluvial facies is gradual and reflects increases in the degree of transportation and reworking.

Subaerial stratovolcanoes are not stable entities. The rapid build-up of steep upper slopes by eruptions combined with the unconsolidated nature of the pyroclastic units greatly enhances downslope movement by fluvial sheet-flow or other mass movement processes ranging from lahars to dry avalanches (Parsons, 1969, Sharp and Nobles, 1953). In addition, wave action at the subaerial-subaqueous interface would cause additional modification such as abrasion, mixing, and winnowing (Blatt, Middleton, Murray, 1972, p. 143). If modification is intense, some units may be completely removed from the geological record of the volcanic ediface, although their highly mixed products may be preserved

Figure 3 Facies relationships in a volcanic terrain



Hypothetical cross section, showing relationships of vent facies and alluvial facies rocks.



— Hypothetical cross section, showing facies relationships of two vent complexes (A and B) and the intervening volcanic sediments derived from them.

(from Smedes & Prostka, 1972)

in the flanking alluvial apron. Such transportation will produce strongly mixed products.

Subaqueous stratovolcanoes are more stable and tend to undergo modification principally by mass movement of unconsolidated materials. There is less mixing of detritus in such volcanoes.

The nature of the vent and alluvial facies is variable and depends on the intensity, duration, and character of the volcanism; the distance from the vent and the amount of subaerial transport; the slope of the volcano; the environment of volcanism, whether subaerial or subaqueous; the climate, which includes such factors as the amount of rainfall and the presence of glaciation; and the total amount of transportation. The transition between the two facies will vary from volcano to volcano depending on these factors, but recognition of vent or near-vent facies is critical in volcanic reconstruction.

Proximal and distal can be used in conjunction with vent and alluvial facies. These are more relative terms and must be used with discretion when applied to a particular deposit. In general, the more distal a deposit, the more modification that has occurred. However, unless there is a related proximal deposit with which it can be compared, one cannot determine how distal the deposit really is.

Pyroclastic and volcanically derived epiclastic units are the most useful deposits in facies analysis. This is because their diverse origins and ready modification by secondary transport provide many measurable variables such as grain size, bedding, composition, degree of sorting, angularity, and heterogeneity of clasts and matrix (Ayres, 1977). Additional criteria that may be used to identify vent facies are vent-associated alteration zones, volcanogenic dikes, and the presence of felsic flows and domes.

Volcanic Fragmental Rocks

Criteria for the recognition of various genetic types of volcanic breccias (after Parsons, 1969) are given in Table 1. The major genetic types can be classified as either primary or secondary breccias.

Primary Breccias

Primary breccias include autoclastic, alloclastic, and pyroclastic types and are produced directly by active flow or explosive activity.

Autoclastic breccias comprise two major categories: flow breccia and crumble breccia, both of which are confined to the vent facies. Flow breccias which are autobrecciated flows, occur when highly viscous lava brecciates as a result of shear stresses within the moving flow. Crumble breccia forms when masses of solidified lava break off the unstable flank of a growing flow or dome due to the effects of gravity.

Alloclastic breccia is produced by intrusive activity. The two main types are intrusion and vent breccias. Both are minor components of volcanism and are confined to the vent facies.

Pyroclastic breccias consist of Vulcanian, Strombolian, pyroclastic flow, hydrovolcanic, and hyaloclastic breccias. Except for hyaloclastic breccias, these are considered to be part of the vent facies. Vulcanian breccias result from strong explosive activity caused by the rapid exsolution of magmatic gases within felsic to intermediate magma. The breccias contain angular clasts of previously consolidated rock and/or juvenile magma which decrease in size away from the vent. Strombolian or lava fountain breccias result from explosive activity within magmas of generally mafic composition. Consequently, the tephra are more vesicular and more rounded. Pyroclastic flow breccias are produced

Table 1 Criteria for the Recognition of Volcanic Breccias
(after Parsons, 1969)

Type of breccia	Structural features	Fragments	Matrix
Primary Breccia Autoclastic Flow Breccia	No bedding but form distinct layers bounded on one or both sides by flow material	No sorting Angular Monolithic Venicular	Same composition as fragments and may grade into fragments No glass shards
Crumble Breccia	Bedding absent or poorly developed Unit is lenticular	No sorting Angular Monolithic Dense	Same composition as fragments No glass shards
Explosion Breccia (Rare)	Massive Limited extent	No sorting Angular Monolithic	Same composition as fragments Low abundance
Alloclastic Intrusion Breccia	Massive	Rounded to angular No sorting Monolithic to heterolithic	Igneous matrix
Explosion Breccia & Breccia Flows	Massive to poorly stratified	No sorting Dense Heterolithic Angular to subrounded Wide size range	Same composition as fragments Small lithic and crystal fragments with microcrystalline interstitial material
Vent Breccia	Occupy vent Unstratified	No sorting Dense Heterolithic to monolithic Angular to subrounded Wide size range	Same composition as fragments Variable abundance

Type of breccia	Structural features	Fragments	Matrix
Pyroclastic Vulcanian Breccia (Subaerial deposition)	Bedding present Moderage graded bedding	Heterolithic to monolithic (including essential, accessory & accidental fragments) Angular Wide size range Chaotic deposit	Clastic or tuffaceous Variable abundance (to 50%) Angular, crystal and lithic fragments Heterolithic
Vulcanian Breccia (Subaqueous deposition)	Good to moderate bedding Lower dip than subaerial deposits Local cross-bedding Very variable (range from fine tuff to lahars)	Dense Wide size range Angular to subrounded Heterolithic	Fine-grained tuff (both glass and lithic particles) 50-70%
Strombolian Breccia	Well bedded Common graded bedding Form cones Bomb sags present	Vesicular to scoriaceous Subrounded Monolithic Partly glassy Wide size range Bombs present	Rare to minor Coarse ash and cinders-same composition as fragments Poorly consolidated
Pyroclastic Flow Breccias (Subaerial) (ash-flows, block avalanches)	No bedding - but forms wide-spread stratigraphic unit	Unsorted Monolithic Abundant pumice	Same composition as fragments but mainly glass shards and crystals Commonly welded Devitrification common
(Subaqueous)	Stratified Graded bedding	Sorted Monolithic Abundant pumice	Mainly glass shards that are identical in composition to fragments No welding
Hyaloclastic Breccias	No bedding to moderately stratified (depends on grain size) Some subaqueous reworking	Unsorted Chaotic Monolithic Angular to rounded Pillow fragments common Glassy to crystalline	Globules and granules of glass Partly altered to palagonite

Type of Breccia	Structural Features	Fragments	Matrix
Hydrovolcanic Breccia Phreatomagmatic (Subaerial)	Unbedded to bedded tuff cones	Unsorted Chaotic deposit (in part) Monolithic to heterolithic Coarse ash to fine lapilli Angular Many fragments glassy and vesicular	Glassy ash Palagonite common Variable abundance
(Subaqueous)	Bedded tuff cones with some minor structures formed by subaqueous reworking	Coarse ash to fine lapilli Microvesicular & glassy Unsorted Monolithic Angular	Angular, broken, glassy granules More abundant calcite cement than subaerial deposits Local marine fossils
Secondary Breccia			
Laharic Breccias	No bedding but forms stratigraphic unit Commonly graded	Poor sorting Angular to subrounded Dense Monolithic to locally heterolithic Pumice rare	Clastic texture (sand to clay size) Similar in composition to fragments Abundant (to 75%)
Epiclastic Breccias	Well bedded All normal sedimentary structures	Moderate sorting Subrounded to rounded Heterolithic No pumice Fragments may be weathered	Rounded, sorted sand and silt No glass shards

by Pelean or Plinian eruptions and occur as ash-flows or block avalanches. Pyroclastic flow breccias may travel long distances from the vent and are not good indicators of vent locations. Phreatic eruptions occur as the result of steam explosions when rising magma comes into contact with groundwater. Hyaloclastic breccias are produced by rapid chilling of subaqueous flows. The resultant glassy breccias are a minor component of the volcanic pile and are rapidly destroyed by erosion.

Secondary Breccias

Secondary breccias comprise two major types: laharic and epiclastic. Laharic breccias are produced when water-saturated unconsolidated materials lose stability and move down the volcanic slope to be deposited on the flanks of the volcano. Their position is commonly within the coarse alluvial facies. Epiclastic breccias are volcanic materials which have been reworked to the point where they have normal sedimentary attributes. If abundant epiclastic breccias are present, they indicate sites well away from the vent, within the alluvial facies.

The size distribution of clasts within some breccia deposits may delineate vents because in general, the largest clasts are deposited closest to the vent (Fisher, 1964). This parameter must be used with discretion and only applies to breccias produced by Vulcanian, Strombolian, or Hawaiian eruptions. Size distribution in primary pyroclastic deposits of Pelean or Plinian activity is less reliable because much of the material is removed from the vent as pyroclastic flows, and, in the case of Plinian eruptions, large clasts are produced only rarely. Furthermore, reworking of any type of primary breccia will cause mixing and transport of clasts and many of the large clasts will be moved downslope.

Other Criteria for Vent Location

Vents are commonly the loci of fumarolic and hotspring activity. The hydrothermal solutions passing through the vent complex can be strongly reactive with the host rocks and may create various types of alteration (Ijima, 1974). The alteration commonly varies in intensity, with the most intense alteration near the vent. During regional metamorphism the original alteration assemblage will be largely destroyed, but the alteration can still be recognized by chemical or mineralogical anomalies. The presence of metamorphosed alteration zones may be indicative of vents, but must be used with caution because hot springs may occur at considerable distances from the vent, or the alteration could be related to a subsequent vent which produced part of the overlying sequence but was not the vent from which the altered unit was erupted.

The presence of dike swarms may be indicative of volcanic centres (Baragar, 1973), but extreme caution must be exercised in the interpretation of dikes. Unless they are related to the enclosing formation, the possibility exists that the dikes could be feeding a higher vent that is displaced relative to vents that produced the enclosing formations.

Felsic flows and domes are also excellent vent indicators because they generally occur only in the immediate vicinity of their source vents (Baragar, 1973). However, it must be stressed that they may be produced at secondary vents on the flanks of the volcano, rather than at the main vent.

Environments of Volcanism and Deposition

A final point to consider in the reconstruction of a volcanic sequence is the environments of both volcanism and deposition. Volcanoes may form subaqueously and/or subaerially. Furthermore, subaerially erupted products may incur final deposition in a subaqueous environment, particularly when the volcano forms an island. Determination of environments can be difficult, but subaqueous depositional environments are easier to recognize than subaerial environments. Pillows indicate a subaqueous environment and the abundance of amygdules can be used to determine relative depths of flow emplacement (Moore, 1970). Accretionary lapilli generally indicate a subaerial environment (Moore and Peck, 1962), whereas pyroclastic flows may indicate either environment, depending on the internal morphology of such deposits (Fiske and Matsuda, 1964).

There is abundant evidence in the form of pillowed flows and other criteria that much of the study sequence was subaqueously deposited. However, this does not mean that the vent was subaqueous. In fact, the nature of many of the fragmental units implies subaerial eruption on a volcanic island.

Present Study

The study area is in the Western Peninsula region of the Lake of the Woods, Northwestern Ontario (Fig. 1). It is 26 km south-southwest of Kenora and 35 km northwest of Sioux Narrows. Most of the outcrops are on numerous islands in the lake (Fig. 30) and the area can be reached by boat from either of the two towns.

The area was chosen because: 1) there is a diversity of volcanic products ranging from flows through pyroclastic units to epiclastic sedimentary rocks, 2) the structure is relatively simple, 3) previous work by Lawson (1885, 1913), Thompson (1936), Goodwin (1965, 1970), Davies (1967, 1970), and Wilson (1975) had outlined the major stratigraphic units, and 4) the area is part of the type Keewatin sequence of Lawson (1885). A Ph.D. thesis by B. Brown on the structural history of the area is currently in progress at the University of Manitoba.

The area has the low relief typical of most of the Precambrian Shield, and maximum relief is about 25 m. About 65 percent of the area is covered by water. Outcrop density is less than 3 percent, but shoreline outcrops are well exposed and in many places, provide almost continuous sections through the formations.

Methods of Study

The author spent three months in the field during the summer of 1975 and fall of 1976. Geological data were plotted on acetate sheets attached to air photos at a scale of 1:7920. Data were later transferred to a base map at the same scale. The map in this thesis is a reduced version at a scale of 1:31,680 (Fig. 30).

Data was collected from both the well exposed shoreline outcrops and from more poorly exposed inland outcrops. Many outcrops are covered with algal growth above the water line, but these were cleaned by applying a slightly diluted solution of laundry bleach with a whisk broom. Several days after such treatment, brief rinsing produced clean exposures. Inland outcrops are lichen and moss-covered, but traverses were made across the larger islands and on Wiley Point Peninsula. Data collected included general lithologic descriptions, types of clasts and their degrees of rounding and size ranges, qualitative and quantitative measurements of clast to matrix ratios, bedding attitudes, characteristics of bedding and formational contacts, grading, facing criteria, schistosity, jointing, and any other features that might occur in outcrop.

In addition, about 750 samples were collected. All samples were slabbed and ground to remove saw marks. The flat surfaces were then etched in concentrated hydrofluoric acid for 25 seconds. This was done to accentuate primary textures that otherwise would have been obscured on fresh surfaces. Some slabs were also stained with a saturated solution of sodium cobaltnitrate to test for potassium feldspar. Approximately 250 thin sections were examined and modal analyses were made on 22 of these.

Five clasts from conglomerate formations were analysed for major oxides and several minor elements by X-ray fluorescence and atomic absorption techniques. Other analyses (Goodwin, 1970, Wilson and Morrice, unpublished) on rocks of the study area are also included (Table 10).

GEOLOGICAL SETTING

Stratigraphy

The area is part of the Manitou Lake - Lake of the Woods metavolcanic belt which is 64 km wide and 190 km long. Like most metavolcanic belts of the Superior Province, it has an easterly trend and has been truncated and deformed by numerous large post-volcanic granitoid plutons.

Using morphological and chemical data from this and other early Precambrian metavolcanic belts, Wilson et.al. (1974) and Wilson (1975) have recognized four major stages in the development of the volcanism. From oldest to youngest, these are: 1) Lower Mafic Group, 2) Middle Mafic Group, 3) Middle Felsic Group, and 4) Upper Diverse Group (Fig. 1).

Throughout this thesis the terms mafic, intermediate, and felsic refer to basaltic, andesitic to dacitic, and dacitic to rhyolitic chemical compositions respectively. These compositions were commonly determined on the basis of color index in the case of aphanitic rocks, or mineralogy in the case of coarser grained rocks.

The Lower Mafic Group consists of interlayered pillowed and massive basalt flows. Pillows are compositionally uniform and amygdules or other internal structures are rare.

The Middle Mafic Group is also dominantly basaltic flows, but the flows differ from those in the Lower Mafic Group in greater abundance of amygdules and common development of flow top breccia. The internal structure of pillows is variable, with radial and concentric fractures, and concentrations of amygdules in concentric zones.

The Middle Felsic Group is dominantly fragmental volcanic rocks with a basal andesite that grades rapidly upward into dacite which forms most of the Group. The breccia fragments are generally angular and the matrix is compositionally similar to the fragments. In most of the group, bedding is poorly developed; lahars appear to be the dominant depositional form.

As the name implies, the Upper Diverse Group is characterized by a diversity of volcanic rock types and interlayered sedimentary rocks. The metavolcanic rocks range in composition from basalt to rhyolite, and both flows and fragmental rocks are common. Ash-flows are locally present. Pillowed basaltic flows can be distinguished from similar flows in the Lower and Middle Groups by the presence of variolites and fine-grained sedimentary material between the pillows.

In most of the Upper Diverse Group, units of different chemical composition are interlayered. However, in some areas volcanism progressively changed from basalt through andesite and dacite to rhyolite, accompanied by both concomitant and post-volcanism sedimentation. Greywacke is the dominant sedimentary rock, with argillite, conglomerate, ferruginous chert and iron formation occurring in lesser abundance. Some of the conglomerates contain granodioritic cobbles which could have been derived from either contemporaneous granitic diapirs or from older crust.

Numerous synvolcanic dioritic to peridotitic sills, dikes, and irregular plutons are present in the sequence, but are generally restricted to specific groups (Wilson, 1975). Small felsic dikes and stocks occur within all parts of the volcanic sequence and range in age from synvolcanic to post-volcanic. Large post-volcanic granitic batholiths border the belt.

According to Wilson (1975), the mafic unit at the base of the study sequence is part of the Middle Mafic Group, whereas the remainder is part of the Upper Diverse Group. Thus, according to Wilson, the Middle Felsic Group is missing in this part of the volcanic belt. However, it is the author's opinion that the Middle Felsic Group is also represented within the lower part of the study sequence, but exact subdivisions cannot be made between the Middle Felsic and Upper Diverse Groups.

Structure

Upright isoclinal folds with northeasterly to northwesterly trends have produced subvertically-dipping strata. Fold axes plunge gently and are commonly deflected around the numerous granitic plutons which intruded the metavolcanic belt. The folds were probably produced by a combination of isostatic downsinking of the volcanic pile and intrusion of the plutons (Goodwin, 1970). Foliation is well developed throughout the region and is usually parallel to bedding and flow contacts.

The study area is an easterly trending, south-facing homoclinal sequence with the trace of a gently curved anticlinal axial surface at its northern margin. The emplacement of several small post-volcanic granitic plutons caused localized bending of the strata.

Large faults that produced extensive stratigraphic offsets are rare, but smaller faults that produced local displacement are common. Within the study area, these smaller faults apparently have caused lateral termination of some of the formations. Most of the faults appear to be post-volcanic.

Metamorphism

Metamorphic grade in the study area is lower to middle greenschist facies. The original ferromagnesian minerals have been largely replaced by chlorite and amphibole, and plagioclase by albite. Epidote and carbonate are also present as a result of metamorphic alteration. Preservation of original textures by pseudomorphs after primary minerals varies from poor to good, with the best preservation in felsic clasts and worst preservation in the matrix of fragmental units and in fine-grained flows.

STRATIGRAPHY OF THE WESTERN PENINSULA AREA

Introduction

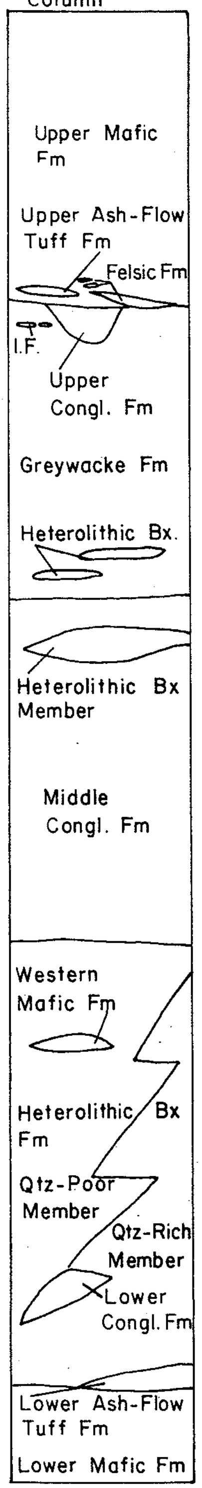
The study has been focused on a 4 km thick sequence of intermediate to felsic fragmental rocks which occurs between two extensive pillowed mafic flow formations. Nine formations, some of which are divisible into members, have been defined in the fragmental sequence (Table 2). These formations range in thickness from 150 m to 2500 m, but a characteristic of all formations is their variable thickness and lenticular shape. A variety of rock types are represented and included ash-flow tuff, heterolithic to monolithic breccias, monolithic conglomerate, greywacke, and minor flows.

Directly above a mafic platform, intermediate breccia forms most of the lower part of the sequence. Several distinctive types can be recognized from variations in clast population, but the clasts and matrix of all units appear to have originated from subaerial Vulcanian and Plinian eruptions. These primary breccias were transported down the flank of the volcano by secondary processes that mixed material from various sources. They were eventually deposited on the subaqueous flanks of the volcano by gravity slides and are now secondary deposits. The vent was either north or south of the study area.

According to Wilson's (1975) stratigraphy, a hiatus in volcanism occurred between deposition of the mafic platform and production of the breccia. However, the lack of evidence for a hiatus such as cherts and seawater alteration of basalt indicates that there was a continuous progression from subaqueous Middle Mafic to subaerial Middle Felsic volcanism.

Table 2 Summary of Formations Within the Study Sequence

Stratigraphic Column



Formation	Member	Maximum Thickness	Overall Composition	Rock Types	Bedding	Origin and Depositional Environment	Comments
Upper Mafic		>2000 m	Mafic	Pillowed to massive flows, and tuff		Subaqueous flows and pyroclastic eruptions	Caps the study sequence
Upper Ash-Flow Tuff		500 m	Felsic	Quartz-bearing ash-flow tuffs	Diffuse contacts between individual flows	Subaerially (?) derived ash flows deposited subaqueously	Consists of indeterminate number of ash flows identical to those in Lower Ash-Flow Tuff Formation. It may occupy a valley-like depression
Felsic	Upper Eastern Lower Eastern Western	15 m 50 m 150 m	Felsic	Monolithic lapilli-tuff, breccia, tuff, and autoclastic flows	Thin to thick bedded beds have sharp to diffuse contacts. Ungraded to well developed normal grading	Subaqueously or subaerially erupted pyroclastic rocks and flows that were deposited subaqueously	Deposited during deposition of Upper Mafic Formation
Upper Conglomerate		500 m	Intermediate	Monolithic conglomerate consisting of medium to coarse-grained well-rounded granodioritic clasts in a matrix similar in composition to the clasts	Bedding contacts diffuse. Beds are generally ungraded, but some weakly developed normal grading. Thick-bedded	Derived from areally restricted dome(s) which underwent rapid subaerial erosion. Conglomerate subaqueously deposited by debris flows	The formation is laterally restricted and appears to occupy a valley-like depression in the underlying greywacke
Greywacke	Iron Formation	<10 m		Layered chert and magnetite	Thin-bedded	Chemical precipitation in a subaqueous environment	
		2500 m	Intermediate	Greywacke and siltstone beds with minor interbedded chert. Some interbedded thin heterolithic breccia and pebbly greywacke units	Well bedded, generally graded beds ranging from a few cm to several metres in thickness. Most beds consist of a and e members of Bouma cycle, but a few complete cycles were present	Deposited by subaqueous turbidity flows	Has an overall distal character
	Heterolithic Breccia	100 m	Intermediate	Heterolithic breccia formed of angular to subrounded volcanic clasts	Diffuse contacts between thin to thick ungraded beds	Subaerially derived well reworked breccias deposited subaqueously by debris flows	Breccia consists of numerous beds with greywacke. Some clasts differ from those in Heterolithic Breccia Formation
Middle Conglomerate	Heterolithic Breccia	400 m	Intermediate	Heterolithic breccia formed of angular to subrounded felsic to mafic volcanic clasts and minor granodioritic clasts in an intermediate matrix	Diffuse contacts between thick ungraded beds	Subaerially derived well reworked breccias deposited subaqueously by debris flows	
		1000 m	Intermediate	As in Upper Conglomerate Formation	Diffuse contacts between generally ungraded thick beds. Some normal and reverse grading locally present	As in Upper Conglomerate Formation	Largest of three conglomerate formations. Largest clasts concentrated in the Lower Central Zone. The Western and Upper Central Zones characterized by deposits with clasts generally under 3 cm in diameter. Eastern Zone has a high matrix content and numerous volcanic sandstone beds
Western Mafic		500 m	Mafic	Pillowed and massive flows, with minor tuff		Subaqueous flows	
Heterolithic Breccia	Quartz-Poor	900 m	Intermediate	Heterolithic breccia formed of angular to subrounded felsic to mafic volcanic clasts in an intermediate matrix	Generally ungraded thick beds with diffuse contacts	Subaerially derived, highly reworked pyroclastic breccias deposited subaqueously by debris flows	Clast-rich
Lower Conglomerate		250 m	Intermediate	As in Upper Conglomerate Formation	Thin to thick, ungraded to normal graded beds with sharp to diffuse contacts	As in Upper Conglomerate Formation	Occurs as a laterally restricted lens
Heterolithic Breccia	Quartz-Rich	800 m	Intermediate to Felsic	Heterolithic breccia formed of angular to subrounded felsic to mafic volcanic clasts plus quartz grains in an overall intermediate matrix	Diffuse contacts between ungraded to normal graded thin to thick beds	As in Quartz-Poor Breccia Member	Has a higher matrix content than the Quartz-Poor Breccia Member. The quartz abundance is up to 15 percent
Lower Ash-Flow Tuff		200 m	Felsic	Quartz-bearing ash-flow tuffs	Generally diffuse contacts between individual flows	Subaerially (?) derived ash flows deposited subaqueously	Strongly foliated
Lower Mafic		>1000 m	Mafic	Pillowed and massive flows		Subaqueous flows	Massive flows predominate. The formation forms the base upon which the rest of the sequence was deposited

The western part of the main breccia formation completely encloses a 500 m thick mafic lens which appears to represent a contemporaneous basaltic shield volcano. The mafic shield is buried by breccia, but during much of the breccia's deposition, the shield appears to have acted as a barrier to transportation of some of the breccia.

Monolithic breccia is relatively rare. It is more felsic than the heterolithic breccia and is confined to the upper part of the sequence where it is associated with autoclastic flows of the same composition. This unit appears to be at or close to its original vent.

Monolithic conglomerate forms three, virtually identical formations. The most unique feature of the conglomerate is the uniform granodioritic composition of the clasts, although the texture varies from fine to coarse-grained porphyritic. While most of the clasts are obviously plutonic, they were derived from a restricted source in the volcanic terrain. This source was probably a dome or group of domes which were erupted on the flanks of the volcano to produce subaerial islands which would act both as a restricted source of clasts and a barrier to breccia deposition. Wave action along the shore of the island(s) would be capable of rounding the clasts derived from the dome(s). The resultant detritus was then incorporated within gravity slides that entered the subaqueous environment to form the conglomerate formations. The occurrence of three distinct formations indicates that production of the source rock was cyclic. The source area was either north or south of the study area.

The greywacke formation consists of innumerable fine-grained turbidite beds which may have been derived from the west. They were deposited during the waning stages of the volcanism which produced the coarser fragmental formations.

LOWER MAFIC FORMATION

A sequence of pillowed and massive mafic to intermediate flows whose base is not exposed underlies the fragmental sequence, and has a minimum thickness of 1 km. It is part of Wilson's Middle Mafic Group and forms the core of an anticline. This formation was examined only briefly and the thickness of individual flows could not be accurately determined.

Pillowed Flows

Where not extensively deformed, pillows range in size from less than 20 by 30 cm to more than 60 by 150 cm, and selvages range in thickness from less than 5 mm to more than 15 mm. Most pillows are internally massive, but a few variolitic and amygdaloidal pillows were observed. The variolites are up to 7 mm and carbonate amygdules up to 4 mm in diameter. However, the typical concentric zonations of Wilson's Middle Mafic Group were not observed.

Discontinuous white to grey chert occurs between pillows at one locality on the south side of Shammis Island. The discontinuous nature of the chert indicates that it was likely deposited by solutions percolating through pillowed flows rather than by precipitation of silica from sea water on the sea floor (Macdonald, 1972, p. 363).

Massive Flows

Fine to coarse-grained massive flows occur throughout the formation, but are most abundant near the base of the observed part of the formation. They are commonly less than 20 m thick where contacts can be inferred.

Mineralogy

The pillowed and massive flows have a similar mineralogy, although the massive units commonly have a coarser grain size. Greenschist facies metamorphism has destroyed most of the primary mineralogy and the mafic minerals now consist of up to 50 percent chlorite and smaller amounts of actinolite and epidote. The only primary textures observed were ophitic to subophitic actinolite pseudomorphs after pyroxene, found locally in both pillowed and massive flows. The unusual presence of such textures in the pillows cannot be explained. Plagioclase content is variable, but averages 40 percent. Although the plagioclase is albitized, primary euhedral to highly corroded crystal shapes are preserved. Iron-titanium oxides form less than 2 percent and occur as finely disseminated grains; minor pyrrhotite is also present. Carbonate content is low in many of the thin sections, but is readily observed in many of the pillowed outcrops. Due to the high degree of recrystallization and the generally high carbonate content, it was difficult to obtain good samples for chemical analysis. However, one basalt analysis obtained by Goodwin (1970) has been included in Table 10.

Genesis

The vent and morphology of the mafic volcano are not known. The formation has a lateral extent of 30 km, as indicated by Wilson and Morrice (1977), but its thickness is unknown. In its type area, the Middle Mafic Group is 5 km thick. These dimensions imply a relatively large subaqueous volcano, possibly of shield type. The lack of observed vent features suggests that the study area represents a section through the flank of the volcano. The presence of pillowed flows shows that deposition was subaqueous, and the scarcity of amygdules implies emplacement in moderately deep water (Jones, 1969).

FELSIC ASH-FLOW TUFF FORMATIONS

Ash-flow tuff forms two formations in the eastern part of the area. Although the formations are separated stratigraphically, their similarity to one another facilitates their description in one section.

The formations are characterized by 6 to 20 percent quartz grains, 2 to 9 mm in diameter, 10 to 30 percent plagioclase crystals up to 5 mm long, and 5 to 40 percent volcanic lithic clasts in a strongly foliated, very fine-grained light brown felsic matrix. The matrix consists of a mixture of sericite, quartz, and minor carbonate and iron-oxides (Table 3).

The Lower Formation occurs on an isolated island 100 m wide and 300 m long just above the Lower Mafic Formation. The Upper Formation is better defined, it is 500 m thick and occurs on two islands near the base of the Upper Mafic Formation. It can be traced laterally for 1200 m, buts its extrapolated length is 4 km. The thickness relative to observed lateral extent and porphyritic texture have led some previous workers to classify this and other similar units as intrusions (Thompson, 1936).

The better exposed Upper Formation which was formed by an indeterminate number of ash-flow units will be described first. It has sharp contacts with enclosing mafic flows, although both rock types are intensely foliated at the contacts.

The quartz grains vary from euhedral to anhedral, and many are deeply embayed (Fig. 4). A few are broken. Undulatory extinction is common to most grains. The quartz abundance varies vertically through the formation. Most of the formation contains about 15 percent quartz phenocrysts (Fig. 5), but there are laterally continuous, concordant

Table 3 Modal Analyses* of the Ash-Flow Tuff Formations

	Upper Formation						Lower Formation	
Sample Number	649	668	97a	97	653	100	734_3	735_1
Phenocrysts								
Monocrystalline Quartz	9.2	9.8	6.6	5.4	20.8	10.4	13.2	0.8
Polycrystalline Quartz	5.8	1.4	-	3.8	-	1.8	1.8	4.0
Plagioclase	14.8	31.8	20.2	18.2	10.6	20.0	12.8	15.0
Clasts								
Pumice-Like Material	0.6	-	-	-	-	0.6	-	-
Felsic Plagioclase Porphyry	8.8	3.6	3.6	5.0	2.8	6.8	-	6.8
Felsic Plagioclase - Quartz Porphyry	-	-	-	-	-	2.0	39.0	-
Intermediate to Mafic Volcanic	1.4	1.2	1.2	-	1.6	0.8	-	-
Matrix								
Mixture of Sericite, Quartz, Carbonate, Epidote, and Iron-Titanium Oxides	59.4	52.6	68.4	67.6	64.2	56.6	33.2	73.0
Chlorite Veinlets	0.2	0.2	-	0.2	-	1.2	-	0.4

* 500 points counted per thin section

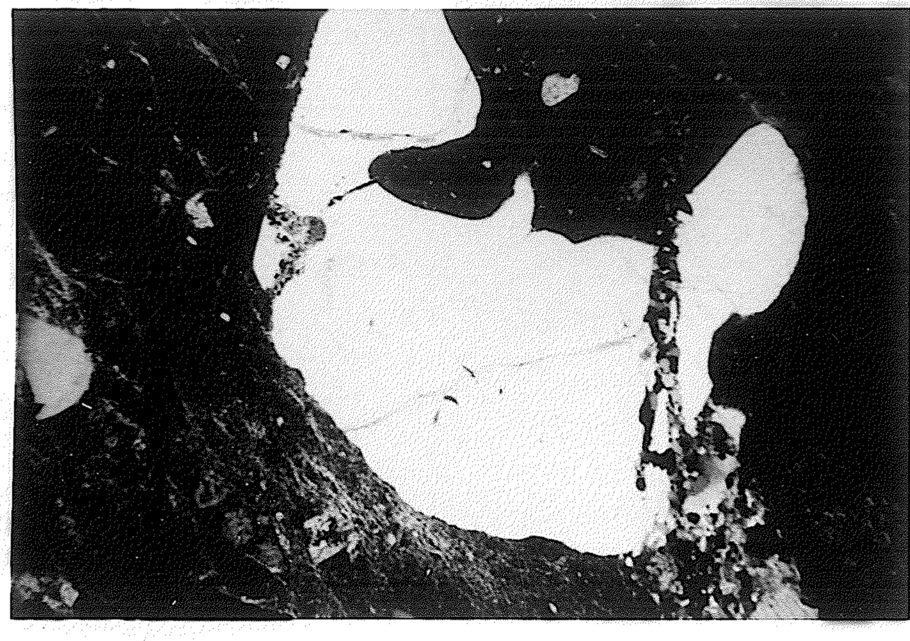


Figure 4
A highly embayed quartz crystal in the Upper Ash-Flow Tuff Formation. The field of view is 6.5 x 10.0 mm.

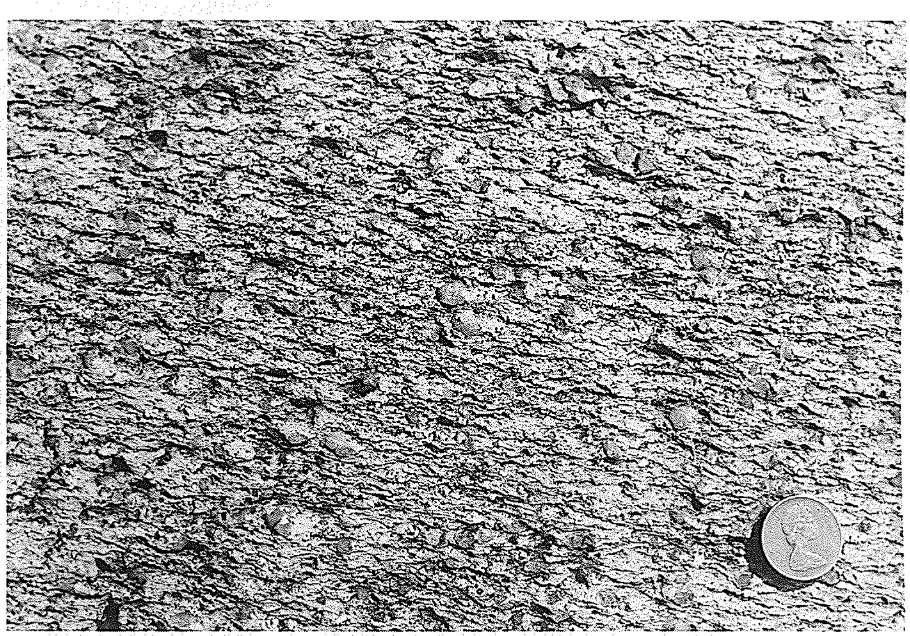


Figure 5
Upper Ash-Flow Tuff Formation showing quartz phenocrysts in a highly foliated matrix. Coin in lower right is 1.9 cm in diameter.

zones 1 to 2 m thick that have a lower quartz content; in places, as low as 6 percent. These zones have both sharp and gradational contacts with zones of high quartz content. Other than the quartz variations, there are no primary structures such as bedding or layering.

The plagioclase occurs as subhedral crystals that commonly have rounded corners. They are weakly to highly albitized and the degree of alteration reflects the intensity of deformation in various parts of the formation.

Definite lithic clasts are present, but always form less than 10 percent of the formation (Table 3). All have been tectonically elongated and their contacts with matrix have commonly been partly or totally obliterated by recrystallization and development of foliation. Most clasts are felsic and less than 1 cm long. They are commonly porphyritic, with plagioclase or plagioclase plus quartz phenocrysts in a strongly recrystallized groundmass of fine-grained quartz, plagioclase, and sericite. The plagioclase phenocrysts are euhedral with sharp corners, as opposed to the generally rounded corners of the plagioclase crystals in the rest of the unit. However, the plagioclase phenocrysts and crystals are about the same size and were probably derived from the same magma. Most quartz phenocrysts are less than 3 mm in diameter, whereas individual quartz crystals can be up to 9 mm in diameter. Sparse aphyric intermediate and rare mafic clasts were also observed in the formation. In two thin sections, possible flattened pumice was found. It forms elongated areas up to 5 mm long that consist of fine-grained petrographically indistinguishable felsic material with a discontinuous laminated structure defined by tiny iron-titanium oxide grains.

Foliation is much better developed than in adjacent formations. Layered zones are variably foliated. These variations in intensity of foliation could reflect primary variations in pumice content or degree of welding.

The Lower Formation is very similar to the Upper Formation. Quartz crystal content ranges from 8 to 15 percent, but vertical variations in quartz crystal abundance are generally not as well defined as in the Upper Formation. However, along the north shore of the island, there is one relatively sharp contact between a quartz-poor and quartz-rich zone (Table 3, Figs. 6, 7). The quartz-rich zone also has a very high felsic clast abundance. Euhedral to subhedral albitized plagioclase crystals up to 5 mm long are evenly distributed throughout the formation. Other than the quartz variations, the formation lacks any primary structures such as bedding or layering.

All characteristics of both formations indicate that they represent a succession of ash-flow tuff units. Briefly, this includes the stratified character expressed as variations in quartz content, the broken phenocrysts (Ross and Smith, 1961), the very felsic overall composition, the presence but low abundance of accidental clasts, the occurrence of pumiceous clasts, the small size of clasts (Fisher, 1966), and the layered variable intensity of foliation.

Although most documented ash-flows were erupted subaerially, they can occur in a subaqueous environment (Fiske and Matsuda, 1964). Subaqueous deposition is indicated for the two formations by the presence of nearby pillowed mafic flows and greywacke. However, because ash-flows are very mobile and can move considerable distances away from the vent, the eruptions could have been either subaerial or subaqueous.

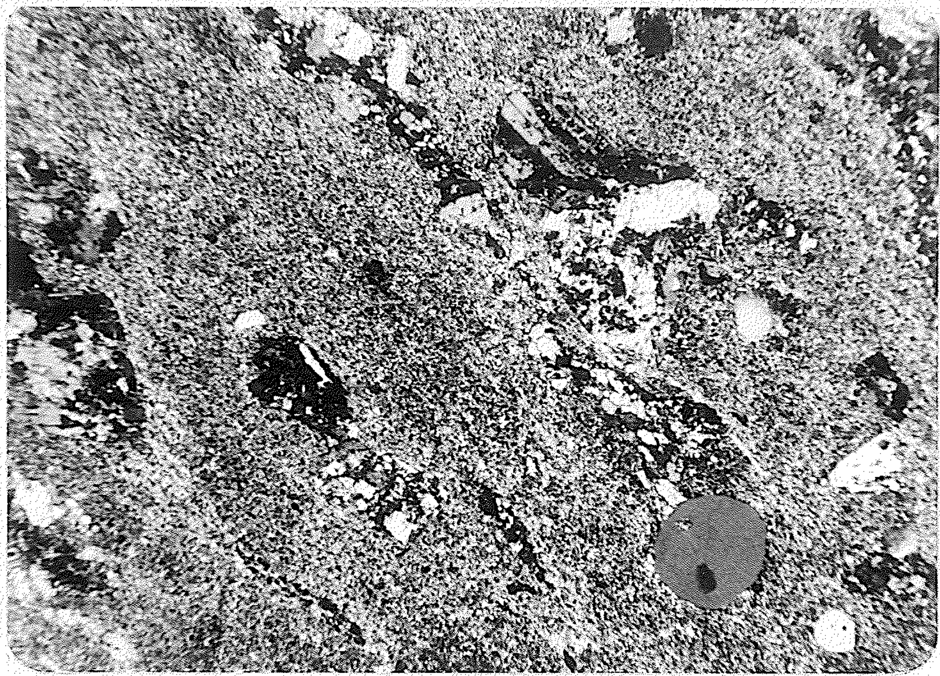


Figure 6
Photomicrograph of a quartz-poor zone (Sample 735_1, Table 9) in the Lower Ash-Flow Tuff Formation. Crossed nicols. Field of view is 3.0 x 4.5 mm.

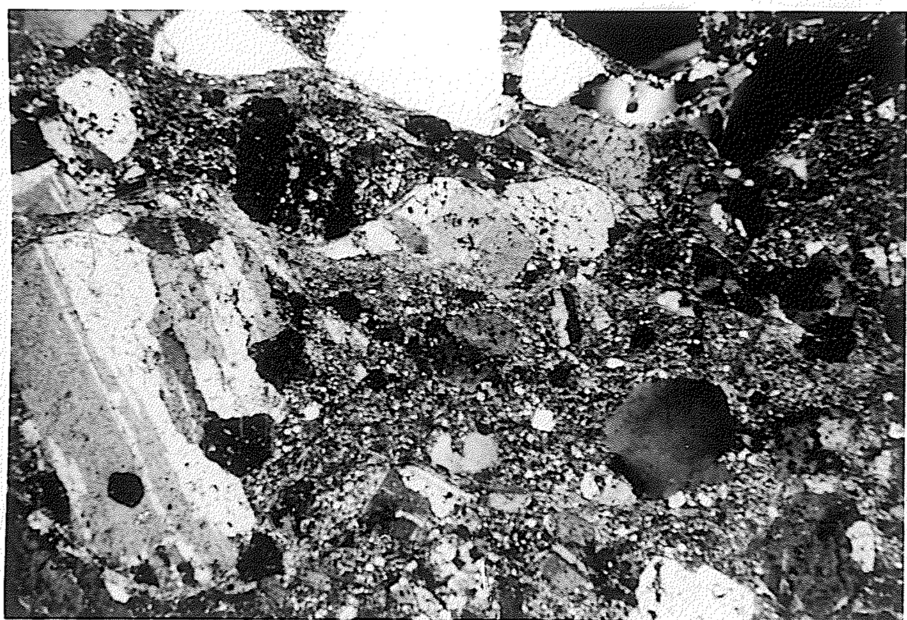


Figure 7
Photomicrograph of a quartz-rich zone (Sample 734_3) in the Lower Ash-Flow Tuff Formation. The large feldspar to the left is in a lithic clast. Crossed nicols. Field of view is 6.5 x 10.0 mm.

Many ash-flows have a wide lateral distribution, although they conform to pre-existing topography. The restricted extent of the two formations is thus somewhat unusual. It may reflect pre or post-depositional faulting or deposition in a valley. The present configuration of the Upper Formation could reflect faulting, but because there is no evidence of fault displacement in the underlying formations, fault control is unlikely. It is most likely that the formations were deposited in valleys similar to that which was filled by the Upper Conglomerate Formation.

HETEROLITHIC BRECCIA FORMATION

The Heterolithic Breccia Formation overlies the Lower Mafic Formation except northwest of Queen Island, where the Lower Conglomerate Formation forms a thin lens between the two formations. The breccia has minimum and maximum thicknesses of 100 and 1200 m respectively, but extends laterally beyond the edges of the study area. It comprises two members: a quartz-rich member in the east and a quartz-poor member in the west (Table 4). The breccia is contemporaneous with, and encloses the Western Mafic Formation and a smaller mafic lens north of Queen Island.

Quartz-Rich Member

The quartz-rich member forms the lower part of the breccia and has a maximum thickness of 800 m. It thins westward and terminates southwest of Crow Rock Island (Fig. 30).

Bedding characteristics are given in Table 4. Numerous siltstone and argillite units up to 1 m thick occur in the lower part of the member. Local scour structures are present at the top of these finer units, with the scours being filled by overlying quartz-rich breccia.

Clast content is variable and ranges from 10 to 70 percent, with clasts ranging in diameter from 2 mm to 3 m and averaging 12 cm. There is a complete size gradation between clasts and matrix, but 2 mm is used as an arbitrary cut-off between clasts and matrix. The clast population is somewhat variable throughout the member, but the estimated abundances throughout the member are 38 percent intermediate volcanic, 25 percent felsic volcanic, 15 percent quartz, 15 percent

Table 4 Characteristics of the Quartz-Poor and Quartz-Rich Members of the Heterolithic Breccia Formation

	Quartz-Poor Member	Quartz-Rich Member
Clast Types (in order of decreasing abundance)	- fine-grained porphyritic intermediate volcanic; some clasts are weakly scoriaceous - fine-grained mafic volcanic - fine-grained aphyric to weakly porphyritic felsic volcanic - coarse-grained granophyric and porphyritic intermediate (at upper and lower margins of member where it is in contact with monolithic conglomerate) - plagioclase crystals; highly altered and commonly subrounded - argillite	- porphyritic and felted aphyric intermediate volcanic - porphyritic felsic volcanic - aphanitic and aphyric felsic volcanic - quartz grains - plagioclase crystals, commonly subrounded - variolitic and massive fine-grained mafic volcanic - chert - coarse-grained volcanic sandstone - autobrecciated felsic volcanic
Angularity of Clasts	- each clast type has variable angularity, with felsic and intermediate clasts being primarily angular, and mafic clasts subrounded	- angularity of volcanic clasts is identical to that in the quartz-poor breccia member - chert is angular and quartz is angular to subrounded
Size Range of Clasts	- clasts range from 2 mm to about 2.5 m in length or diameter, with most clasts being 20 to 30 cm in diameter in horizontal outcrop sections; the clasts have been stretched vertically so that vertical dimensions are up to five or six times greater than horizontal dimensions - the largest observed clast was mafic, but this is an anomalous clast and not indicative of mafic clasts in general; mafic clasts average 15 to 20 cm in diameter	- clasts range from 2 mm to 3 m in diameter or length, with most clasts 10 to 15 cm in diameter; the clasts are not as highly stretched as those in the quartz-poor member - largest observed clast was autobrecciated felsic 3 m in diameter, but this was anomalous and not indicative of felsic clasts in general
Matrix	- 2 mm in diameter and in order of decreasing abundance, consists of a foliated assemblage of subrounded albitized plagioclase crystals, recrystallized lithic clasts similar to the larger clasts, subrounded quartz grains, and disseminated carbonate and iron-titanium oxides	- consists of a generally foliated assemblage of subrounded albitized plagioclase crystals, quartz grains, recrystallized lithic clasts, chlorite, actinolite, pyrite, iron-titanium oxides, and carbonate
Bedding Characteristics	- beds are between 1 and 10 m thick, but actual contacts are transitional and poorly defined - normal grading is absent in most of the member, but in the Queen Island area grading occurs in some matrix-rich beds - most beds in the member are clast-supported	- beds range in thickness from 1 to about 10 m - bedding contacts are gradational, which may indicate some amalgamation and rapid deposition of beds - most beds are ungraded, but some of the thicker beds exhibit normal grading - most beds tend to be matrix-supported - siltstone and argillite interbeds occur in lower part of member - overall, bedding can be more readily distinguished in this member

plagioclase, 5 percent mafic volcanic, less than 1 percent chert, and less than 1 percent coarse-grained volcanic sandstone.

The intermediate clasts exhibit wide textural variability and range from fine-grained aphyric to strongly porphyritic with up to 60 percent blockly plagioclase phenocrysts, 2-4 mm long, in a fine-grained groundmass. Some clasts contain sparse quartz amygdules up to 0.5 mm in diameter. The aphyric clasts have a felted texture, but the groundmass textures in the porphyritic clasts have been recrystallized to fine-grained aggregates of quartz, plagioclase, chlorite, epidote, and actinolite. In all clasts where primary textures are preserved, the plagioclase has been replaced by albite.

The felsic clasts are generally porphyritic, but phenocryst content ranges from 2 to 45 percent. Plagioclase phenocrysts greatly predominate, but quarts phenocrysts are locally present and form up to 2 percent of some clasts. Their size is commonly under 3 mm in diameter. Rare pyroxene phenocrysts, now pseudomorphed by amphibole are present in a few clasts. Groundmass grain size ranges from aphanitic to fine-grained and the biotite-amphibole-chlorite content ranges from 0 to less than 3 percent.

A single 3 m long subrounded autobrecciated felsic clast was observed in the breccia. This clast consists of elongated angular aphanitic fragments in a fine-grained matrix of identical material.

The quartz and plagioclase are subhedral to euhedral, and have undergone minimal rounding due to transportation. The quartz ranges from 2 mm to 5 mm in diameter and the plagioclase from 2 to 3 mm in length. They resemble phenocrysts found in clasts within the breccia, except for the size of quartz, and quartz to plagioclase ratio. A volcanogenic origin is favoured for these grains because of their angularity and the lack of any granitoid clasts within the breccia.

Chert clasts occur sporadically throughout the breccia, and range in abundance from 0 to 3 percent. They are commonly smaller than the volcanic clasts and average 1 to 3 cm in diameter, but in one area, chert clasts up to 55 cm were observed.

Mafic clasts are identical to basalt flows in the Lower Mafic Formation, and occur throughout the member. Most clasts are subrounded, fine-grained and average 5 cm in diameter.

Sparse volcanic sandstone clasts ranging from 2 to 5 cm in diameter were found in the central part of the study area. They consist of angular to subrounded lithic fragments, quartz, and plagioclase grains in a fine-grained matrix.

The breccia matrix varies in abundance from 30 to 90 percent, but is largely recrystallized. Angular to subrounded quartz and plagioclase grains up to 2 mm in diameter form about 50 percent of the matrix, with plagioclase predominating over quartz. The remainder consists of felsic to intermediate lithic clasts compositionally similar to the larger clasts, as well as a large percentage of petrographically indistinguishable material. Sparse pyrite occurs throughout the breccia, but in the basal 30 m of the western part of the member there is up to 10 percent pyrite (Fig. 30). It forms rounded to irregular aggregates up to 2 cm in diameter and finer disseminated grains. A similar 20 m thick pyrite-bearing zone occurs in the upper part of the member on the north shore of Oliver Island (Fig. 30). Most of the pyrite was probably introduced, but the possibility that some or all of the pyrite represents clastic grains cannot be discounted. A clastic origin is suggested by the concordant nature of the pyrite-bearing zones as well as the marked increase in pyrite content within these zones.

Genesis of the Quartz-Rich Breccia Member

The breccia appears to have been emplaced by debris flows such as mud flows. Fisher (1971) stated that such "deposits are characteristically poorly sorted, commonly contain large fragments resting unsupported in finer-grained matrix, may be internally structureless within undivided units...and may contain elongate fragments strongly aligned approximately parallel to flow surfaces". Locally, they exhibit reverse grading. The flows move by laminar flow and large fragments are carried in suspension because of the high density and strength of the flow (Johnson, 1970). The flows may travel for many kilometres on low slopes and may overlie soft sediments with little or no erosion. With the exception of reverse grading and aligned clasts, these characteristics are all found in the breccia member. The normal grading within some of the units indicates that the density was decreased in some flows, permitting a certain amount of gravitational settling to occur within the flow. The gradational bed contacts within the breccia and intercalation between flows and underlying deposits indicate a rapid emplacement of numerous beds. Although the data is not totally diagnostic of a debris flow origin for the units in the breccia, no other mechanism could produce the generally unsorted, heterolithic units with gradual bed contacts.

Debris flows can occur in both subaerial and subaqueous environments. Thus, the depositional environment must be deduced from the nature of associated deposits. The presence of pillowed mafic flows directly above the western end and beneath the entire breccia (Fig. 30) implies subaqueous deposition.

The argillite and siltstone units which occur in the lower section of the breccia were probably derived from gravitational settling of fine sediments, possibly airborne tuff which fell into the water and eventually settled out. Their presence in the lower section of the breccia indicates that the lower part of the breccia was deposited at a slower rate than the upper part. The scour structures at the top of some units indicate that some overlying debris flows were capable of eroding earlier deposits.

A major problem in interpreting the breccia is the origin of the pronounced clast heterogeneity. Debris flows can mix clasts which are incorporated within them, but the various types of clasts must be present at the source of the flow because few clasts are picked up by moving debris flows.

Because pyroclastic eruptions can occur only in very shallow water or subaerial conditions, eruption of large volumes of pyroclastic material will axiomatically produce subaerial edifices (Ayres, 1977). Most of these eruptions will produce monolithic breccias with only minor accessory and accidental clasts. In a subaerial environment, mixing of the originally monolithic breccias can occur by downslope movement involving any or all of the following mechanisms: streams, ice, wind, wave action, or gravity slides. Streams and gravity slides are probably the dominant mechanisms. Once mixing has occurred, the resultant heterolithic breccias can be moved to their final depositional sites by debris flows.

In the quartz-rich breccia it is impossible to rule out any of the above mixing mechanisms, but the angularity of most clasts indicates that they were not exposed to high energy regimes such as streams or wave action for extended periods of time. A possible exception to this are the mafic clasts which are more rounded than the other clast types, indicating greater stream or wave action. The mixing must have occurred subaerially rather than subaqueously because down-slope subaqueous movement is mainly by debris flows in which only local mixing occurs.

The general angularity, large size, and composition of most lithic clasts in the breccia indicates that the clasts could have been derived through any or all of the following mechanisms:

a) Vulcanian eruption of felsic to intermediate magma

b) explosive disruption of pre-existing volcanic units

c) gravity collapse of domes or flows

Vulcanian eruptions are the most likely eruptive mechanisms because these typically produce angular clasts. The mafic clasts were either explosively ejected and rounded by subsequent transport or eroded from solidified flows by stream action.

The chert and volcanogenic sandstone clasts may have been derived from local sedimentary deposits that were broken up by explosive activity, or by erosion. Some or all of the plagioclase could have been derived from the eruptions that produced the lithic clasts because the size and abundance of plagioclase phenocrysts in the clasts is similar to the individual plagioclase crystals in the breccia. The angularity of the plagioclase as well as the quartz indicates that streams or wave action were minor components of reworking. This would rule out derivation of the mineral grains by erosion of flows or large lithic clasts comparable in phenocryst content to those in the breccia, since such erosion would produce more rounded grains. Furthermore, the largest observed quartz phenocrysts in the lithic clasts are 1.5 mm, whereas the average diameter of quartz grains in the breccia is 2.5 mm.

The high quartz content of the breccia (10-15%) relative to the quartz phenocryst content of the clasts (<2%) indicates that if the source was the same for the quartz grains and clasts, the quartz must have been concentrated by special mechanisms. The only other mechanism that could have produced the quartz and plagioclase is winnowing of the eruptive column by winds (Ross, 1955, Walker, 1971). Plinian eruptions produce only ash and fine lapilli in a high eruptive column which is ideal for fractionation of crystals. The presence of Plinian eruptions is indirectly corroborated by the presence of quartz-bearing felsic ash-flow tuffs having the same quartz content and size, east of the breccia. Although these pyroclastic flows did not provide quartz and plagioclase directly to the breccia, their presence along with the larger clasts in the breccia indicates that both Plinian and Vulcanian eruptions occurred during formation of the Heterolithic Breccia Formation.

All of the felsic to intermediate volcanic clast types were produced either at the same vent that erupted magmas of a range of compositions or at several vents, each of which erupted magma of restricted compositional range. If the clasts were derived from different vents, individual debris flows although heterolithic, should reflect specific chemistries of individual vents. However, since individual debris flows have the same heterogeneity throughout the breccia, the favoured source is a single vent which furnished several different lithic compositions. The mixing of clast types must have occurred on the volcanic slope prior to incorporation within the debris flows.

Minor Overlying Units

At its western end, the member is overlain by two laterally restricted units: the Lower Conglomerate Formation; a 250 m thick by 3 km long lens of monolithic conglomerate and by a 50 m thick by 600 m long lens of pillowed mafic flows (Fig. 30). The conglomerate largely overlies the Lower Mafic Formation, but overlaps onto the western end of the breccia. The mafic flows on the other hand overlie the breccia and are not in contact with the conglomerate. Both units are overlain by the quartz-poor breccia member.

The lenticular shape of the conglomerate indicates that it may occupy a slight topographic low. The fact that it overlies part of the breccia may imply that the breccia was part of a fan which provided topographic relief against which the conglomerate was deposited. The conglomerate resembles two formations higher in the sequence and will be discussed in conjunction with these formations.

Quartz-Poor Breccia Member

This member directly overlies the Lower Mafic Formation in the west, but in the east it overlaps the western part of the quartz-rich member, the Lower Conglomerate, and the mafic flow lens (Fig. 30). In the upper part, it is intertongued with the quartz-rich member; the member thins and eventually terminates eastward as the quartz-rich member thickens. It has a maximum thickness of 900 m and extends beyond the edge of the study area. It encloses a 500 m thick lens of mafic flows termed the Western Mafic Formation. Pertinent characteristics of the member are given in Table 4.

The member is similar to the quartz-rich member with respect to the presence of most clast types. However, it lacks aphyric intermediate volcanic, chert, volcaniclastic sandstone, and autobrecciated felsic volcanic clasts; has a lower abundance of quartz grains and felsic clasts, and a higher abundance of mafic and intermediate clasts. It also contains three clast types not observed in the quartz-rich member: weakly scoriaceous intermediate volcanic, argillite, and medium to coarse-grained porphyritic granodioritic clasts. The last clast type is identical to clasts in the conglomerate formations and occurs only close to the breccia - conglomerate contacts. Both argillite and granodioritic clasts form less than 1 percent of the breccia.

In an attempt to quantify semi-quantitative observational data which indicated an east to west increase in mafic volcanic clasts, modal analyses were done on outcrops. However, the lack of clean outcrops restricted the analysis to 5 sites (Fig. 30, Table 5). To standardize the measurements, a fish net with junction points spaced 5.5 cm apart was placed on the outcrops and used as a counting grid. The results do not verify the observed east to west increase in mafic volcanic clasts, and in fact indicate a wide scatter in clast distribution patterns. However, there is insufficient data for statistical analysis of clast distribution patterns.

Clast shape varies from angular to subrounded, but most clasts appear to be subangular (Figs. 8, 9). The felsic clasts are more angular

Table 5 Outcrop Modal Counts* of Quartz-Poor Breccia (refer to Fig. 30 for locations)

Site Number	1	2	3	4	5
Felsic Clasts	2.6	23.4	0.3	5.3	
Intermediate Clasts	63.6	23.1	42.3	42.9	
-scoriaceous			5.2		
Mafic Clasts	1.9	8.1	24.6	14.6	22.5**
Matrix	31.9	45.4	27.6	37.2	

*total counts per site vary from 282 to 980
**only mafic clasts were counted at this site

Figure 8
Heterolithic quartz-poor breccia member at modal count site #1. Intermediate clasts are indicated by the letters A and B, mafic clasts are indicated by the letters C and E, and a felsic clast is indicated by D. Hand lens is 5.5 cm in length.

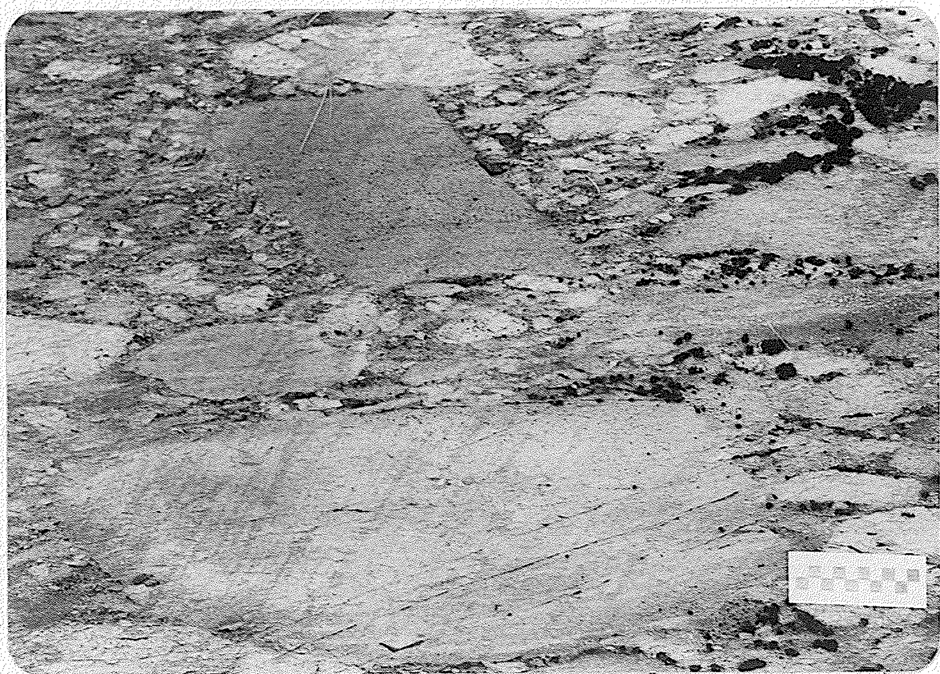


Figure 9
Heterolithic quartz-poor breccia member at modal count site #3. Most clasts are intermediate in composition. The length of individual squares in the scale is 1 cm.

than intermediate clasts whereas the subrounded to rounded mafic clasts are least angular. The major exceptions to this are the granodioritic clasts which are well rounded. Primary shapes of most clasts within the clast-supported beds cannot be determined precisely because the clasts have been tectonically stretched about a vertical axis so that they now have axial ratios ranging from 2:1 to more than 6:1. As a result, beds have been somewhat flattened.

There is a difference in clast size on opposite sides of the Western Mafic Formation. On the west, clast diameter averages 30 to 40 cm, whereas in the east it averages 20 to 30 cm. In addition, the western part contains mafic tuff interbeds having an aggregate thickness of about 50 m. Mafic tuff is absent in the east.

Matrix content is variable and ranges from 20 to 70 percent, but is generally less abundant than in the quartz-rich member. Primary textures have been largely destroyed by recrystallization, but intermediate lithic material appears to have been the major component. The remainder consists of albitized plagioclase and quartz crystals. The combined plagioclase and quartz content of the matrix is about 10 percent.

The degree of development of bedding and grading in individual units in the breccia are dependent on matrix content. Bedding contacts and normal grading are not observed where matrix content is less than 40 percent, but as matrix content increases they become better developed. They are best developed north of Queen Island in a restricted zone of matrix-rich beds that changes abruptly to matrix-poor beds both laterally and vertically. The normal grading is due to changes in average clast size.

The contacts between the breccia and the underlying and overlying conglomerate formations are gradational, with the contact zone ranging in thickness from tens of metres in the west to only a few metres in the east. This zone of mixing is limited generally to one or two beds. The clasts in the conglomerate are very distinctive (see conglomerate section), and their proportions decrease away from the conglomerate formations. The contact zone also contains 1 to 10 cm thick discrete, but continuous pelitic layers that are not present elsewhere in the breccia.

Genesis of the Quartz-Poor Breccia Member

Overall, the breccia appears to have been deposited by debris flows in a manner similar to the quartz-rich member. The normal grading observed within the matrix-rich beds indicates that gravitational settling of clasts occurred within some flows having a lower density. The presence of the pillowed flows in the stratigraphically equivalent Western Mafic Formation indicates that the breccia was also deposited subaqueously.

The pronounced clast heterogeneity also implies subaerial eruptions. The similarity of many of the clast types in both members indicates that the same vent produced most, if not all the clasts in the two members, and that the same mixing processes were probably in effect.

The interdigitation of quartz-rich and quartz-poor breccia members may reflect a prevailing westerly wind during the Plinian eruptions. The wind would tend to concentrate the crystals on the eastern side of the volcano. Material derived from that side would be rich in quartz, whereas material derived from the west would be relatively deficient in quartz.

The greater relative percentages of intermediate to mafic clasts in the quartz-poor member reflects a lack of felsic Plinian eruptions during deposition of the member.

The final points to consider are the overall westward increase in clast size and abundance of mafic clasts. It is most likely that both characteristics reflect a shorter distance to source in the west.

WESTERN MAFIC FORMATION

A lens of massive and pillowed, aphyric and porphyritic mafic flows 0.5 km thick and 4 km long occurs within the quartz-poor breccia near the western boundary of the study area. Pillow breccia and tuff is locally present near the top of the lens.

The mafic flow sequence contains several thin matrix-poor and quartz-poor breccia lenses up to 10 m thick and 100 m long which appear to be individual ungraded beds. The clasts in the breccia are similar to those elsewhere in the heterolithic breccia and are commonly less than 20 cm in diameter, with a maximum diameter of 60 cm. The matrix content ranges from 20 to 60 percent. Some lenses have more mafic matrix than breccia elsewhere, but there is no increase in the content of mafic lapilli and blocks. The higher mafic content of the matrix probably reflects a higher content of mafic ash, possibly derived from the eruptions that produced the mafic flows and tuff beds of the Western Mafic Formation. The same eruptions probably produced the mafic tuff beds found in the heterolithic breccia west of the Western Mafic Formation.

The configuration of the mafic flow sequence implies that it was a small shield volcano on the flanks of a major volcano. The intercalation of breccia in the flow sequence shows that mafic flows and heterolithic breccia were being deposited synchronously, although the flow sequence was a slightly positive area during most of this period. The shield may have acted as a divide to debris flows originating further upslope on the volcano. This divide may have in part, acted to divert some of the very coarse debris flows to the west.

MONOLITHIC CONGLOMERATE FORMATIONS

Monolithic granodioritic conglomerate forms three lenticular formations that range in length from 2.5 to 13.5 km and in thickness from 250 to 1000 m (Fig. 30). The three formations are very similar and apparently had a common source. They could be separate formations reflecting periodic renewal of the source area, or alternatively, the three formations could be tongues of a single conglomerate unit. The characteristics of the formations are given in Table 6.

All three formations consist of rounded to well rounded granodioritic pebbles, cobbles, and boulders in a medium to coarse sandstone matrix that consists primarily of smaller fragments of the granodiorite. The matrix has a variable chlorite content which reaches a maximum of about 20 percent of the matrix in the basal part of the formations (Fig. 10). Volcanic clasts are extremely scarce to nonexistent within the conglomerate.

Two textural varieties of granodiorite are present in about equal proportions distributed uniformly throughout all three formations: porphyritic with fine-grained groundmass, and porphyritic with medium to coarse-grained groundmass and generally larger phenocrysts than found in the former clasts (Figs. 11, 12). The two textural types represent the end members of a textural gradation. Rather than two specific clast sources, they indicate different cooling rates within one source. Several clasts contain mafic xenoliths up to 4 cm long.

Modal analyses of five clasts are given in Table 7. The clasts contain up to 50 percent elongated, euhedral to subhedral albitized plagioclase phenocrysts, 25 to 35 percent anhedral quartz, 5 to 15

Table 6 Characteristics of the Monolithic Conglomerate Formations

	Dimensions of Fm	Clasts	Matrix (material is 2 mm diam.)	Bedding Characteristics	Contacts with Enclosing Fms.
Upper Conglomerate Formation	- at least 2.5 km, but possibly as much as 4 km long, with a maximum thickness of 0.5 km	- well rounded med. to coarse-grained granodiorite - average diameter is 15-25 cm; largest clast was 1 m diameter - average clast size decreases upward	- matrix is compositionally similar to the clasts - averages 25 percent - tends to have a higher chlorite content near the base	- bedding contacts very diffuse - weakly developed normal grading in some beds - individual beds at least 10 m thick	- basal contact with greywacke not exposed - upper contact with mafic flows and Felsic Fm is sharp
Middle Conglomerate Formation Western and Upper Central Zone	- 13.5 km long, with a maximum thickness of 1.0 km	- well rounded med. to coarse-grained granodiorite - average diameter is 3 to 5 cm; largest clast was 30 cm - clast size tends to be uniform within both zones	- matrix is compositionally similar to the clasts - ranges from 30 to 50 percent	- bedding contacts diffuse - generally ungraded but rare normal grading is present - in beds where the contacts could be observed, thickness is 2 to 3 m	- basal contact with heterolithic breccia is gradational over a zone up to several tens of metres thick - upper contact with greywacke is very sharp, with no interbedding of conglomerate or greywacke
Lower Central Zone		- well rounded med. to coarse-grained granodiorite - average diameter is 40 to 50 cm; largest clast was 2 x 0.8 m - average clast size decreases upward	- matrix has a slightly higher chlorite content than the matrix elsewhere in the formation - matrix ranges from 30 to 40 percent	- bedding contacts very diffuse - ungraded beds - thickness of beds could not be determined	- basal contact with heterolithic breccia is gradational over a zone several metres thick - upper contact with Upper Central Zone is gradational over several tens of metres
Eastern Zone		- more than 99 percent of clasts are well rounded med. to coarse-grained granodiorite, but also some fine-grained volcanic clasts ranging from felsic to intermediate comp. - average diameter is 15 to 25 cm; largest clast was 1 m - clast size is variable in the zone	- matrix is compositionally similar to the granodiorite clasts - forms approximately 80 percent	- bedding contacts diffuse to fairly sharp - most beds ungraded but some normal and reverse grading present - numerous interbeds of fine to medium-grained volcanic sandstone - thickness of beds ranges from 1 to at least 10 m	- upper contact and lower contacts are gradational over several tens of metres
Lower Conglomerate Formation	- 3.5 km long, with a maximum thickness of 0.25 km	- well rounded medium to coarse grained granodiorite - average diameter is 20 to 40 cm; largest clast was 2.5 x 2 m - average clast size decreases upward in the formation	- matrix is compositionally similar to the granodiorite clasts - averages 20 percent; 10 to 15 percent in lower half and 30 percent in upper half of formation - some matrix-rich lenses up to 30 cm thick and 5 m long occur in the lower half;	- bedding contacts diffuse in lower half and sharp in much of the upper half - lower half ungraded, but upper half consists of normal graded beds commonly less than 1 m but up to 6 m thick	- basal contact with mafic flows and quartz-rich breccia is not exposed, but appears to be sharp - upper contact with quartz-poor breccia is gradational over 8 to 10 m - thin beds of pelite occur in upper contact zone

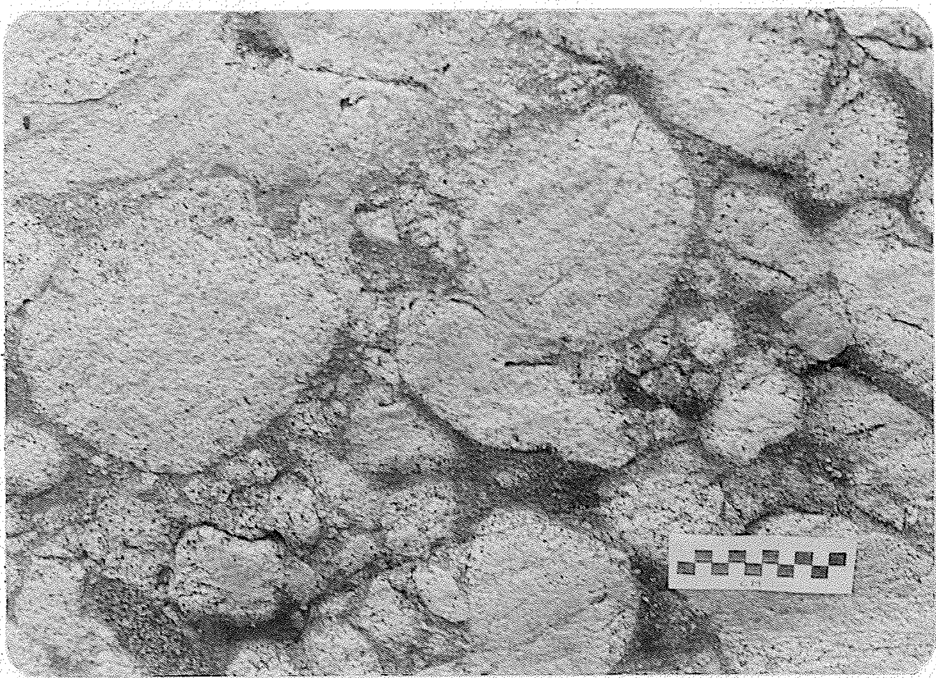


Figure 10
Well rounded granodioritic clasts in the central basal zone of the Middle Conglomerate Formation. Matrix is more chloritic than clasts. The coarse-grained mafic area in lower left is a xenolith within one of the clasts. The fine-grained felsic clast at centre right is one of the rare fine-grained volcanic clasts found in the formation. Black bars on scale are 1 cm long.

Figure 11
Photomicrograph of a granodioritic clast (D-692) from the Middle Conglomerate Formation. Dark phenocrysts consist of albitized plagioclase. Groundmass is relatively fine-grained. Field of view is 6.5 x 10 mm.

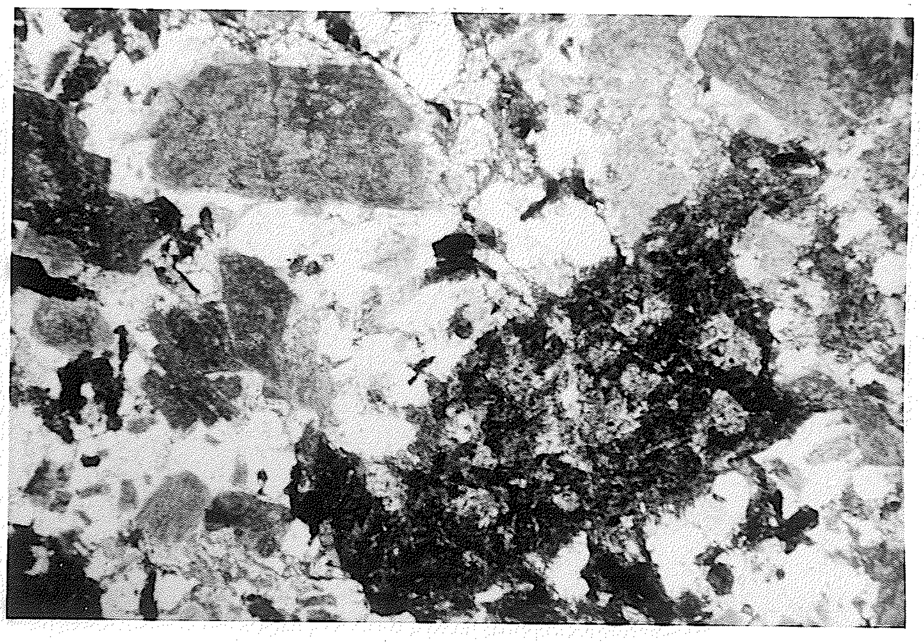


Figure 12
Photomicrograph of a granodioritic clast (D-228) from the Middle Conglomerate Formation. Mineralogy consists of albitized plagioclase, quartz, chlorite, epidote, and minor iron-titanium oxides. Groundmass is medium to coarse-grained and plagioclase phenocrysts are larger than those observed in Figure 11. Field of view is 6.5 x 10 mm.

Table 7 Modal Counts of Conglomerate Clasts which were Chemically Analysed (see Fig. 30 for locations, Table 10 for analyses)

	Sample Numbers				
	Middle Fm.			Lower Fm	
	84	228	692	247	654
Components					
Plagioclase	44.4	49.9	46.8	48.8	45.3
Quartz	32.9	31.2	28.8	29.1	30.3
Chlorite	13.6	5.3	5.6	7.4	6.3
Sericite	2.0	6.5	10.0	5.7	9.1
Epidote	3.3	4.3	7.7	6.4	5.3
Fe-Ti oxides	0.5	0.7	1.1	0.8	0.2
Carbonate	2.5	2.0	-	1.8	1.7
Vein Carbonate	1.8	-	-	-	0.3

percent chlorite, 2 to 10 percent fine-grained sericite, 3 to 8 percent fine-grained epidote, less than 1 percent disseminated iron-titanium oxide, and up to 2.5 percent fine-grained carbonate. The clasts have relatively uniform plagioclase, quartz, and carbonate contents, but vary significantly in chlorite, sericite, epidote, and iron-titanium oxide contents.

The five clasts whose modal analyses are presented in Table 7 were chemically analyzed and these results were added to six clast analyses (Table 10) reported by Goodwin (1970). The samples were chosen on the basis of minimal alteration expressed petrographically by low carbonate and/or low chlorite contents.

All the analyzed conglomerate clasts have similar silica, alumina, sodium, titania, and phosphorous contents, but there is considerable variation in iron, magnesia, potash, and manganese contents. The variations are expressed as a scatter of points on the variation diagrams (Figs. 21, 22) and indicate that some alteration has occurred in the samples. The two diagrams show that the conglomerate formations lack any well defined stratigraphic chemical evolution. On a chemical basis, the clasts can be referred to as rhyodacite.

Lower Conglomerate Formation

This is the thinnest and least extensive of the three formations. Going upward in the formation, bedding changes from poor to absent at the base to well developed at the top, average clast size decreases from 30 cm to 10 cm in diameter, and matrix content increases from 20 percent to 30-40 percent. Some exceptionally large clasts up to 2.5 m in diameter are present in the lower part of the formation (Fig. 13).

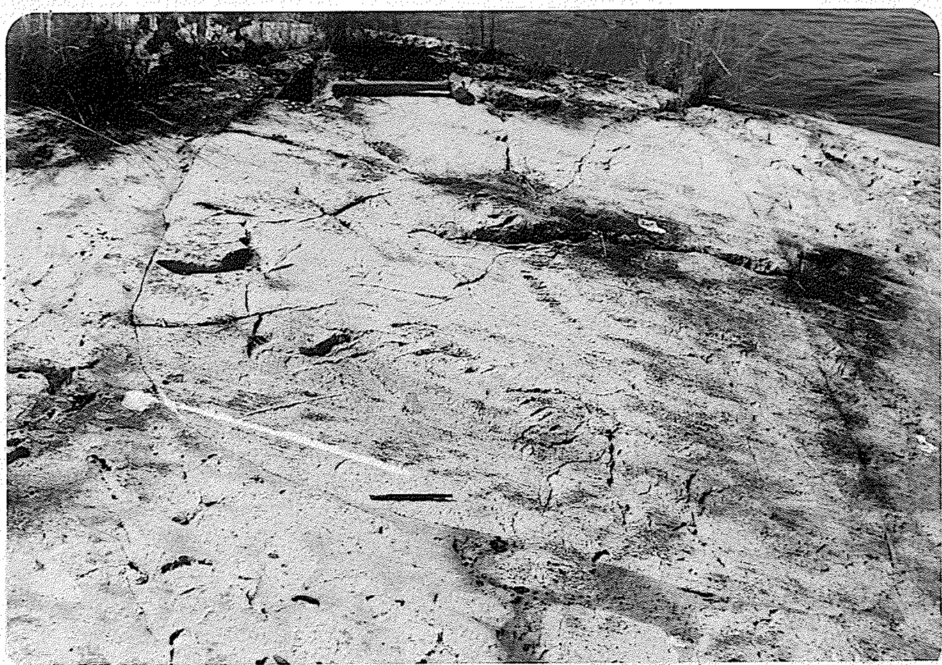


Figure 13
Large granodioritic clast in the lower part of the Lower Conglomerate Formation. Clast is 2.5 x 3.5 m. Hammer is 40 cm long.

Continuity of beds is not determinable because of sparse outcrop.

In the upper half, most beds are less than 1 m thick and are normally graded. Individual beds grade upward from a relatively thick clast-supported cobble conglomerate to thinner, upper pebbly sandstone. The upper part of the formation also contains matrix-rich beds 2 to 5 m thick that contain up to 50 percent matrix.

Localized lenticular beds up to 30 cm thick and 5 m long occur throughout the formation. Clasts constitute less than 30 percent of these beds (Fig. 14) and the matrix has a higher chlorite content than matrix elsewhere in the formation.

Middle Conglomerate Formation

The Middle Conglomerate Formation varies vertically and laterally in clast size and matrix content, and three geographic zones can be identified: the western, central, and eastern zones. These correspond to similar zones in the Greywacke Formation. The central zone is divided into upper and lower subzones. Contacts between the zones are gradational. The lateral continuity of beds within and between zones cannot be determined because of the discontinuous nature of outcrops and similarity of beds within any particular geographic zone.

The central lower zone consists of ungraded beds with diffuse contacts. Clast content decreases slightly from 60-70 percent at the base to 50-60 percent at the top, and the average clast diameter decreases from 40-50 cm at the base to 10 cm at the top. The lower half of the zone has a strong bimodal size distribution.

Three kilometers east of Queen Island, the matrix content begins to increase and the central zone grades into the eastern zone which

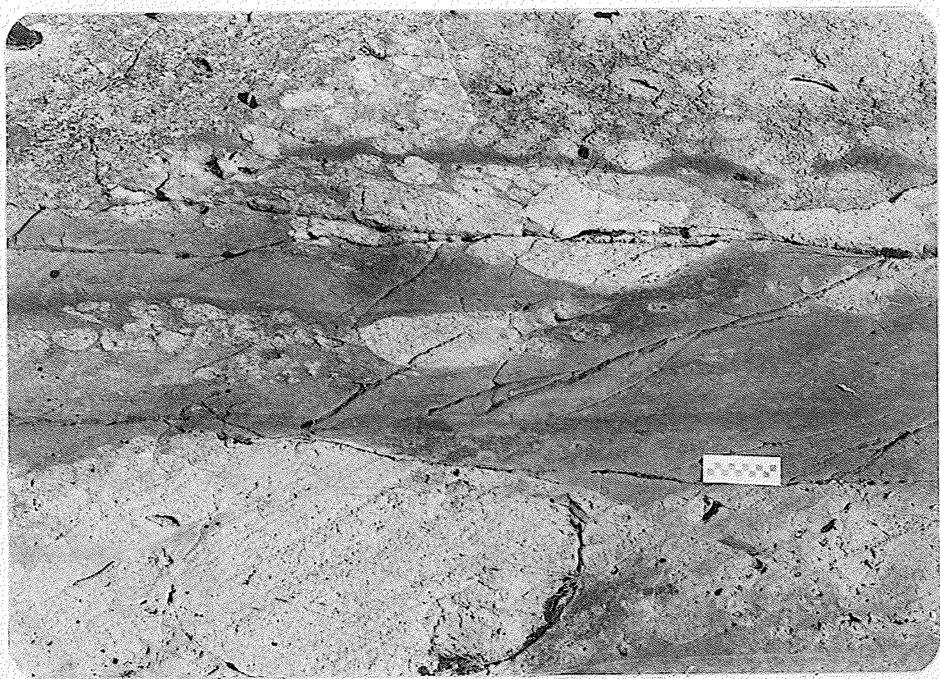


Figure 14
A matrix-rich bed in the Lower Conglomerate Formation. Black bars on scale are 1 cm long.

occurs as two tongues separated by heterolithic quartz-poor breccia. Clast content is generally 10 to 25 percent, bur ranges from 2 to 80 percent. Clasts average 30 cm in diameter, but range from 2 mm to 2.5 m. Bedding within the zone is poorly defined because bedding contacts are diffuse. Overall grading is lacking, but rare normal and reverse graded beds occur. The graded beds have poorly developed contacts and grading is indicated by an overall increase or decrease in average clast size.

On Oliver Island, in the centre of the eastern zone there is a mixing of clast types. Along the west shore of the island and further west, only granodioritic clasts are present, but along the southeast shore and further east, clasts of fine-grained felsic and intermediate volcanic rocks are present. The volcanic clasts range from 5 to 70 percent and average 25 percent of the total clast content. These clasts are identical to volcanic clasts in the heterolithic breccia formation in terms of size, shape, and composition.

Numerous ungraded to normally graded beds of fine to coarse volcanic sandstone 1.5 to 4 m thick are interbedded with the eastern zone conglomerate, both east and west of Oliver Island. These beds are distinctly different from the conglomerate matrix and consist of 40 to 60 percent plagioclase, less than 10 percent quartz, and 30 to 50 percent fine-grained felsic to intermediate volcanic clasts. The constituents are angular to subrounded and less than 3.5 mm in diameter.

In the eastern zone, heterolithic quartz-poor breccia forms two mappable members (Fig. 30) and an unmappable 5 m thick lens 100 m west of Oliver Island. The lower member, which is 2 km east-northeast of Queen Island, is less than 120 m thick. It is exposed on four small islands and its lateral extent is unknown. The upper and more extensive member is east of Queen Island and about 1 km above the Heterolithic Breccia Formation. It has a maximum thickness of 600 m at the eastern margin of the study area. It thins westward and terminates abruptly, possibly against a fault.

The breccia units are generally similar to the main breccia formation except for the small lens which contains only 5 to 10 percent matrix, compared to 30 to 40 percent matrix in the other units. Numerous rounded granodioritic clasts similar to those that characterize the conglomerate formations also occur in the two main members. At the contact between the matrix-poor breccia and overlying matrix-rich conglomerate, clast content decreases upward from 95 to 35 percent over a distance of less than 1 m.

The western and upper central zones are compositionally similar, consisting primarily of ungraded, matrix-rich beds with diffuse contacts. Clasts are generally less than 3 cm in diameter (Fig. 15). Normal grading is rarely found in thick beds that contain clasts up to 30 cm in diameter. These graded beds have two distinct parts: a thick base containing larger clasts and a relatively thin upper portion containing smaller clasts. The graded beds also have a lower matrix content and better developed bedding contacts than the ungraded beds which make up more than 95 percent of the western and upper central zones.

Upper Conglomerate Formation

This formation closely resembles the Lower Formation and the central lower zone of the Middle Formation (Table 6). Bedding contacts

Figure 15
Typical deposits found in the western zone of the Middle Conglomerate Formation. Clasts and matrix are similar in composition except for minor thin lenses of slightly more chloritic matrix. Hand lens is 5.0 cm in length.

and grading are poorly developed. Average clast diameter is 30 cm, but clasts are largest near the base and decrease in size upward. Matrix content averages 25 percent, but increases from 20 percent at the base to about 30 percent at the top.

Except for the upper contact, the margins of the formation are poorly exposed. It terminates rather abruptly against greywacke to the west and the inferred but reasonably well defined contact has a slope of at least 30 degrees. The eastern termination is not exposed and although it is interpreted to be 3 km from the western termination, the formation may extend further east.

The formation has a high thickness to length ratio and the underlying Greywacke Formation is markedly thinned beneath the conglomerate (Fig. 30). The combined thickness of the greywacke and conglomerate is equal to the thickness of the greywacke itself, immediately east and west of the conglomerate. Thus, the conglomerate appears to occupy a paleotopographic depression produced by erosion.

The eastern half of the conglomerate is overlain by 200 m of pillowed mafic flows that abut against conglomerate further west. The western flow termination is not exposed, but appears to be a topographic depression similar to that in which the conglomerate was deposited. Both the flows and western half of the conglomerate are overlain by a continuous unit of felsic lapilli-tuff and breccia.

Genesis of the Conglomerate

The monolithic nature of all the conglomerate formations indicates a compositionally uniform provenance. Furthermore, because the clasts differ from clasts found in adjacent breccia formations, the source must have been both areally restricted and geographically removed from the source of the heterolithic breccia because an areally extensive conglomerate source area would have provided granodioritic clasts to the breccia. Also, a high percentage of volcanic clasts would be expected in the conglomerate. In places, deposition of conglomerate and breccia was contemporaneous. The difference in degree of rounding of clasts within the conglomerate and breccia implies differences in mode of reworking. A high energy regime such as beaches or streams, or a combination of the two was necessary to produce the rounding of the granodiorite clasts.

The igneous texture of the granodiorite clasts suggests that the source was a subvolcanic intrusion. However, if such an intrusion was the source, considerable erosion would be required, and a more heterolithic deposit should result because volcanic country rocks would also be eroded.

A more plausible provenance would be a large dome complex. Such domes are readily eroded positive areas that could provide clasts of a single composition, but with somewhat variable textures reflecting different cooling rates at different levels in the dome. The dome(s) must have been partially or totally above water, probably isolated offshore islands or slightly above beach level on the main volcano where wave action would produce the observed rounding. Such offshore islands could also act as barriers to heterolithic debris flows. Any fine-grained or glassy clasts derived from the original dome carapace would be abraded to silt-sized material and become incorporated in the conglomerate matrix. The presence of the heterolithic breccia members and some fine-grained volcanic clasts in the eastern part of the

Middle Conglomerate Formation indicates that the volcano was still producing other clast types, but most of the breccia was being blocked by the offshore domes.

The domes would not be the typical small domes that have been described in the literature (Williams, 1956, Fisher, 1960, Mathews, 1952, Minikami, Ishikawa, and Yagi, 1951). Such small domes would produce small volumes of relatively fine-grained, and largely glassy clasts. A much larger dome or dome complex is required to produce both the observed textures in the clasts and the large volume of clasts. A rough approximation of the minimum total volume of the domes that produced the three formations at different times in the volcano's history can be made by assuming that the present formational thicknesses represent the thickest cross-sections of three deposits that were lenticular. This minimum total volume is 33 km^3. The minimum volume of the dome(s) responsible for the Middle Conglomerate Formation would be at least 20 km^3.

The similarity of the three conglomerate formations indicates that the domes were present periodically throughout most of the depositional history of the volcanic sequence, but were not an active provenance at all times. The periodicity of the formations and the general upward decrease in clast size within each formation suggests that there were three major periods of dome development related to the initiation of the three conglomerate formations. Gradual erosion of the domes would have produced the vertical changes observed in each formation.

Although the rounding of the clasts was probably caused by fluvial or beach processes (Hubert, Lajoie, and Leonard, 1970), the final deposition of the conglomerate was the result of debris flows. Rivers and beaches normally will not produce deposits as extensive as the conglomerate. Also, the conglomerates lack beach or fluvial characteristics such as cross-bedding, channel deposits, or imbrication of clasts.

Debris flows appear to be the most probable depositional mechanism. This is supported by the lack of grading within most beds, the high matrix content, and minor reverse grading such as found by Fisher (1971).

The relatively high matrix content in most of the conglomerate suggests that they were deposited in a submarine environment below wave base (Turner and Walker, 1973, Walker, 1975). The occurrence of pillowed mafic flows and greywacke in contact with the formations further corroborates a deep-water depositional environment.

Direct evidence of transport directions of the conglomerates is absent. However, the lenticular shapes of the formations and clast distribution patterns in the formations imply that transport was in an approximately north-south direction, although the absolute sense of transport cannot be determined.

GREYWACKE FORMATION

This wedge-shaped formation overlies the Middle Conglomerate Formation and extends beyond the boundaries of the study area. It ranges in thickness from 0.5 km in the east to 2.5 km in the west. Lateral variations, although not extensive, permit the formation to be divided into three zones: the Western, Central, and Eastern Zones (Fig. 30). Some of the variables are: overall bed thickness, presence or absence of complete Bouma cycles, and the presence of breccia interbeds. It must be stated that overall, the three zones have a greater similarity than differences with one another. The zones were chosen to highlight some minor variations within the formation.

The main characteristics of the greywacke are given in Table 8. The formation is characterized by the presence of innumerable beds that generally grade upward from greywacke to argillite. Individual beds range from a few centimetres to 25 m in thickness. Complete Bouma cycles as defined by Bouma (1962) are rare. Rather, the principal Bouma members are the a and e members; the a member commonly being 1 to 3 times as thick as the e member. These morphological characteristics are similar to those in greywacke deposited by turbidity currents.

In decreasing order of abundance, the petrographically identifiable components of the deposits consist of euhedral to subhedral albitized volcanogenic plagioclase, angular to subrounded volcanic lithic clasts of felsic to mafic composition, approximately equal amounts of monocrystalline and polycrystalline quartz, and coarse-grained rounded granodioritic clasts (Table 9). According to Figure 16, the greywacke is lithic and feldspathic wacke.

Table 8 Characteristics of the Greywacke Formation

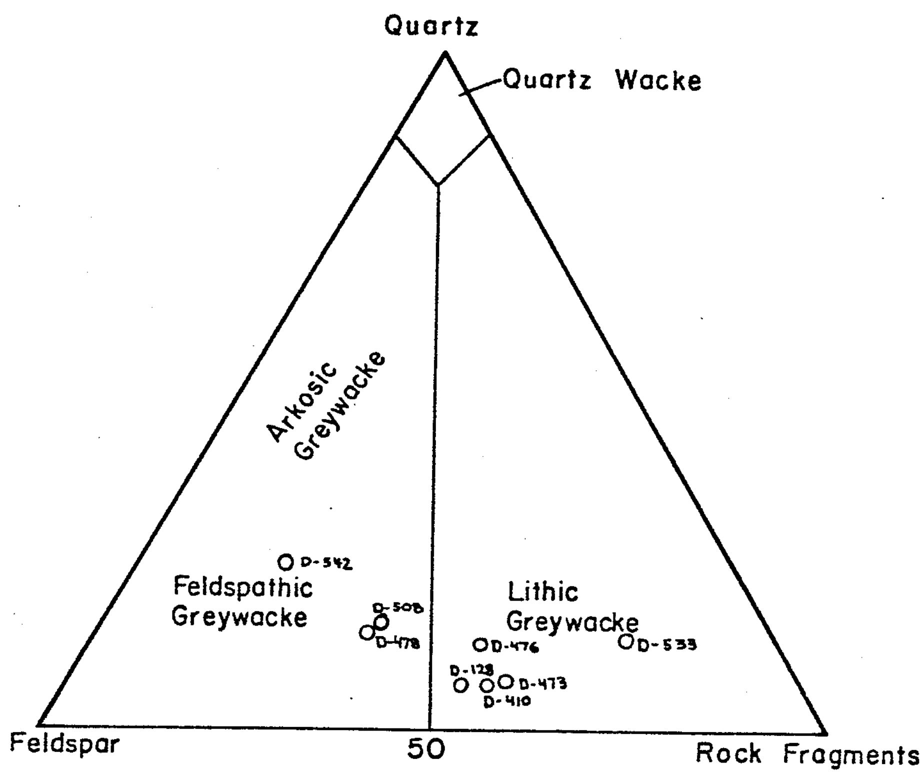
	Western Zone	Central Zone	Eastern Zone
Thickness of Formation	- approximately 2.5 km thick	- extreme variable, from 800 m to more than 2 km - this variability reflects the presence of the overlying lens-shaped upper conglomerate formation	- thin eastward from 800 m to less than 300 m
Type and Nature of Deposit	- characterized by greywacke beds containing argillaceous to silty to sand sized material - beds vary in thickness from less than 0.1 m to more than 25 m, however, most beds are less than 1 m thick - many of the silty beds contain ungraded lenses of sandy material 3-10 cm long - most beds show a and e Bouma members; however, several beds showing complete Bouma cycle were observed - subvertically oriented scour channels were observed at base of one bed - argillaceous interbeds are less common than in Central Zone - numerous 2 to 25 m thick heterolithic volcanic breccia interbeds that contain aphyric pink felsic and medium to coarse-grained porphyritic, hornblende-rich volcanic clasts in addition to clast types found in heterolithic breccia formation - several beds contain only the pink clasts and may be classified as pebbly greywacke - small epidote-rich concretions present in some beds	- generally monotonous greywacke beds from 2 cm to 2 m thick - only a and e members of Bouma cycle with local small-scale scour and flame structures - argillaceous interbeds commonly form up to 40 percent of the zone - local beds contain up to 5 percent angular to subrounded rip-up clasts of argillite or siltstone - local chert beds up to 3 cm thick - overall grain size tends to be finest in this zone, compared to the Western and Eastern Zones - small epidote-rich concretions present in some beds	- characterized by argillaceous to sandy normal graded greywacke beds consisting of a and e members of Bouma cycle 2 cm to several meters thick, which are interbedded with greywacke beds containing numerous rip-up clasts of argillite or siltstone - several thick beds of unknown thickness were also found to contain up to 10 percent felsic to mafic volcanic clasts - local iron formation clasts found in upper part of zone
Relative Proximity to Source (according to Walker, 1967)	- proximal and distal, with distal character dominant	- proximal and distal with distal character dominant	- distal
Lower Contact	- indistinct; grades over a distance of tens of metres into heterolithic breccia	- very sharp with Middle Conglomerate Formation	- in west, contact with Middle Conglomerate Formation is not exposed - in east, sharp contact with heterolithic breccia
Upper Contact	- in sharp contact with 100 m x 2 km lens of heterolithic breccia and mafic flows	- not exposed, but assumed to be with upper conglomerate formation	- contact difficult to interpret because of poor exposure

Table 9 Modal Analyses of Greywacke and Matrix of Quartz-Rich Breccia**

Sample Nos.	128	410	473	476	478	508	533	542	746**
Monocrystalline Quartz Grains	0.6	2.0	0.4	1.2	1.0	1.8	1.0	4.8	13.6
Polycrystalline Quartz Grains with less than six domains	1.2	1.0	-	-	-	1.4	0.6	2.0	1.6
Polycrystalline Quartz Grains with more than six domains	0.8	0.4	0.8	2.0	4.2	-	1.2	0.4	6.2
Plagioclase	16.8	10.8	7.6	14.8	22.6	12.0	5.2	20.4	34.2
Petrographically Indistinguishable Matrix	53.4	52.0	62.0	45.6	37.4	38.4	47.6	62.8	29.6
Chlorite in Matrix	-	-	2.0	0.4	-	0.4	7.6	-	0.8
Epidote in Matrix	5.0	14.0	-	10.6	1.4	11.2	-	-	-
Biotite in Matrix	-	6.4	6.6	6.2	10.0	1.4	0.2	-	-
Amphibole in Matrix	-	0.6	-	-	-	-	-	-	-
Iron-Titanium Oxides in Matrix	1.8	0.4	0.2	1.0	-	0.8	0.8	1.0	1.4
Carbonate in Matrix	1.6	0.2	9.4	4.4	7.8	3.6	14.6	3.6	4.8
Aphyric Felsic to Intermediate Volcanic Clasts	16.6	7.0	0.8	2.0	15.6	5.2	17.4	-	7.0
Plagioclase-Quartz Phyric Felsic Volcanic Clasts	-	-	10.4	11.0	-	1.5	2.0	5.4	-
Aphyric Intermediate Volcanic Clasts	2.2	2.8	-	-	-	2.2	1.0	-	0.8
Aphyric Mafic Volcanic Clasts	-	1.2	-	0.4	-	-	-	-	-
Granodioritic Clasts	-	0.2	-	0.4	-	-	-	-	-

* 500 points counted per thin section
** matrix of quartz-rich breccia from the Heterolithic Breccia Fm

Figure 16 Classification of Greywacke
(after Pettijohn, 1975)



Grain size within the formation encompasses a wide range, from less than 1 mm to 25-30 cm in diameter.

The very fine-grained matrix which forms about 50 percent of the greywacke is recrystallized. It may have originally been volcanic lithic clasts, in which case all of the greywacke would have been lithic.

Western Zone

This zone extends from the western edge of the study area to about 2 km east of Wiley Point. It consists mostly of normally graded greywacke beds containing a and e members of the Bouma cycle. However, several complete or nearly complete Bouma cycles were found on an island 1.2 km southeast of Wiley Point.

One of the characteristics of the zone is the presence of about 5 percent ungraded heterolithic breccia and pebbly greywacke units ranging in thickness from a few metres to about 25 m. The very thick units probably consist of several individual beds, but bedding contacts were not observed. Most of the breccias are compositionally similar to the heterolithic quartz-poor breccia found elsewhere in the sequence. However, several of the pebbly greywacke units contain up to 20 percent rounded to sub-rounded aphyric pink felsic and medium to coarse-grained, porphyritic hornblende-rich mafic clasts that are commonly less than 5 cm in diameter. The two clast types were rarely found in the heterolithic breccia units, which indicates that they may have been derived from a different source area.

Two pebbly greywacke beds on Queen Island are less than 1 m thick, whereas most pebbly greywacke beds to the west tend to be 2 to 10 m thick. Although the beds on Queen Island are not stratigraphically equivalent to beds in the west, the general easterly decrease in average bed thickness may indicate that the source was located in the west.

On an island 1.2 km southeast of Wiley Point, there are several units of another anomalous breccia characterized by clasts of aphyric mafic volcanic rock, mafic to intermediate hornblende porphyry, and black chert. The clasts are in an olive-green mafic matrix composed mainly of epidote and actinolite. The clasts are angular to subrounded and range in size from less than 5 mm to 35 cm, with most averaging 3 cm in diameter. The beds range in thickness from 3 to 27 m, with the thickest beds containing the largest clasts.

On the same island, two 3 to 5 m thick greywacke beds contain both angular blocks and vertically-oriented rods of argillaceous siltstone. The blocks are up to 40 cm in diameter and the rods (Fig. 17) are up to 30 cm long. Although the rods may be primary in shape because they occur in the same beds as the undeformed blocks, they are probably tectonically deformed blocks because they have the same orientation as the regional tectonic lineation.

Possible metamorphosed concretions were observed on Wiley Point and Queen Island. They are rounded to ellipsoidal, 4 mm to 1 cm in diameter, and are more resistant to weathering than the surrounding rock. In places, they are partly coalesced. Although confined to definite units, they cut across bedding planes. The concretions consist of 30 to 50 percent iron-rich epidote and 50 to 70 percent quartz, albitized plagioclase, and lithic clasts, whereas the enclosing rock consists of 5 to 10 percent epidote, and 90 to 95 percent quartz, albitized plagioclase, and volcanic lithic clasts. Henderson (1972) has observed

Figure 17
Coarse greywacke containing subvertically oriented rod-like clasts of argillaceous siltstone, 1.2 km southeast of Wiley Point. Black bars on scale are 1 cm long.

similar concretions in early Precambrian greywackes of the Slave Province.

Central Zone

This zone includes Queen Island and extends about 1 km west and 5 km east of that island. The boundary between it and the Eastern and Western zones is gradational.

The zone is characterized by innumerable greywacke beds locally interbedded with chert (Table 8, Fig. 18). It differs from the Western Zone principally in its lack of complete Bouma cycles and interbedded breccia. Most of the zone consists of beds that contain the a and e members of the Bouma cycle. Some beds contain up to 10 percent angular argillite or siltstone clasts up to 15 cm in diameter which appear to have been ripped up from underlying beds. These clasts are concentrated in the central parts of the beds. The pebbly greywacke beds mentioned earlier occur only on the western side of Queen Island.

The zone is thinnest directly beneath the Upper Conglomeate Formation. This thinning is believed to be erosional.

Eastern Zone

This zone extends from 3 km west of Oliver Island to the eastern edge of the study area. It differs from the Central Zone principally in having a greater abundance of beds that contain rip-up and volcanic clasts. The contact between the two zones is not exposed, but is assumed to be gradual. The zone is characterized by 2 cm to 3 m thick normally graded beds containing a and e members of the Bouma cycle, interbedded with weakly normally graded beds to 1.5 m thick, containing rip-up clasts of bedded siliceous argillite (Fig. 19). Near the top of the

Figure 18
Greywacke Formation on the east side of Queen Island. It consists of greywacke beds interbedded with dark argillite and light coloured chert. Bed thickness varies from a few centimeters to 2 m. The greywacke beds contain a and e members of the Bouma cycle. The hammer is 40 cm long.

Figure 19
Rip-up clasts of argillite in the eastern zone of the Greywacke Formation. The clasts were derived from the upper portions of underlying beds. Pencil is toward the top of the beds.

formation several beds contain up to 10 percent angular to subrounded intermediate to mafic volcanic clasts and sparse iron formation clasts. The clasts are up to 30 cm long, but the iron formation clasts have been folded. This folding may have occurred during transport because the folded chert-magnetite layers are parallel to the clast boundaries. The iron formation clasts occur in two outcrops 1.5 km west of a 10 m thick iron formation unit within the Greywacke Formation. However, this iron formation was not the source of the clasts because the abundant volcanic clasts that are associated with the iron formation clasts imply a source further upslope.

Genesis of the Greywacke

Most of the greywacke's constituents suggest a volcanic derivation. The relatively low abundance of quartz (Shiki, 1962) and the association with volcanic clasts suggests but does not prove a volcanic provenance for the quartz. The presence of more than six domains in much of the polycrystalline quartz implies a derivation from either a metamorphic terrain or volcanogenic quartz veins (Henderson, 1972), because the occurrence of both monocrystalline and polycrystalline quartz in the same samples rules out in situ metamorphism as the cause of the polycrystallinity. The lack of metamorphic lithic clasts suggests that volcanic quartz veins were the most likely source of polycrystalline quartz. Although the shape and nature of the quartz grains are not diagnostic of either a plutonic or volcanic source (Blatt and Christie, 1963), their overall angular shape does indicate a lack of extensive reworking, and by implication, a volcanic source.

The subhedral to euhedral habits of most plagioclase grains indicate minimal reworking. Their most likely source was an unconsolidated deposit such as tuff. Their albitized nature prohibits any speculation about the composition of the volcanic source.

The aphyric intermediate to felsic clasts are identical to many of the clasts in the Heterolithic Breccia Formation and in the breccia interbeds within the greywacke. All these clasts appear to have been derived from the same volcanic source area, although the pink felsic and hornblendic mafic clasts in the pebbly greywacke beds show that some material was derived from a different volcano. The fact that the pebbly greywacke beds are thicker and contain larger clasts in the west suggests a western source.

The relatively abrupt change from deposition of the underlying monolithic conglomerate to greywacke indicates major changes in the nature of volcanism. It may even represent a hiatus. The source of the conglomerate was abruptly terminated, either by active downsinking or submergence or by complete erosion of the conglomerate's source. Once this source was removed, the main volcano should have become once again the dominant source. However, since deposition of coarse breccia was not resumed, the volcano may have been largely dormant. The eastern transition from breccia to greywacke indicates that as the main vent became dormant, a combination of erosion and downsinking brought the volcano below sea level. It was thus effectively rendered incapable of providing further substantial volumes of heterolithic debris flows.

The greywacke appears to have been deposited as a subaqueous alluvial fan because it is underlain and overlain by subaqueously deposited formations. It also lacks any cross-cutting channels that should be present if it were a subaerial alluvial fan.

Since turbidity flows which give rise to greywacke deposits can travel for tens of kilometres (Walker, 1970), the Greywacke Formation is compared with Walker's (1967) criteria for recognition of proximal and distal turbidites.

Proximal	Distal
- thick coarse beds commonly beginning with a massive or plane laminated division	- thin fine-grained beds beginning with a ripple cross laminated division
- little if any interlayered argillite and chert	- interlayered shale and chert
- presence of complete Bouma sequences	- complete Bouma sequences rare
- beds poorly graded	- beds well graded
- scours, channels, washouts common	- a few small scours, no channels
- individual sandstone beds commonly amalgamated	- individual sandstone beds rarely amalgamated

Most of the characteristics of all three zones agree with the definition of distal facies. Only with a small area of the Western Zone do the presence of some complete Bouma cycles and scours indicate a proximal facies. Although scour channels were only observed at the base of one bed, it is noteworthy that they are oriented subvertically. This indicates transport in a north-south direction which conflicts somewhat with other evidence supporting a western source for most of the greywacke. Such evidence includes the eastward formational thinning and eastward thinning of separate pebbly greywacke beds.

In summary, it appears that the majority of the greywacke was derived from the west. Interbedded breccias and possibly some greywacke were derived from the main volcano lying to the north or south.

FELSIC FORMATION

The Felsic Formation consists of flows and pyroclastic rocks that form three lenticular members in the uppermost part of the sequence (Fig. 30). The western and thickest member is south of Queen Island. It is at the same apparent stratigraphic level and probably related to the Upper Felsic Ash-Flow Formation which occurs 2 km east of it. The two eastern members are 5 km further east of the western member.

The western member has a maximum thickness of 150 m and a length of 2.9 km. The lower contact of the member is not exposed, but it is relatively sharp; the covered interval is less than 2 m wide. The upper contact is exposed at two locations and is also sharp. The member consists of approximately 1 percent bedded tuff, 95 percent heterolithic lapilli-tuff and breccia, and 4 percent monolithic breccia which may represent autoclastic flows. The beds range in thickness from 1 to 7 m. Grading is present only within the tuff.

The tuff occurs in only one outcrop. It consists of 15 percent quartz grains up to 2 mm in diameter, some of which are embayed, up to 5 percent albitized plagioclase up to 2 mm in diameter, and about 80 percent highly foliated matrix which consists of sericite, epidote, quartz, and albitized plagioclase. The matrix probably consisted of fine-grained lithic clasts prior to metamorphism.

The lapilli-tuff and breccia consist of 80 percent angular to subrounded felsic clasts and 20 percent matrix. Clasts range from 2 mm to 1 m in diameter. The subrounded clasts are aphyric to weakly porphyritic, with 1 to 5 percent lath shaped albitized plagioclase phenocrysts up to 1 mm long, but generally less than 0.2 mm, in a very fine-grained groundmass of quartz, albitized plagioclase, sericite, and epidote. The angular clasts consist of 1 to 2 percent sericitized orthoclase phenocrysts up to 1.5 mm in diameter, 20 percent sericite, 25 percent granular fine-grained epidote, 45 percent albitized plagioclase microlites up to 0.3 mm long, and 5 to 10 percent fine-grained quartz.

In addition to their petrographic and shape differences, the angular and subrounded clasts differ in other parameters. The subrounded clasts have a 1 to 3 cm wide white rim which grades into the massive interior. The angular clasts lack the rim, but are flow layered and have a trachytic texture of plagioclase microlites within the flow layers. The layering is formed by variations in the abundance of fine-grained granular epidote in diffuse layers averaging 5 mm in width. Epidote-rich layers contain up to 40 percent epidote, whereas epidote-poor layers contain 5 to 10 percent.

Chemical analysis of one of the clasts by Goodwin (1970) (Table 10) indicates a rhyodacitic composition. The matrix of the lapilli-tuff and breccia is compositionally similar to the previously described tuff. Quartz, which forms 3 to 15 percent of the matrix is angular to subrounded and up to 2 mm in diameter; some of the larger grains are embayed. Less than 5 percent of the matrix is euhedral to subhedral albitized plagioclase laths which reach lengths up to 2 mm. The remainder consists of sericite, quartz, epidote, and very fine-grained albitized plagioclase in indeterminate amounts.

A single isolated unit of monolithic autoclastic breccia occurs on a small island 600 m west of the closest pyroclastic deposits. The breccia is 15 m thick and consists of 70 percent subangular aphyric clasts up to 4 cm in diameter in a compositionally identical, highly sericitized foliated matrix. Compositionally and texturally, the clasts are similar to the flow-layered angular clasts in the pyroclastic deposits.

The two eastern members occur within the overlying mafic flow sequence at a slightly higher stratigraphic position than the western member. The lower member occurs on two islands 500 m apart. It is 500 m above the mafic flow - greywacke contact and has a maximum thickness of 50 m. Although it appears to be discordant with the enclosing mafic flows, bedding measurements indicate that the two exposures are connected. The upper member is 220 m above the lower member. Its lateral extent is unknown and its exposed thickness is 15 m.

The western exposure of the lower member consists of a 15 m thick felsic massive flow that is overlain by fine-grained ungraded felsic tuff. The eastern exposure consists of a 3 m thick felsic monolithic breccia that is overlain by about 1 m of well bedded, fine-grained intermediate tuffaceous sediments (Fig. 20). These in turn are overlain by pillowed mafic flows. The breccia has a bimodal size distribution; it contains about 70 percent angular to subrounded aphanitic felsic clasts averaging 10 cm in diameter in a matrix with a high chlorite content. The overlying tuffaceous sediments have a grain size less than 2 mm. In decreasing order of abundance, they consist of subhedral albitized plagioclase, chlorite, subrounded quartz, and epidote.

The upper member is an autobrecciated flow that is identical to the autobrecciated flow in the western member.

Figure 20
Monolithic felsic breccia overlain by well bedded intermediate tuffaceous sediments. The outcrop is in the eastern end of the lower eastern member of the Felsic Formation. Coin in lower left is 1.9 cm in diameter.

Genesis of the Felsic Formation

The components of the formation appear to have originated both as flows and from pyroclastic eruptions. The flow-layered clasts in the western member were probably derived from explosive or slumping disruption of a flow, whereas the white-rimmed clasts and crystals in the matrix were probably derived by magmatic explosion and subjected to alteration in sea water while still hot.

The occurrence of pillowed flows above and below the formation indicates that it was deposited subaqueously. The formation was derived from a restricted source and transport of the components had to be short because other volcanic clasts do not occur within the formation. The presence of the autoclastic flows also implies relatively short transport distances.

The lenticular nature of the individual members indicates that transportation was more north-south than east-west.

UPPER MAFIC FORMATION

The 3 km thick Upper Mafic Formation caps the fragmental sequence. The formation exhibits the greatest degree of deformation of any formation, with the exception of the Ash-Flow Tuff Formation. Only its lower portion was examined. The basal contact is sharp where it is exposed. Because the formation encloses three members of the Felsic Formation, contemporaneous mafic and felsic eruptions must have occurred.

The formation consists of pillowed flows petrographically similar to those in the Lower Mafic Formation, and minor tuff. Many of the pillows are deformed with length to width ratios up to 15 to 1. Many pillows contain deformed variolites up to several centimetres long. Primary textures in the tuffaceous rocks have been destroyed by deformation and recrystallization. Several chemical analyses by Goodwin (1970) and Wilson and Morrice (unpublished) are included in Table 10. They show that the formation is tholeiitic.

INTRUSIONS

A wide variety of minor intrusions ranging in composition from mafic to felsic occur in the area. They form sills, dikes, and small bosses, most of which appear to have been metamorphosed to the same degree as the enclosing formations.

Mafic sills up to 175 m thick occur in the Lower Mafic Formation and in the lower part of the Heterolithic Breccia Formation. Some sills have cumulate textures. Numerous mafic dikes up to 2 m wide and with diverse orientations occur in most of the fragmental formations, particularly in the eastern part of the sequence.

The most numerous intrusions are porphyritic felsic to intermediate dikes that range in width from 2 to 20 m. They have diverse orientations, although many are either parallel to or perpendicular to the enclosing formations. The dikes are compositionally variable, but most contain both quartz and plagioclase phenocrysts in concentrations ranging from 2 to 25 percent in total. Individual phenocrysts range in size from 2 to 6 mm.

Most dikes are massive, but some are strongly foliated and similar to the Ash-Flow Tuff Formations except for the lack of broken phenocrysts and lithic clasts. Some of the dikes are also compositionally similar to certain clasts in the Heterolithic Breccia Formation.

The dikes are concentrated in two areas: south of Wiley Point and north of Queen Island. Associated with these dike concentrations are two small bosses: a 100 m in diameter coarse-grained granodioritic boss in the west, and a larger syenitic boss characterized by marked grain size variations, in the north. Both bosses have a weakly developed foliation that is parallel to the regional foliation. A 100 m thick diorite sill occurs on Queen Island.

Although most of the mafic to felsic intrusions appear to be synvolcanic, most are not directly related to the volcanism that produced the study sequence. Most of the dikes occur higher in the sequence than many of their compositionally identical fragmental counterparts. Additionally, because the fragmental formations were deposited well away from the vent(s), they would probably not contain many contemporaneous dikes. The dikes were most likely produced by later volcanism.

The only post-volcanic intrusion is a north-trending diabase dike in the central part of the area. It ranges in width from 20 to 70 m.

CHEMISTRY

Twenty-four analyses are available from the sequence (Table 10). They were obtained by the author, by Goodwin (1970), and by Wilson and Morrice (unpublished data, 1977). The chemical data have been previously discussed by Goodwin (1970) and Wilson and Morrice (1977) as part of investigations of the entire volcanic sequence. The data are only briefly treated here with respect to the examined stratigraphic units.

The samples include rhyodacite, dacite, andesite, and basalt. Some of these samples have high volatile contents and are probably altered. This alteration is probably also reflected by the scatter of data points on the variation diagrams (Figs. 21, 22). Many of the analyses are of clasts from fragmental rocks and as such, do not represent the precise composition of their respective formations.

On the AFM diagram (Fig. 21), samples are clustered in two areas: most of the mafic flows are basaltic and form a tholeiitic trend whereas the intermediate to felsic units show a wide scatter in the alkali-rich part of the diagram and form a crude calc-alkaline trend. However, in this section of the diagram tholeiitic and calc-alkaline trends are more or less superimposed and the magma series cannot be accurately defined. In order to resolve this ambiguity, the samples were plotted on the MgO/Al_2O_3 versus $(Na_2O + K_2O)$/total $FeO + TiO_2$ plot of Green (1975; Fig. 22). Again there is a bimodality of points, with the mafic samples in the tholeiitic field and the felsic to intermediate samples in the calc-alkaline field.

It is significant that the basalts have a tholeiitic affinity

Table 10 Chemical Analyses

	Upper Mafic Fm								Felsic Fm	Upper Congl. Fm		Greywacke Fm
Sample No.	W45	W49	W50	G146	G147	G149	G150	G151	G148	G144	G145	G143
Classification	Bs	Bs	Bs	Bs	An	Bs	Bs	Bs	Ry	Dc	Dc	Dc
SiO_2	47.85	49.00	48.20	51.00	55.50	52.05	47.50	53.00	72.75	68.60	66.25	60.70
Al_2O_3	12.96	13.93	15.31	15.60	14.70	15.30	12.60	15.20	14.45	16.70	15.60	15.90
Fe_2O_3	2.66	4.84	3.45	2.03	2.30	2.10	1.86	2.31	0.0	0.92	1.45	1.92
FeO	7.44	6.68	8.00	8.52	5.96	9.36	9.04	8.20	0.60	0.80	1.60	5.20
MgO	12.00	8.17	8.17	8.40	5.60	4.60	10.20	6.25	0.70	1.20	1.30	4.50
CaO	9.92	10.30	9.50	4.80	8.36	7.05	11.10	10.65	1.22	2.00	3.20	3.15
Na_2O	1.52	1.68	2.12	3.04	5.78	2.42	1.88	2.56	3.54	4.90	4.12	3.24
K_2O	0.14	0.01	-	0.74	0.26	0.38	0.30	0.35	4.30	1.65	2.10	2.38
TiO_2	0.52	0.67	0.62	0.83	0.63	0.75	0.61	0.86	0.07	0.25	0.26	0.44
MnO	0.21	0.19	0.22	0.20	0.19	0.20	0.19	0.20	0.02	0.02	0.03	0.12
CO_2	0.02	0.08	0.08	0.62	0.36	2.00	2.88	0.37	1.00	1.52	0.62	0.33
H_2O	4.23	3.64	3.76	3.22	1.08	3.85	1.35	0.80	0.57	0.84	1.09	2.32
P_2O_5	0.13	0.10	0.18	0.25	0.08	0.18	0.13	0.26	0.06	0.18	0.24	0.27
Ni (ppm)	380	176	112	160	190	160	270	150	100	100	100	100
Cu (ppm)	42	132	79	120	44	120	160	110	20	43	32	25
Co (ppm)	53	55	39	60	60	60	60	60	20	60	60	60
Zn (ppm)	52	67	59							41	18	120
	99.60	99.52	99.61	99.25	100.80	100.22	99.64	101.01	99.28	99.58	97.86	100.47

Sample locations are shown on Fig. 30.
Samples prefixed by D were collected by the author.
Samples prefixed by W were collected by Wilson and Morrice (unpublished data).
Samples prefixed by G were collected by Goodwin (1970).

Classification Symbols
Bs - Basalt
An - Andesite
Dc - Dacite
Ry - Rhyodacite to Dacite

Table 10 Chemical Analyses (continued)

	Middle Conglomerate Fm							Heterolithic Breccia Fm		Lower Congl. Fm		Lower Mafic Fm
Sample No.	G139	G140	G141	G142	D84	D228	D692	G137	G138	D247	D654	G136
Classification	Ry	Ry	Ry	Dc	Dc	Dc	Dc	Ry	Dc	Ry	Dc	Bs
SiO_2	70.50	68.70	71.25	67.00	65.50	66.53	66.10	74.10	66.00	69.30	67.25	46.60
Al_2O_3	15.90	16.70	15.10	15.80	15.40	15.20	14.87	14.80	14.15	15.15	15.76	11.00
Fe_2O_3	1.16	1.16	1.40	1.56	1.00	1.37	1.01	0.31	1.02	1.06	0.34	1.78
FeO	1.64	1.00	1.36	1.56	2.18	1.48	1.90	1.32	2.44	1.25	0.77	8.88
MgO	1.85	2.25	0.80	2.60	1.95	1.60	1.06	0.72	2.00	0.85	1.10	10.40
CaO	1.75	1.80	1.00	3.50	3.56	3.40	4.46	0.80	4.46	2.00	1.58	11.35
Na_2O	6.42	2.80	4.86	4.82	5.24	6.26	4.78	0.86	3.90	5.24	6.63	1.06
K_2O	0.69	2.38	1.89	2.22	1.67	1.08	1.90	4.22	1.56	1.97	3.72	0.03
TiO_2	0.19	0.23	0.22	0.46	0.37	0.32	0.32	0.72	0.25	0.37	0.25	0.52
MnO	0.04	0.02	0.03	0.06	0.06	0.06	0.08	0.03	0.07	0.03	0.02	0.21
CO_2	3.05	0.72	0.40	1.66	1.33	1.28	1.84	4.41	0.85	1.22	0.68	1.51
H_2O	0.71	0.56	0.99	1.05	1.19	1.22	1.63	0.88	1.20	1.49	1.32	3.41
P_2O_5	0.16	0.29	0.23	0.46	0.25	0.18	0.19	0.05	0.24	0.19	0.18	0.30
Ni (ppm)	100	110	100	120	31	25	19	270	100	14	37	310
Cu (ppm)	30	20	22	20	21	16	62	56	25	11	43	150
Co (ppm)	60	60	60	60	10	10	10	60	60	10	17	60
Zn (ppm)	44	32	37	33	64	43	34	19	44	35	66	110
	104.06	100.61	99.53	102.75	99.70	100.00	100.14	103.22	98.14	100.02	99.60	97.25

Sample locations are shown on Fig. 30.
Samples prefixed by D were collected by the author.
Samples prefixed by W were collected by Wilson and Morrice (unpublished data).
Samples prefixed by G were collected by Goodwin (1970).

Classification Symbols
Bs - Basalt
An - Andesite
Dc - Dacite
Ry - Rhyodacite to Dacite

Figure 21 AFM Diagram showing the chemical variation in the metavolcanic sequence from the study area

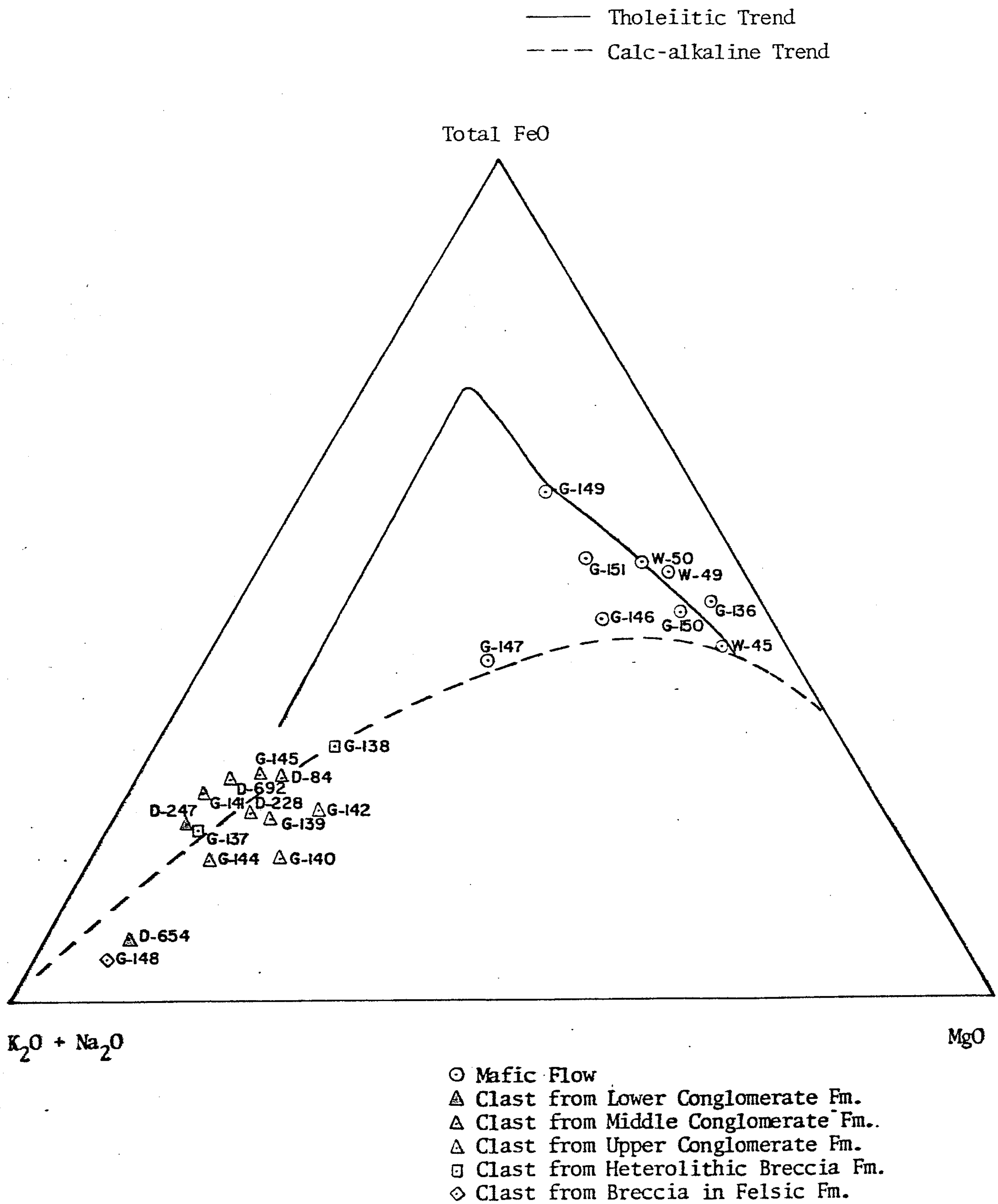
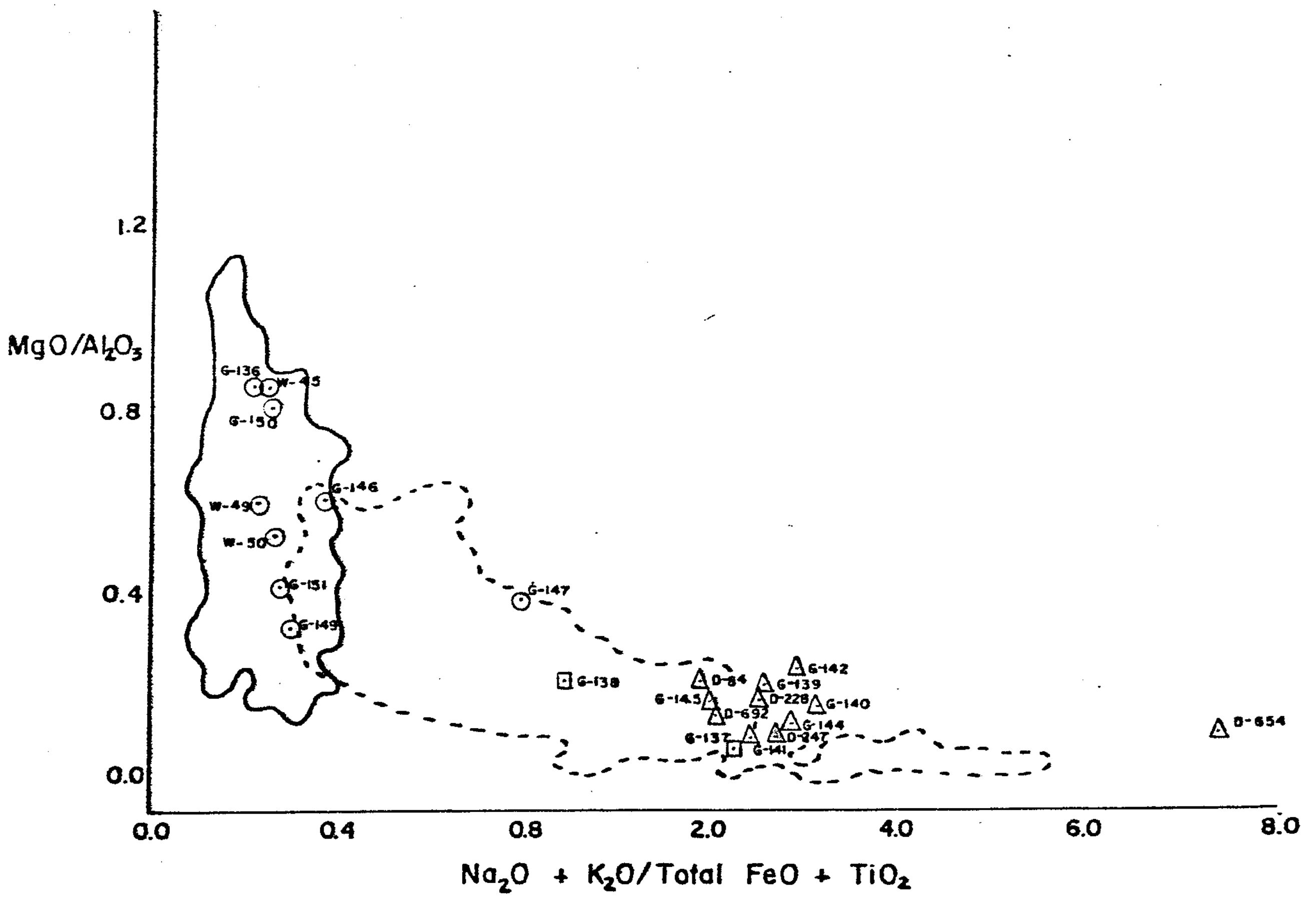


Figure 22 MgO/Al_2O_3 versus $(Na_2O + K_2O)$/Total $FeO + TiO_2$ Diagram (after Green, 1975)

Tholeiitic (solid line) and calc-alkaline (dashed line) fields are defined on the basis of 1800 chemical analyses of modern volcanic rocks



⊙ Mafic flow
▲ Clast from Lower Conglomerate Fm.
△ Clast from Middle Conglomerate Fm.
△ Clast from Upper Conglomerate Fm.
⊡ Clast from Heterolithic Breccia Fm.

whereas the felsic rocks have a calc-alkaline affinity. Such a chemical difference may indicate that the formations were derived from separate magma chambers. However, this is not conclusive proof that separate volcanoes were involved.

SYNTHESIS

The study area is characterized by a fragmental sequence which is underlain and overlain by basalt flows. The sequence contains a wide range of volcanic products that were affected by a variety of transportation mechanisms before final subaqueous deposition. Despite this modification, some conclusions about the nature of the primary volcanism can still be deduced from the nature of the products.

In previous sections, the provenance and depositional history were discussed for individual members and formations. This can now be integrated to produce a model of the volcanism.

Preceding the eruption of the intermediate to felsic fragmental sequence, widespread eruption of pillowed and massive basaltic flows produced a shield of unknown dimensions. In the study area the basaltic volcano was subaqueous (Fig. 23).

Most of the fragmental sequence appears to have been derived from Vulcanian and Plinian eruptions. These eruptions would have produced a stratovolcano either on the apex or flank of the mafic volcano, but the relative position is indeterminable. The important point is that this stratovolcano became emergent early in its history, with an associated major compositional change.

The study area represents a flank section taken either north or south of the vent. The initial intermediate to felsic volcanism that is represented in the Western Peninsula section is a series of felsic ash-flows that were deposited along the eastern margin of the area (Fig. 24) by felsic Plinian eruptions. Although the ash-flows were subaqueously deposited, it is impossible to ascertain whether they were erupted subaqueously or subaerially.

Figure 23
Mafic shield volcano prior to deposition of the fragmental sequence.

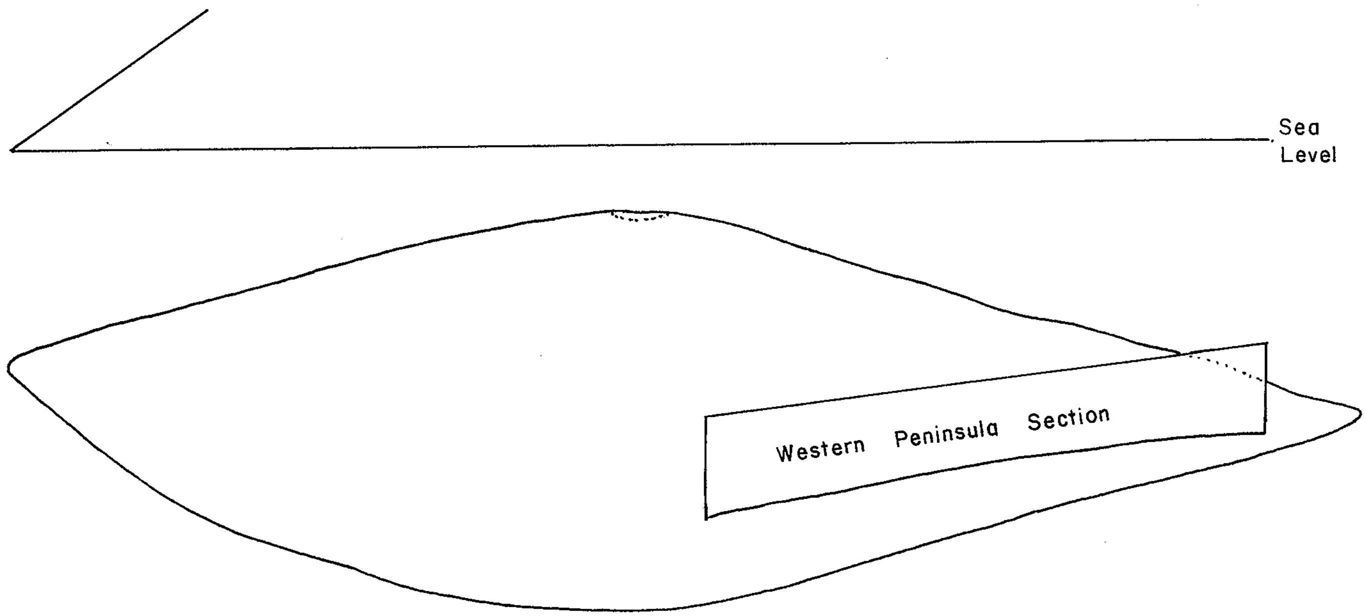
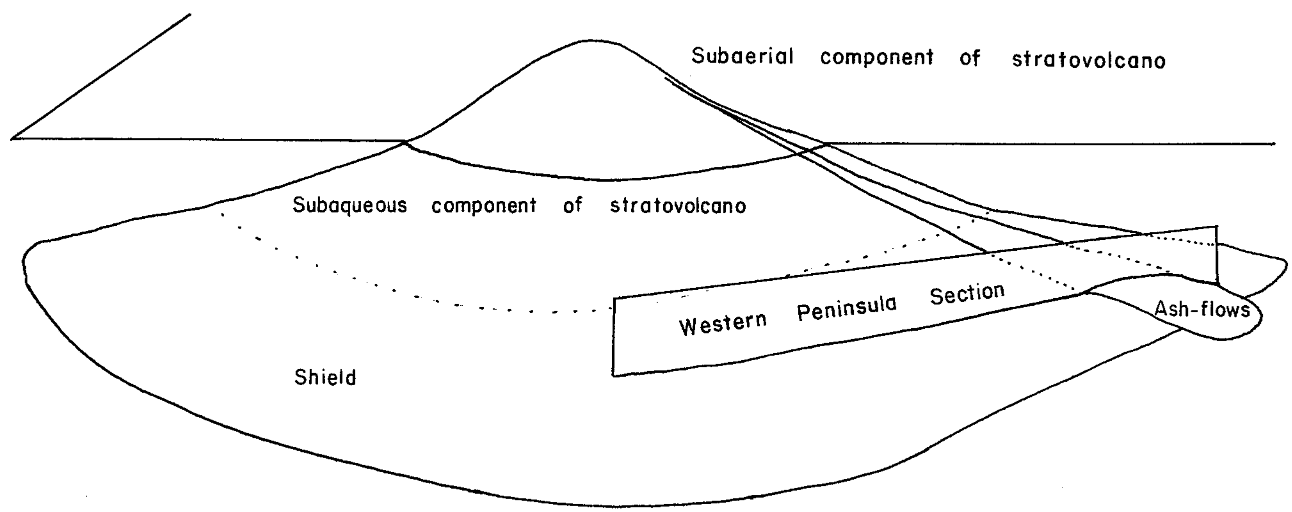


Figure 24
Reconstruction of volcano during deposition of Lower Ash-Flow Tuff Formation following formation of a stratovolcano atop the mafic shield volcano.



Subsequent to the ash-flows, a thick relatively unsorted Heterolithic Breccia Formation consisting of an eastern quartz-rich and a western quartz-poor member was deposited as a series of subaqueous debris flows. The lowermost part of the quartz-rich member was deposited first, but most of the two members were deposited contemporaneously. The quartz-rich member is lenticular in shape and may represent a submarine fan that was produced by north or south-moving debris flows. It appears to have had sufficient positive relief to prevent the laterally equivalent but slightly later Lower Conglomerate Formation from extending over it for any great distance.

The pronounced heterolithic nature of the breccia indicates that mixing of clast types occurred subaerially. In such an environment, clasts could be produced by Vulcanian and Plinian eruptions. The unstable nature of the source and high slopes would lead to production of debris flows. Most clasts would undergo minimal rounding within such flows. The more rounded nature of mafic clasts indicates that these underwent a greater degree of modification, possibly caused by streams prior to incorporation within the debris flows. Prevailing westerly winds were responsible for concentrating Plinian-derived quartz crystals on the east side of the volcano.

Prior to deposition of the quartz-poor breccia member, the Lower Conglomerate Formation was deposited west of and partially onto the quartz-rich member. The lenticular shape of the conglomerate implies a north-south transportation direction. The formation consists of debris flows and was probably derived from a dome or domes located on the flank of the volcano at or near sea level, where wave action could produce the well rounded large clasts. The monolithic nature of the conglomerate indicates a hiatus in heterolithic debris flow deposition, created when the domes rose to effectively block and dam-up any further debris flows (Fig. 25).

Domal activity would have been a short-lived event. The overall upward decrease in clast size within the conglomerate probably reflects erosional lowering and burial of the domes. This permitted resumption of debris flow deposition along the flanks of the volcano. The easterly thinning of the quartz-poor member indicates that as it built up, successive individual debris flows were able to extend for greater distances over the underlying quartz-rich breccia. The generally lower quartz and matrix content of the breccia member indicates that fewer Plinian eruptions were occurring.

During deposition of the breccia, the Western Mafic Formation and a minor lens of pillowed flows were deposited, probably at the same time, even though they occur at different relative levels in the quartz-poor breccia. This difference in stratigraphic position reflects the west to east transgression of the quartz-poor breccia. The small lens of pillowed flows may be connected to the Western Mafic Formation above or below the present plane of observation.

The lenticular shape of the Western Mafic Formation implies that it was a small shield volcano erupted on the flanks of the major volcano (Fig. 26). The presence of several breccia lenses within the shield indicates that debris flows being produced during eruptions of the shield were actively burying the lower parts of the shield. The shield probably acted as a diversionary barrier to many of the debris flows.

Figure 25
Reconstruction of the volcano during deposition of the Lower Conglomerate Formation on the flank of the earlier quartz-rich heterolithic breccia fan.

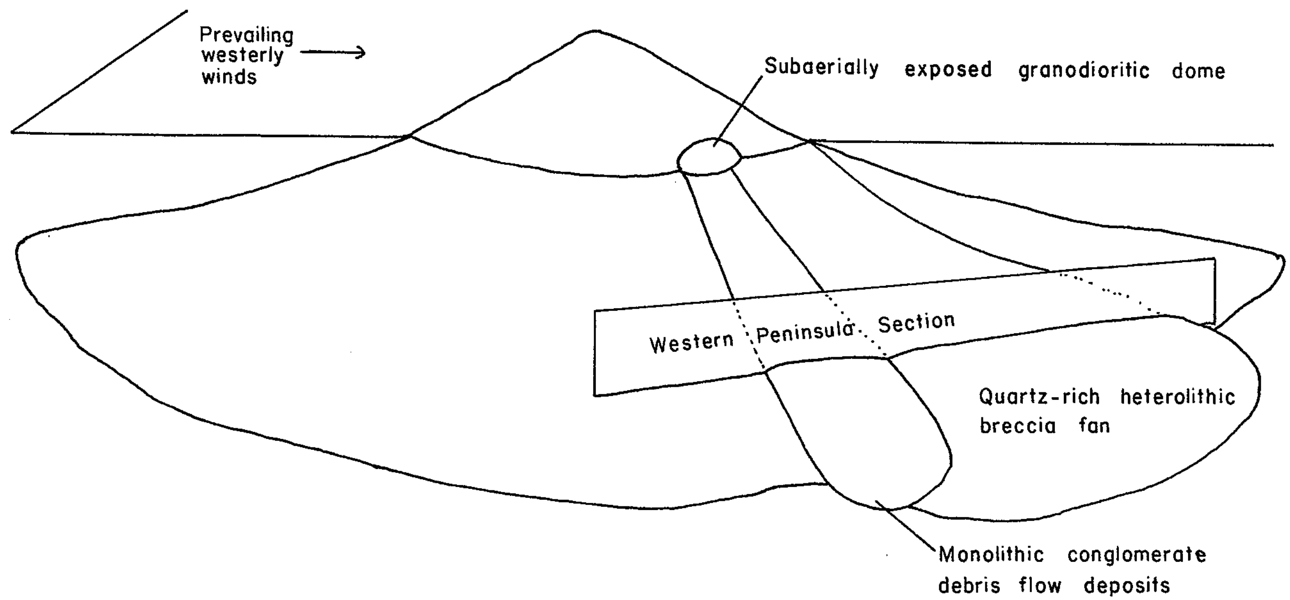
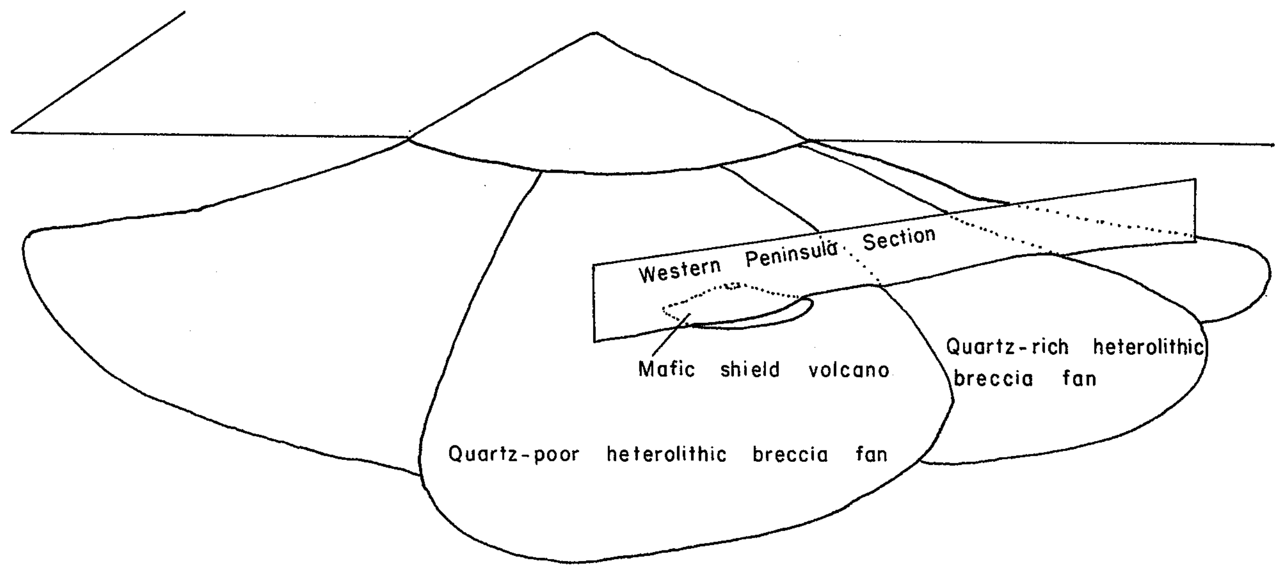


Figure 26
Reconstruction of the volcano during deposition of the Western Mafic Formation (Flank Shield Volcano) within the Heterolithic Breccia Formation.



Deposition of heterolithic debris flows appears to have waned due to the blocking effect of the reactivated domes. The new domes produced the lenticular Middle Conglomerate Formation. This formation is identical in composition and origin to the Lower Conglomerate Formation, but the dome or domes were much larger.

Two heterolithic quartz-poor breccia members occur in the eastern zone of the conglomerate and show that intermittent heterolithic debris flows continued during deposition of the conglomerate. Assuming continued derivation from the north or south, the easterly restriction of the two breccia members implies that breccia derived from the western half of the volcano was blocked by the dome(s) (Fig. 27). The presence of felsic to mafic volcanic clasts within the eastern part of the conglomerate indicates that some mixing of clast types occurred on the eastern half of the volcano. Easterly debris flows would not necessarily be dammed up by the domes. They could then be incorporated with debris flows produced by the domal erosion.

A thick laterally extensive volcanogenic Greywacke Formation overlies the conglomerate and breccia. It thickens westward. The overall absence of proximal characteristics such as thick beds and complete Bouma sequences indicate the distal nature of the formation. The greywacke probably represents the distal part of an extensive subaqueous fan that was derived from a distant tuffaceous source in the west (Fig. 28). The relatively small volume of locally derived and interbedded heterolithic breccia indicates that by this time, the main volcano had been removed from the subaerial environment by a combination of erosion and active downsinking; the latter mechanism was probably dominant.

Figure 27
Reconstruction of the volcano during deposition of the Middle Conglomerate Formation and its contained heterolithic breccia member.

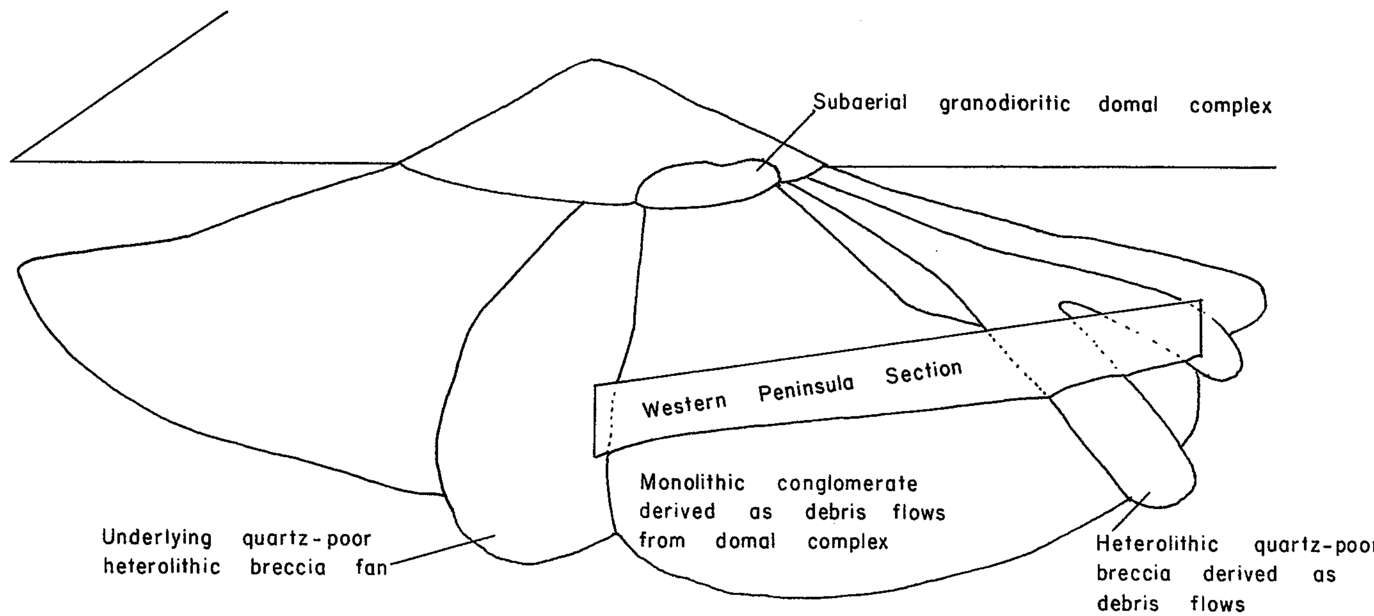
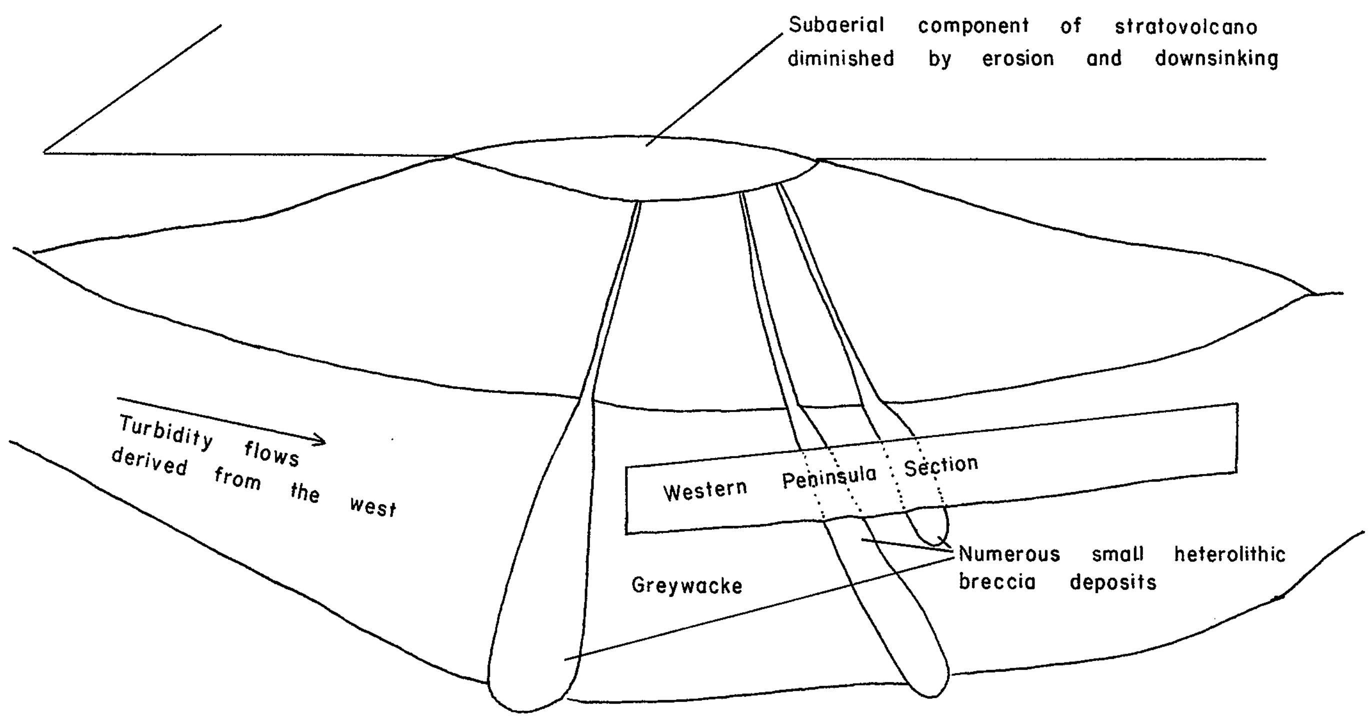


Figure 28
Reconstruction of the volcano during deposition of the Greywacke Formation.



Minor chert-magnetite iron formation occurs in the eastern part of the greywacke and indicates that volcanogenic chemical precipitates were an integral part of the volcanism.

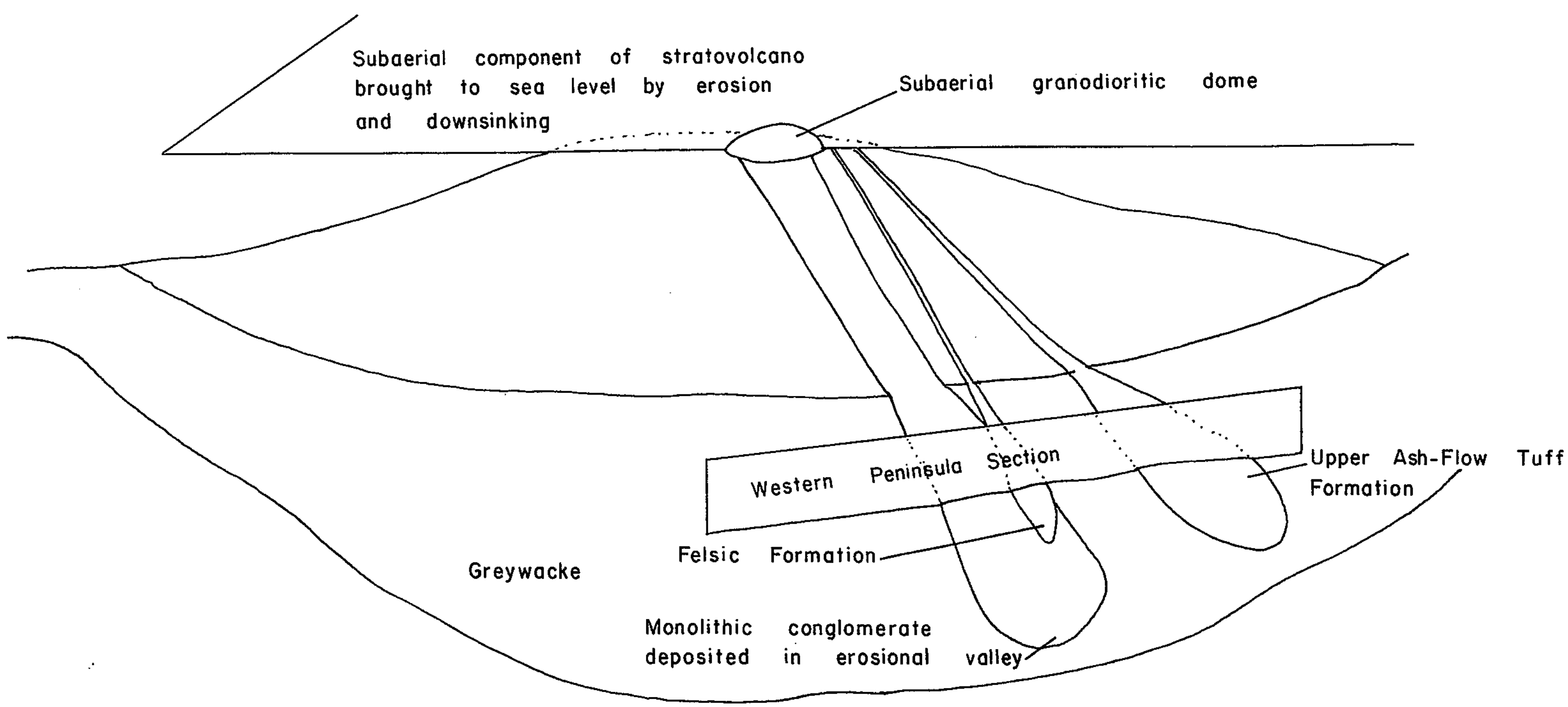
A third and final dome or series of domes was erupted after the cessation of greywacke deposition and produced a third monolithic conglomerate formation. It forms a laterally restricted thick lens which occupies an erosional submarine canyon in the greywacke. The axis of the valley was approximately north-south and the conglomerate was deposited by subaqueous debris flows travelling along the valley (Fig. 29).

With cessation of conglomerate production, a new episode of mafic volcanism occurred. The dominantly pillowed flows show that deposition was still subaqueous. Interbedded with this Upper Mafic Formation are the Felsic and Upper Ash-Flow Tuff Formations (Fig. 29). This intercalation of formations plus the markedly different chemical compositions of the formations implies that two separate magma chambers were involved.

The Upper Felsic Ash-Flow Tuff Formation consists of innumerable quartz-rich ash-flows which were apparently deposited in a submarine valley. Although depositon was subaqueous, the vent's environment is not determinable. The main vent was the most likely source of the ash-flows.

The Felsic Formation consists of three members that were deposited at different times during eruption of the Upper Mafic Formation. The first member, consisting of rhyodacitic tuff, lapilli-tuff and breccia, and autobrecciated flows was deposited at about the same time as the Felsic Ash-Flow Tuff Formation. It has a restricted lateral extent and overlies both the Upper Conglomerate and part of the Upper Mafic Formation. A relatively short transport distance (possibly less than

Figure 29
Reconstruction of the volcano during deposition of the Upper Conglomerate, Felsic, and Upper Ash-Flow Tuff Formations



5 km) is indicated for the members because of the occurrence of auto-brecciated felsic flows and relatively unreworked pyroclastic deposits. The material was probably derived from the same vent which produced the ash-flows because the lenticular nature of the western member indicates that the vent was located to the north or south.

Two later pulses of felsic activity produced the eastern members which consist of essentially the same rock types found in the western member.

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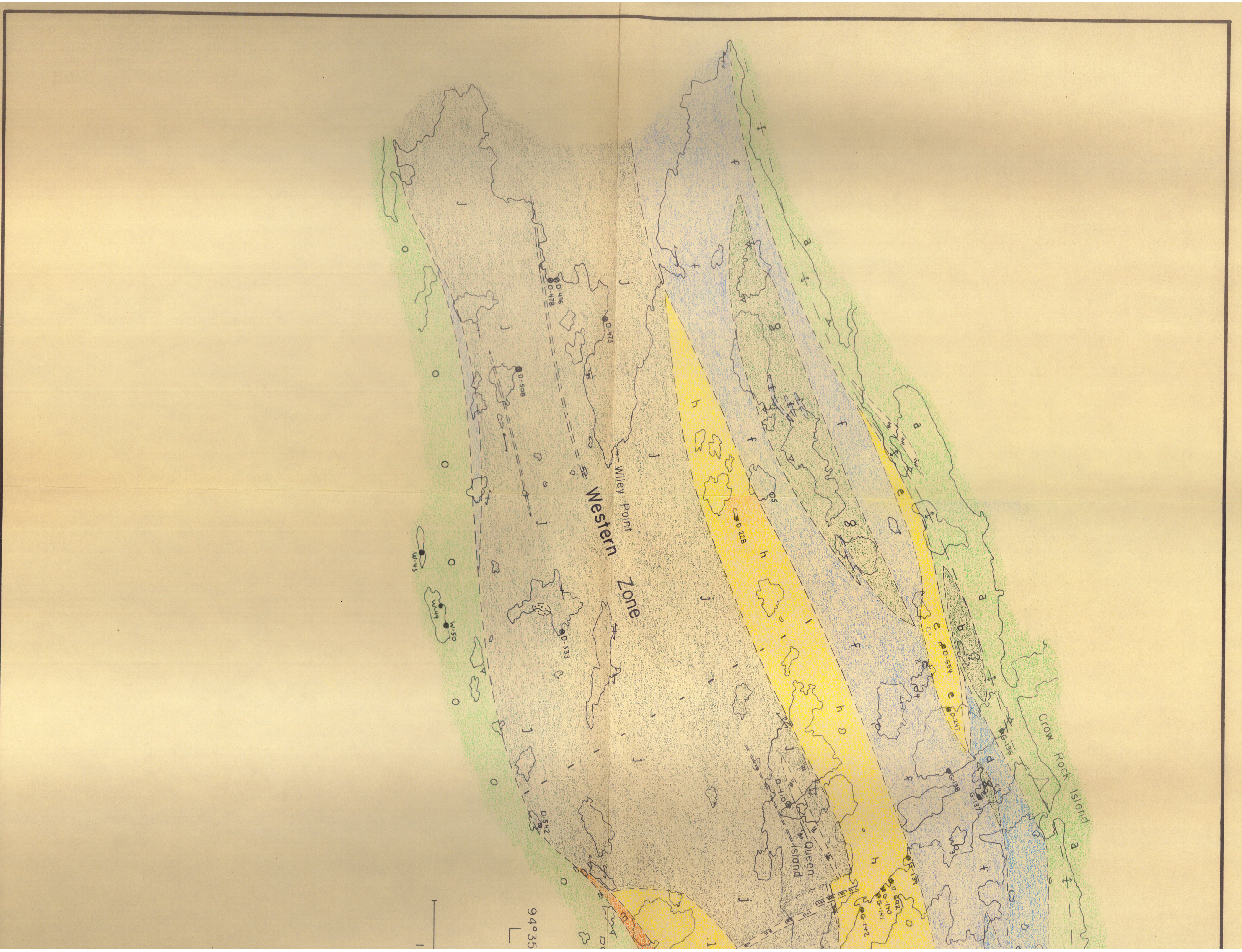
Western Zone
Wiley Point
Crow Rock Island
Queen Island
D-228
94°35

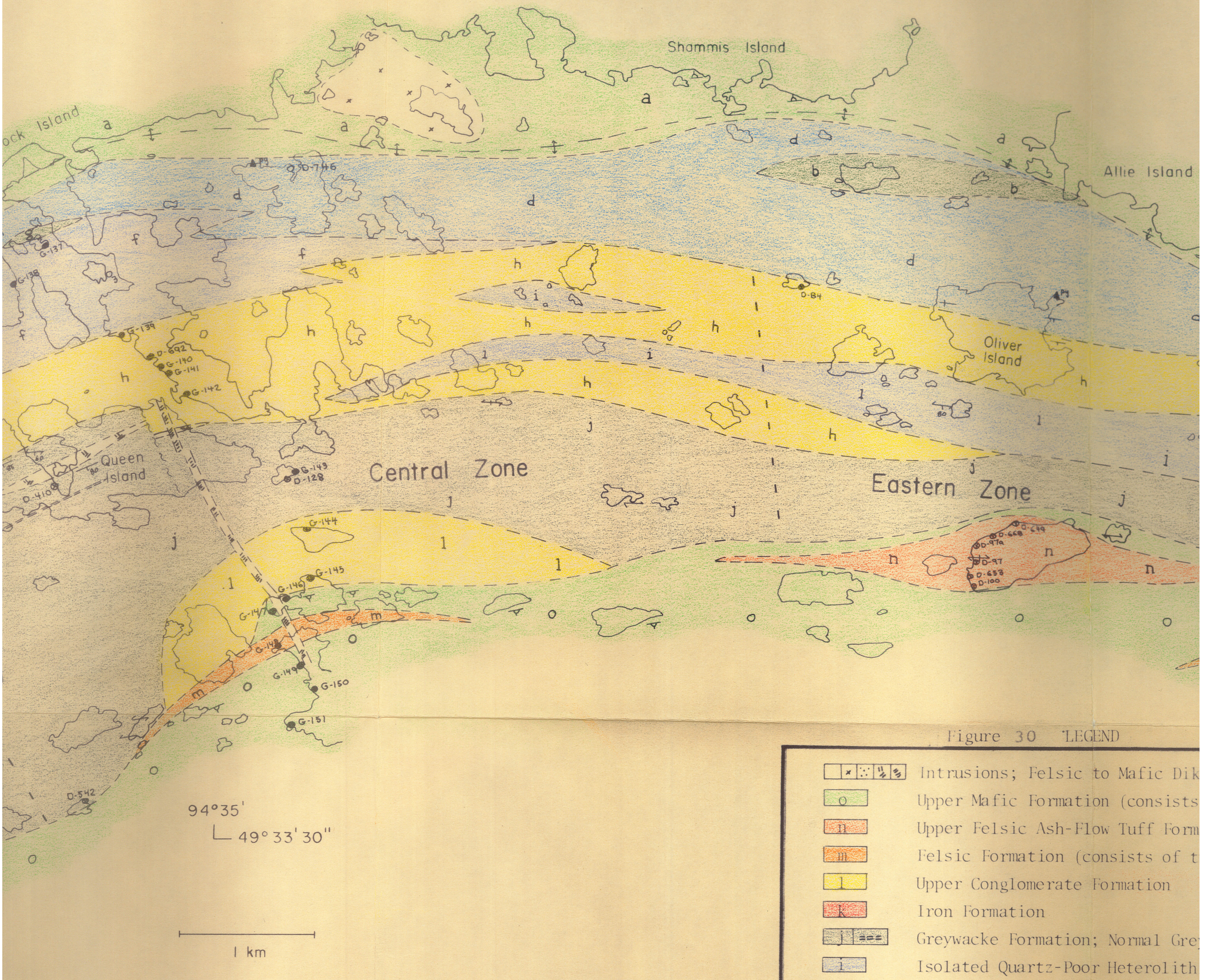

Figure 30 LEGEND

- o — Upper Mafic Formation (consists
- n — Upper Felsic Ash-Flow Tuff Form
- m — Felsic Formation (consists of t
- l — Upper Conglomerate Formation
- k — Iron Formation
- j — Greywacke Formation; Normal Grey
- i — Isolated Quartz-Poor Heterolith
- h — Middle Conglomerate Formation
- g — Western Mafic Formation
- f — Heterolithic Breccia; Quartz-Poo
- e — Lower Conglomerate Formation
- d — Heterolithic Breccia Formation;
- c — Lower Felsic Ash-Flow Tuff Forma
- b — Sill-Like Mafic Intrusions
- a — Lower Mafic Formation (consists

Intrusions; Felsic to Mafic Dik

Facing Indicators; Pillows-tops
Graded Beds-dip angle unknown

Foliations; Inclined, Vertical,

Anticlinal Axis; Defined, Assume

Contacts; Defined, Assumed

Fault; Assumed

Sulphide Occurrence

746 Location and Number of Chemical

228 Location and Number of Thin Sect

2 Location and Number of Outcrop

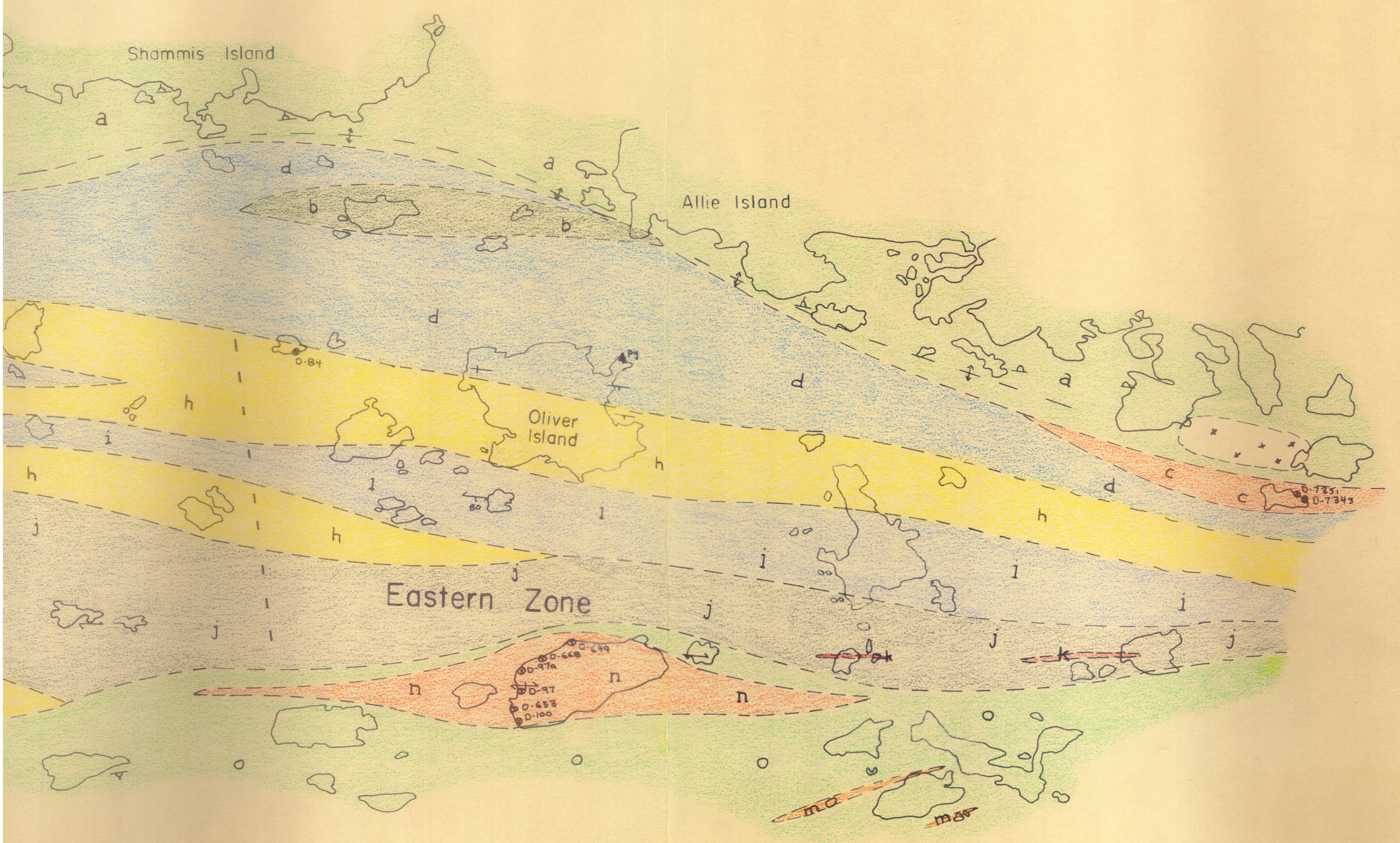

Figure 30 LEGEND

	Intrusions; Felsic to Mafic Dikes, Syenite, Granodiorite, Diorite, Diabase
o	Upper Mafic Formation (consists of pillowed flows and tuff)
n	Upper Felsic Ash-Flow Tuff Formation
m	Felsic Formation (consists of tuff, lapilli-tuff, breccia, and autoclastic flows)
l	Upper Conglomerate Formation
k	Iron Formation
j	Greywacke Formation; Normal Greywacke, Interbedded Breccia and Conglomerate
i	Isolated Quartz-Poor Heterolithic Breccia Lenses
h	Middle Conglomerate Formation
g	Western Mafic Formation
f	Heterolithic Breccia; Quartz-Poor Member
e	Lower Conglomerate Formation
d	Heterolithic Breccia Formation; Quartz-Rich Member
c	Lower Felsic Ash-Flow Tuff Formation
b	Sill-Like Mafic Intrusions
a	Lower Mafic Formation (consists of pillowed and massive flows)
60	Facing Indicators; Pillows-tops known, Graded Beds-dip angle known, Graded Beds-dip angle unknown
60	Foliations; Inclined, Vertical, Unknown Dip Angle
	Anticlinal Axis; Defined, Assumed
	Contacts; Defined, Assumed
	Fault; Assumed
▲ po, py	Sulphide Occurrence
● 746	Location and Number of Chemically Analysed Sample
⊗ 228	Location and Number of Thin Section Modal Analysis
○ 2	Location and Number of Outcrop Modal Analysis