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EARLY PROTEROZOIC LABINE GROUP OF WOPMAY OROGEN: REMNANT OF A CONTINENTAL VOLCANIC ARC DEVELOPED DURING OBLIQUE CONVERGENCE

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Abstract

The 1.87 Ga LaBine Group outcrops along the western margin of Wopmay orogen at Great Bear Lake and rests on a deformed and metamorphosed 1.92 Ga sialic basement complex. It is overlain by rocks of the mainly rhyodacitic Sloan Group. Syn- to post-volcanic plutons of the Great Bear batholith intrude both groups.

From Echo Bay northward to Hornby Bay the oldest rocks of the LaBine Group are mainly andesitic lavas, breccias, and pyroclastic rocks at least 3000 m thick, interpreted to be the remains of a number of large stratovolcanoes. Overlying, and in part interfingering with the stratovolcanoes, are seven major ash-flow tuff sheets, which are locally intercalated with andesite, dacite, rhyolite flows and domes, and a diverse assemblage of fluvial and lacustrine sedimentary rocks.

Sheets of ash-flow tuff include units thicker than 800 m deposited within cauldrons and thin cooling units deposited outside the cauldrons. Intercalated with intracauldron tuff are wedges of breccia and megabreccia, presumably derived from the walls of the cauldrons during subsidence.

Facies relations and the overall evolution of the field from early gas-poor andesitic eruptions to gas-rich eruptions of ash-flow tuff are closely comparable to Oligocene volcanic fields of the United States believed related to subduction. Rocks of the LaBine field were hydrothermally altered by high-level geothermal processes but on the basis of SiO_2, TiO_2, REE, and phenocryst mineralogy they can be classified as calc-alkaline. Therefore, it is concluded that the LaBine Group represents an early Proterozoic volcanic arc developed upon continental crust. Preserved stratovolcanoes and other high-level volcanic strata indicate that the LaBine Group was erupted into a basin which was subsiding concomitant with eruptions. The basin was probably generated in a wrench zone related to oblique convergence.

Laccoliths in Athapuscow Aulacogen together with recent geochronological and field data suggest that the LaBine Group postdates continent-microcontinent collision in Wopmay Orogen and was probably generated above an eastward-dipping Benioff zone which was either segmented or became shallower with time.

Résumé

Le groupe de Labine, qui date de 1.87 Ga, affleure le long de la marge ouest de l'orogène de Wopmay, dans la région du Grand lac de l'Ours, et repose sur un complexe rocheux de caractère sialique, déformé et métamorphisé, âgé de 1.92 Ga. Il est recouvert par les roches principalement rhyodacitiques du groupe de Sloan. Des plutons synvolcaniques à postvolcaniques du batholite du Grand lac de l'Ours traversent les deux groupes.

De la baie d'Echo au nord à la baie Hornby, les plus anciennes roches du groupe de Labine sont principalement des laves andésitiques, des brèches et des roches pyroclastiques d'au moins 3 000 m d'épaisseur, qui d'après certaines interprétations, seraient les restes de quelques grands stratovolcans. Sept vastes nappes de tufs répandues sous forme de coulées de cendres, qui recouvrent les stratovolcans et parfois présentent des interdigitations avec ceux-ci, sont localement intercalées dans des andésites, dacites, coulées et dômes rhyolitiques, et divers assemblages de roches sédimentaires d'origine fluviatile et lacustre.

Les nappes de tufs répandues sous forme de coulées de cendres contiennent des unités de puissance supérieure à 800 m, déposées à l'intérieur des caldeiras, et de minces coulées de lave, déposées à l'extérieur de celles-ci. Des formations en biseau, formées de brèches et mégabrèches, probablement dérivées des parois des caldeiras pendant la subsidence de celles-ci, sont intercalées avec les tufs de l'intérieur des caldeiras.

Les relations de faciès et l'évolution globale du terrain, d'abord soumis à des éruptions andésitiques pauvres en émanations gazeuses, puis aux éruptions gazeuses de tufs répandus en coulées de cendres rappellent fortement les secteurs volcaniques oligocènes des Etats-Unis, que l'on estime associés aux phénomènes de subduction. Les roches du secteur de Labine ont été altérées par des réactions hydrothermales intenses, mais en raison de leur teneur en SiO_2, en TiO_2 et REE et de la minéralogie des phénocristaux, on peut les classer dans les roches calcoalcalines. On en conclut donc que le groupe de Labine correspond à un arc volcanique d'âge protérozoïque inférieur, formé *au-dessus de la croûte continentale. Les stratovolcans et autres niveaux volcaniques créés par une activité volcanique intense, et encore conservés, indiquent que le groupe de Labine s'est écoulé lors d'éruptions dans un bassin, dont l'affaissement a accompagné les éruptions. Le bassin s'est probablement formé dans une zone de déchirement résultant d'une convergence oblique.*

Dans l'aulacogène d'Athapuscow, l'existence de laccolites et les récentes données géochronologiques et données obtenues sur le terrain semblent indiquer que le groupe de Labine est ultérieur à la collision entre continent et microcontinent qui a eu lieu lors de l'orogène de Wopmay, et a probablement été formé au-dessus d'une zone de Benioff plongeant vers l'est, qui s'est fragmentée ou est devenue moins profonde au cours des temps.

INTRODUCTION

In recent years the concept of plate tectonics has provided an actualistic framework to interpret the geology of continents, which contain the vast majority of recorded earth history. Geologists now examine pre-Mesozoic terranes with an eye toward determining an evolutionary scheme for the development of the earth based on similarities with, and dissimilarities to, post-Mesozoic terranes.

Studies of post-Mesozoic volcanic and plutonic rocks suggest it is possible to relate magmatic belts to specific tectonic settings. In fact, studies in Cenozoic volcano-plutonic terranes indicate that most can be related to lithospheric plate motions. Thus, igneous rocks may provide valuable insight into tectonic processes in older, cratonic regions where there is no sea floor record.

The purpose of this paper is to present stratigraphic and geochemical data from the LaBine Group, a 1.87 Ga volcanic field located along the eastern shore of Great Bear Lake, and to discuss the tectonic setting and regional implications.

PREVIOUS WORK

Bell (1901) first investigated the geology in the region of Great Bear Lake as part of a lengthy canoe reconnaissance for the Geological Survey of Canada in 1899. He noted "cobalt bloom and copper stain" along the east shore of the lake but was unable to investigate his discovery as he was under great pressure to reach civilization before freezeup.

The area received only minor attention from prospectors and trappers until 1930 when Gilbert LaBine, then president of Eldorado Mining Company, discovered high grade silver-pitchblende veins at the present townsite of Port Radium. The veins were mined for radium and silver until 1940 when the mine was shut down due to World War II and the resulting disruption of the radium market.

Kidd (1932) examined the mineral deposit for the Geological Survey of Canada in 1931. Kidd subsequently mapped much of the region at a scale of 1:250 000 (1933) and also made a broad reconnaissance of a 20 mile wide strip from Great Bear Lake to Great Slave Lake (1936). Smaller areas near Port Radium were mapped by Robinson (1933), Riley (1935), and Furnival (1939).

In 1941 Eldorado gave Enrico Fermi and associates at Columbia University 5 tons of uranium oxide for their experiments to generate a chain reaction and the mine was reopened to supply the strategic metal uranium to the United States Government. In 1944 the Canadian Government obtained ownership of the property and a program of 1 inch to 400 foot mapping in the vicinity of Port Radium was initiated by the Geological Survey of Canada (Joliffe and Bateman, 1944; Thurber, 1946; Feniak, 1947; Fortier, 1948). Later, Feniak (1952) mapped the MacAlpine Channel area at a scale of 1:50 000 while Lord and Parsons (1947) mapped the Camsell River region.

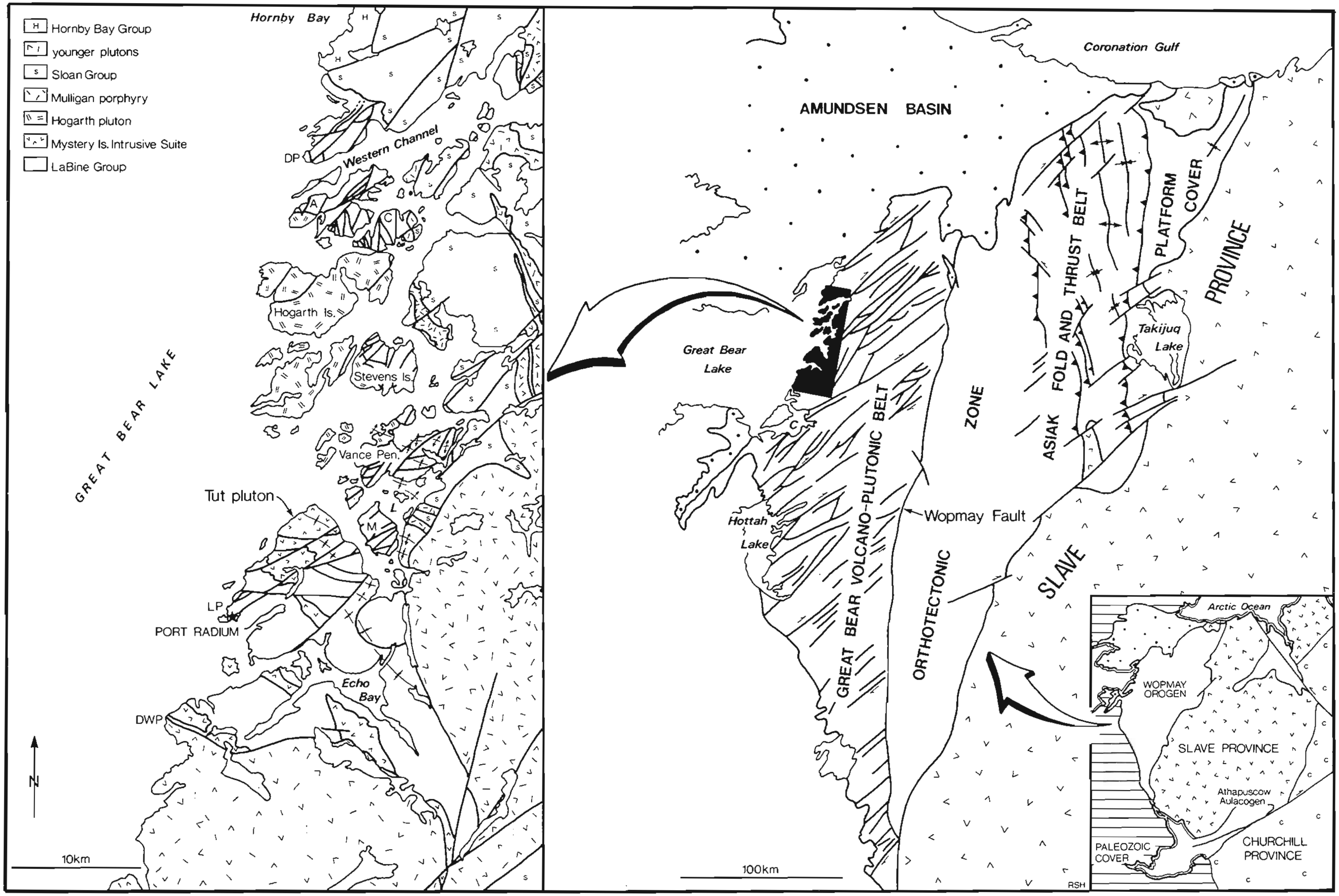
During the next 25 years geological work was mainly confined to detailed studies of the mineral deposits at LaBine Point (Campbell, 1955, 1957; Jory, 1964; Robinson, 1971; Robinson and Morton, 1972; Robinson and Badham, 1974) and in the Conjuror Bay-Camsell River region (Badham, 1972, 1973a, b, 1975; Badham et al., 1972; Shegelski, 1973; Badham and Morton, 1976). Mursky (1973) compiled much of the previously restricted data collected by the Geological Survey of Canada during the war.

Hoffman (1978) made the first comprehensive reconnaissance maps of the area during the middle 1970s and established the regional stratigraphy (Hoffman and McGlynn, 1977). Hoffman (1972) and Badham (1973a) first alluded to a subduction origin for the Great Bear Volcano-Plutonic Belt by pointing out the similarities of the Great Bear batholith with batholiths of the Andes.

REGIONAL SETTING

The LaBine volcanic field lies along the western margin of the Bear Structural Province in the northwestern Canadian Shield (Fig. 8.1). It is part of the Great Bear Volcano-Plutonic Belt (Fig. 8.1) which forms the western part of the early Proterozoic Wopmay Orogen (Fraser et al., 1972; Hoffman, 1973; Hoffman and McGlynn, 1977). The orogen developed along the western side of an Archean craton (Slave Province) between about 2.1 and 1.8 Ga. Hoffman (1980a) divided Wopmay Orogen into 4 tectonic zones: 1) a thin autochthonous cratonic cover and foreland basin sequence that unconformably overlies Archean basement; 2) a fold and thrust belt where rocks of the continental shelf and foredeep are thrust eastward relative to the craton; 3) an orthotectonic zone in which deformed initial rift clastic and volcanic rocks, passive continental slope-rise and foredeep rocks are metamorphosed and intruded by a multitude of syn- to post-tectonic, mesozonal S-type plutons; and 4) the little-deformed Great Bear Volcano-Plutonic Belt, consisting of subgreenschist facies volcanic and sedimentary rocks (McTavish Supergroup) which unconformably overlie a deformed and metamorphosed basement complex, and are intruded by tabular to sheetlike, epizonal I-type plutons of granitoid composition (Great Bear batholith).

High level plutonic rocks of the Great Bear batholith and the deformed basement rocks dominate the southern half of the Great Bear Volcano-Plutonic Belt while their consanguinous volcanic and sedimentary roof (McTavish Supergroup) is widely exposed in the northern half. The McTavish Supergroup is folded about gently-plunging, northwest-trending axes. These folds are asymmetric with the northeasterly dipping limbs generally being much larger (Hoffman, et al., 1976). Thus, the supracrustal rocks become progressively younger to the northeast, with the oldest rocks of the belt exposed only in the southwest. These relations suggest that the Great Bear Volcano-Plutonic Belt has a slight northeastward plunge.



C	=	Conjuror Bay-Camsell River area	DP	=	Doghead Point
DWP	=	Dowdell Point	L	=	Lindsley Bay
LP	=	LaBine Point	A	=	Achook Island
M	=	Mackenzie Island	C	=	Cornwall Island

Figure 8.1. *Maps showing study area (blackened), tectonic subdivisions of Wopmay Orogen (after Hoffman, 1980a), and northwestern Canadian Shield.*

The McTavish Supergroup is divided into 3 groups separated by unconformities: the LaBine Group, Sloan Group and the Dumas Group, in ascending order. The Sloan Group, exposed in the central part of the belt, consists mostly of thick sequences of densely-welded dacite and rhyodacite ash-flow tuff (Hoffman and McGlynn, 1977), perhaps cauldron fill. The Dumas Group exposed on the east side of the belt, comprises mafic lavas and mudstones cut by siliceous sills (S. Bowring, personal communication). The LaBine Group is a diverse assemblage of tholeiitic (Wilson, 1979) and calc-alkaline lava flows and pyroclastic rocks, plus a variety of sedimentary and high-level porphyritic intrusive rocks. The LaBine Group outcrops in 3 areas, all in the western part of the volcano-plutonic belt: one around Conjuror Bay and Camsell River; another at Hottah Lake; and along the eastern shore of Great Bear Lake from Echo Bay northward to Hornby Bay (Fig. 8.1). This last area is the principal subject of this paper.

An ash-flow tuff, high in the LaBine Group stratigraphy at Conjuror Bay, is 1.87 ± .01 Ga (Van Schmus and Bowring, 1980; and personal communication). U-Pb ages of plutons at Port Radium, at least one of which is demonstrably synvolcanic, are indistinguishable at present from the ash-flow at Conjuror Bay (Van Schmus and Bowring, 1980; and personal communication).

There are many exposures near Hottah Lake and at Conjuror Bay where the LaBine Group can be seen to unconformably overlie metamorphic rocks, here informally termed the metamorphic suite of Holly Lake. The suite is cut by many foliated granitoid plutons, one of which has yielded zircons dated as 1.92 ± .01 Ga (Van Schmus and Bowring, 1980). Together the metamorphic suite and the plutons collectively form what is known as the Hottah Terrane. This terrane was intensely deformed prior to deposition of the LaBine Group and has a prominent north-northeast – south-southwest penetrative fabric.

The Great Bear Volcano-Plutonic Belt is generally separated from the orthotectonic zone by the Wopmay fault (Fig. 8.1), although volcanic and sedimentary rocks of the Dumas Group locally overstep the fault and onlap the high grade rocks of the orthotectonic zone unconformably (Hoffman et al., 1976; Hoffman and McGlynn, 1977).

The entire Great Bear Volcano-Plutonic Belt is cut by numerous, nearly vertical, northeast-trending strike-slip faults (McGlynn, 1977) that postdate magmatism in the belt and that bend, splay, and die out towards the Wopmay fault (Fig. 8.1). These faults are but one part of a regional conjugate set of transcurrent faults that occurs throughout Wopmay Orogen (Hoffman, 1980b). Separations of units across these faults are typically hundreds of metres to several kilometers. Many of the fault zones are filled with quartz stockworks up to several hundred metres across (Furnival, 1935).

The Great Bear Volcano-Plutonic Belt is unconformably overlain by middle Proterozoic rocks of Amundsen basin (Hornby Bay Group) to the north (Fig. 8.1) and by Paleozoic sedimentary rocks of the Northern Interior Platform to the west.

STRATIGRAPHY

Introduction

The LaBine Group formed as a composite volcanic field upon sialic crust. Complex facies relations, tremendous variations in topographic relief, and long, varied eruptive histories are characteristics of such fields. The LaBine volcanic field is no exception, but discussion of all rock types

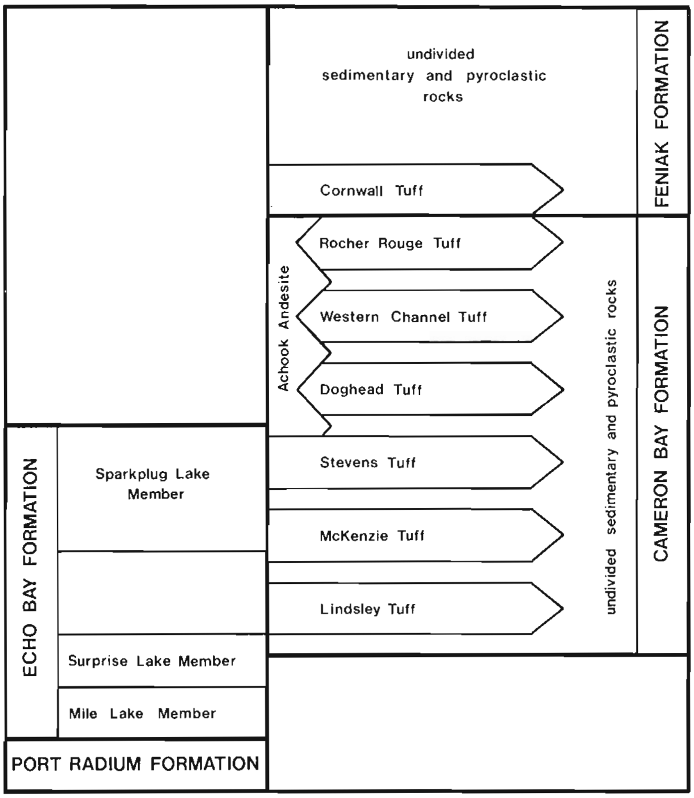


Figure 8.2. *Major stratigraphic subdivisions and nomenclature of the LaBine Group in the study area.*

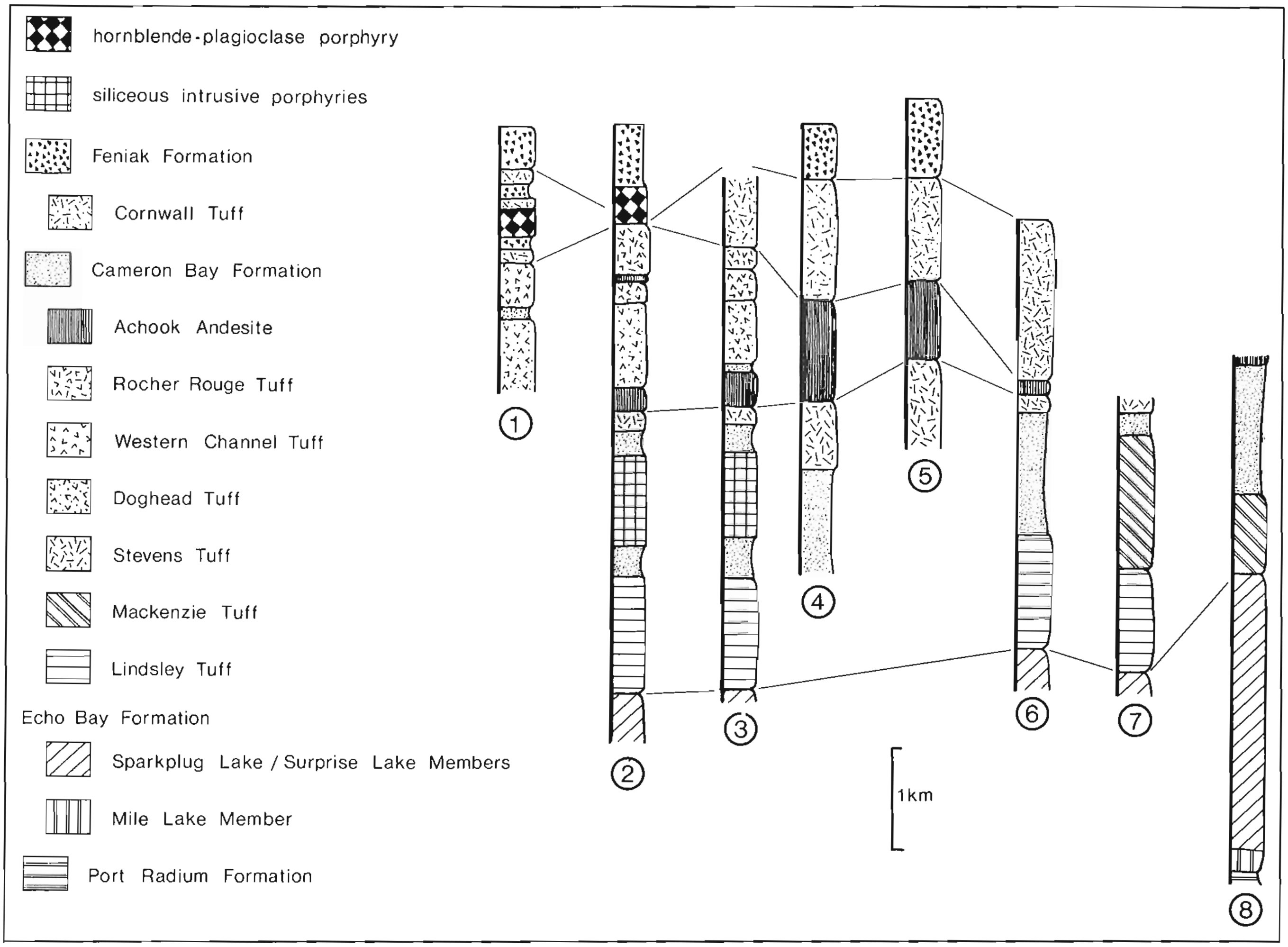
and their structural relations is beyond the scope of this paper. Consequently, only the major stratigraphic units from Echo Bay to Hornby Bay will be discussed here, in an attempt to characterize the general volcanic evolution of this region and provide a broad overview of the volcano-tectonic environment.

In a crude way, the stratigraphy of the map area can be subdivided into two main eruptive phases: an early phase characterized by relatively gas-poor eruptions of andesitic lava represented by the Port Radium and Echo Bay formations, and a younger, more gas-charged, phase typified by voluminous eruptions of ash-flow tuff. The younger, siliceous volcanics are divided into the Cameron Bay and Feniak formations. The stratigraphic nomenclature used in this paper is shown in Figures 8.2 and 8.3.

Port Radium Formation

The Port Radium Formation is the oldest unit in the succession and is exposed only near Dowdell Point and on LaBine Peninsula (Fig. 8.4). The base of the formation is everywhere truncated by younger plutonic rocks of the Great Bear Batholith. These intrusions plus intense folding, brecciation, hydrothermal alteration, and intrusion by at least two additional suites of high-level plutons, make thickness estimates unreliable. The contact with the overlying Echo Bay Formation is placed at the base of the lowest lava flow.

Where undisturbed and relatively unaltered, Port Radium Formation consists predominantly of laminated to thinly bedded siltstone, sandstone, ashstone, and minor conglomerate of andesitic provenance. Relict sedimentary



1 = western Doghead Point
2 = eastern Doghead Point
3 = western Achook Island
4 = central Achook Island
5 = Cornwall Island
6 = Stevens Island
7 = Mackenzie Island
8 = Dowdell Point-Echo Bay

Figure 8.3. *Generalized columnar sections*

structures, such as ripple laminations, graded and convoluted bedding, and low-angle cross stratification, are common. Mudcracks were reported from this unit by Campbell (1955) but none were seen during the present investigation. Rocks initially described by Jory (1964) as "microcrystalline albite tuffs" are sediments and ash that were hydrothermally albitized during emplacement of the Mystery Island Intrusive Suite.

Particularly in the lower parts of the formation, calcareous laminae are abundant and there are at least two 1 m thick carbonate beds near Mile Lake; a similar bed was observed underground in the current mine workings on LaBine Peninsula.

In general, the formation coarsens upwards with granules of aphanitic to porphyritic andesite becoming abundant in the upper 100 m. In some locations a polymictic conglomerate near the top of the formation fills channels cut into the finer grained sedimentary rocks.

Echo Bay Formation

The Echo Bay Formation consists of a thick pile of andesite flows and breccias, sparse rhyodacite flows and breccias, intercalated epiclastic rocks and minor beds of reworked tuff that conformably overlie the Port Radium Formation. It is best exposed in a section from Dowdell Point to Echo Bay, where it is nearly 3000 m thick (Fig. 8.3, 8.4).

The formation is divided into 3 informal members – Mile Lake, Surprise Lake, and Sparkplug Lake members. The stratigraphically lowest member (Mile Lake) comprises 400 m of intercalated epiclastic rocks and lava flows while the overlying Surprise Lake member contains only minor beds of epiclastic rocks between lava flows. Andesite flows and breccias with abundant plagioclase phenocrysts that overlie Mackenzie Tuff are collectively termed the Sparkplug Lake member. This member includes a small, composite andesite cone and vent complex approximately 1 km in diameter located south of Lindsley Bay but stratigraphically higher in the section than most rocks of the Sparkplug Lake member.

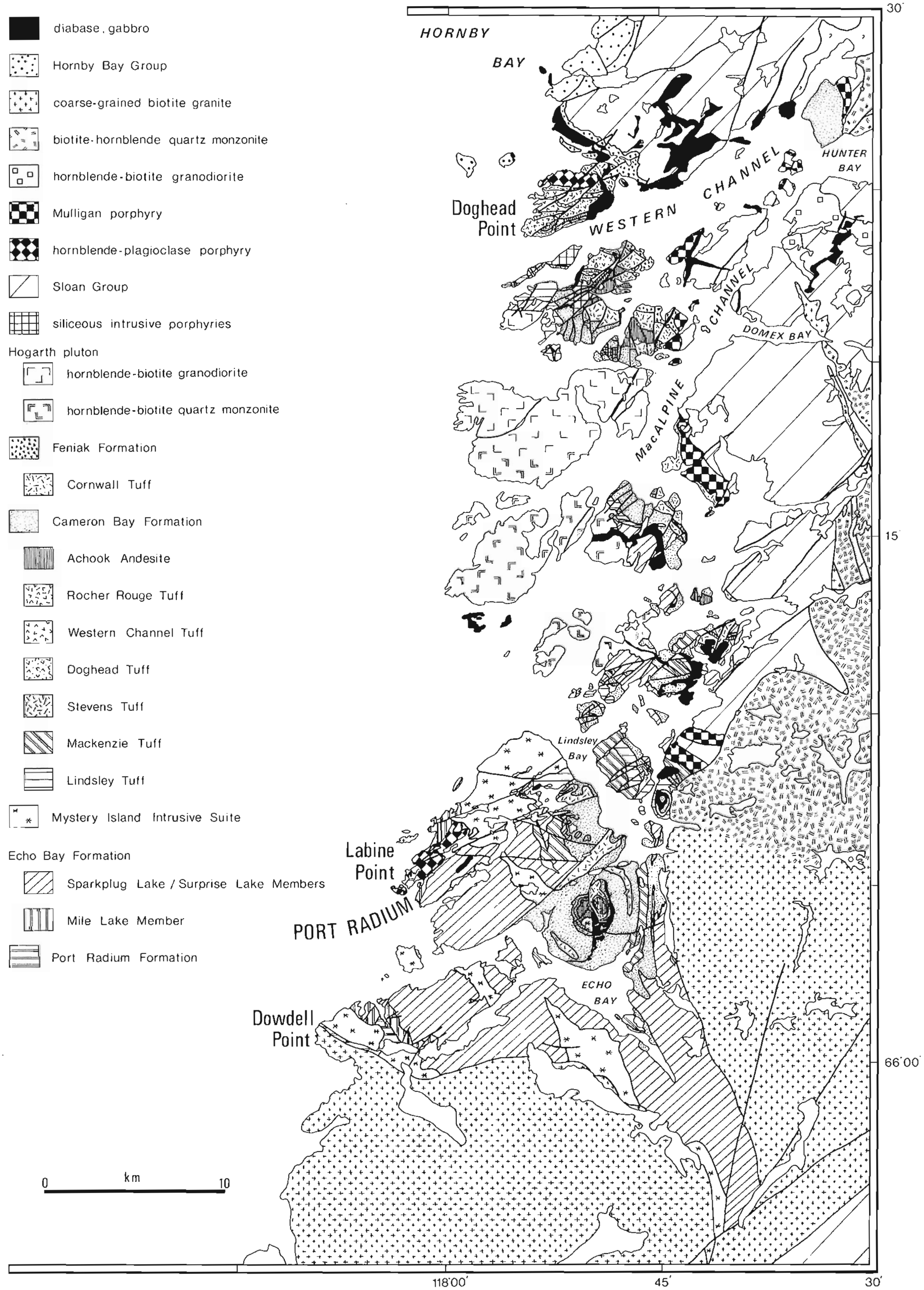


Figure 8.4. *Generalized geological map of the study area*

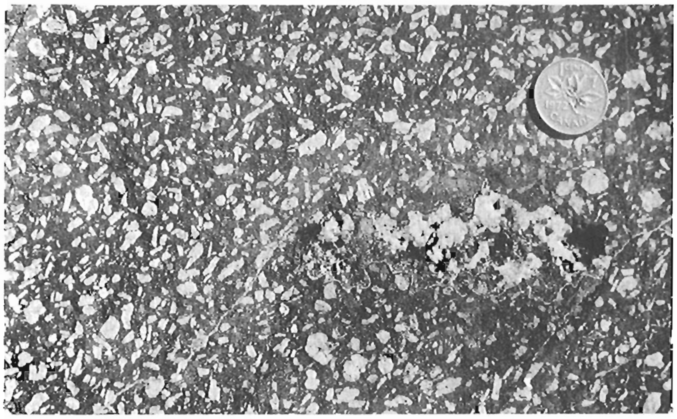


Figure 8.5. *Andesite of the Echo Bay Formation*

In general, lavas of the Sparkplug Lake member are distinguished from those of the Surprise Lake member only by their stratigraphic position.

The lava flows of the Echo Bay Formation are plagioclase porphyritic and the abundance of phenocrysts may range within individual flows from 5 to 40 per cent. Many of the flows show trachytic texture defined by platy plagioclase crystals up to 1 cm across (Fig. 8.5). Before alteration, most flows contained small pyroxene or hornblende phenocrysts, commonly rimmed with opaque Fe-oxides. Relict olivine euhedra occur in some of the lower flows.

All Echo Bay Formation lavas are altered to some degree: ferromagnesian minerals are often replaced by chlorite, opaque Fe-Ti oxides, epidote, and clay minerals. The matrix is commonly a fine grained mosaic of sphene, albite, quartz, chlorites, zeolites, and clay minerals.

Amygdules, commonly sparse but locally up to 20 per cent of the rock, are predominantly silica but in some flows located within alteration haloes around granitoid intrusions, contain mixtures of quartz, epidote, chlorites, pyrite and calcite.

In outcrop, flows are generally massive or columnar jointed but some have platy-jointed or brecciated bases. Brecciated bases grade upward into massive lava, and are often partially oxidized to a brick-red colour. Many individual flows have reddened flow breccias at their tops and margins.

Eruption centres for the lavas are not exposed and lay outside the map area. Flows that intertongue with sediments of the Cameron Bay Formation become thinner and sparser eastward, suggesting that one centre lay west of the map area. Similarly, flows that pinch out to the south and west, and interfinger with conglomerate in the Vance Peninsula region, were presumably erupted from centres to the east or north of the map area.

Epiclastic rocks of the Mile Lake member consist almost entirely of volcanic detritus and are coarse arkosic to lithic sandstone and clast-supported conglomerate, occasionally polymictic but normally dominated by clasts of subrounded to rounded andesite. Some massive conglomerate beds, up to several metres thick, are probably laharic as they contain blocks of a wide variety of size, shape, and rock type floating in a muddy or silty matrix. Many of the sandstones display normal grading and comprise imbricated blocky plagioclase crystals with rounded corners and semispherical augite grains. These beds are probably reworked crystal tuff. Ripple lamination and crossbedding are commonly preserved in the sandstones but exposures are insufficient for paleocurrent analysis.

Cameron Bay Formation

The Cameron Bay Formation is a varied assemblage of volcanic and sedimentary rocks that overlies the Echo Bay Formation, except in the southern part of the area, where both formations interfinger. As used in this paper, the Cameron Bay Formation comprises clastic rocks, rhyolite flows, 6 major units of ash-flow tuff, and several andesite complexes. Major ash-flow tuff units are assigned informal member status within the Cameron Bay Formation. Ash-flow terminology is that of Smith (1960). For convenience, epiclastic rocks stratigraphically near ash-flow tuff members are discussed with those members.

From Vance Peninsula south to Echo Bay massive to poorly-bedded andesite bouldery conglomerates and breccias interfinger with the Echo Bay Formation. These clastics are interpreted as fluvial and debris-flow deposits that formed parts of the volcaniclastic aprons on the vent flanks from which Echo Bay lavas were erupted. An unnamed, flow-banded and flow-folded rhyolite (Fig. 8.6) extrusive with abundant silica-lined cavities to 8 cm occurs on top of gritty sandstone on Mackenzie Island. The eruption centre for this flow is unknown.

Lindsley Tuff Member

The Lindsley Tuff is discontinuously exposed over much of the belt. It is absent in the southwest, overlies Echo Bay Formation in the Lindsley Bay region, and directly overlies both Echo Bay andesite or conglomerate, breccia and rhyolite of the Cameron Bay Formation on Vance Peninsula, Stevens Island, and Achook Island. The Lindsley is a maximum of 1000 m thick and is a single, compositionally zone cooling unit composed of many flow units. Intensely fractured and broken quartz phenocrysts (up to 20%) dominate the lower ash-flows. Altered plagioclase and mafic phenocrysts become progressively more abundant upward in overlying ash-flows. Lithic fragments constitute at most only a few per cent of the unit and are dominantly andesite.

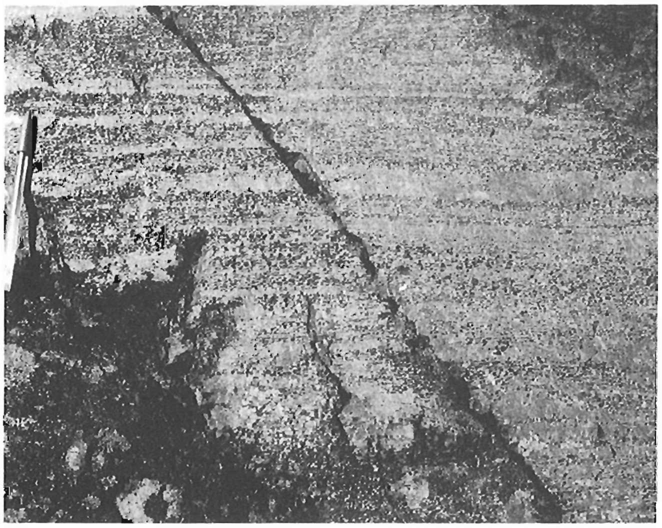


Figure 8.6. *Flow-banded rhyolite flow of the Cameron Bay Formation.*

The tuff is densely welded throughout and pumice is generally not recognizable, probably due to postdepositional recrystallization and alteration. However, on Achook Island, there is a zone with well-developed eutaxitic structure about 35 m above the contact with the underlying Echo Bay Formation.

On eastern Vance Peninsula and northeast of Echo Bay the tuff is always less than 30 m thick and is often absent. Channels, now filled with sandstone and conglomerate, were incised in the tuff after deposition. On Mackenzie Island, 2 km away from Vance Peninsula in pre-transcurrent fault reconstructions, 500 m of Lindsley Tuff is overlain by Mackenzie Tuff with no evidence of erosion. One kilometre to the west of Mackenzie Island, the Lindsley Tuff is overlain by epiclastic rocks and a rhyolitic flow or dome at least 1 km in diameter. Elsewhere, as on Stevens Island and Achook Island, the tuff is overlain by coarse sedimentary rocks, but with no apparent extensive channelling.

Massive to poorly-bedded wedges of breccia containing blocks up to 3 m across are interbedded with the Lindsley Tuff in the Lindsley Bay region. These are interpreted as talus breccias and indicate considerable topographic relief during deposition. The inferred high relief may account for the rapid lateral thickness variations of the tuff.

The abrupt pinchout of thick sections of tuff, coupled with the presence of talus breccias suggests that the Lindsley Tuff ponded against a topographic barrier. As there is no indication of a topographic barrier in the underlying sedimentary rocks, it must have developed during eruption of the tuff.

One possible mechanism to explain these relations is cauldron collapse concurrent with the ash-flow eruptions. The thick sections could represent intracauldron deposition while the thin sections may be remnants of the outflow sheet. The talus breccias would have been shed from the high-standing wall of the cauldron. Lipman (1976) described similar breccias intercalated with intracauldron tuffs in several cauldrons in the San Juan volcanic field of southwestern Colorado. He attributed the breccias in these cauldrons to landslides that resulted from the caving of the steep cauldron margins.

Mackenzie Tuff Member

The Mackenzie Tuff is a composite ash-flow tuff sheet that contains abundant foreign rock fragments and less than 10 per cent phenocrysts of quartz, altered potassium feldspar, plagioclase and sparse ferromagnesian minerals. Eutaxitic texture is commonly well developed, especially on Mackenzie Island (Fig. 8.7). On Mackenzie Island the upper cooling unit contains abundant accretionary lapilli (Fig. 8.8).

The Mackenzie Tuff is exposed only in the southern half of the belt. It is at least 1 km thick on Mackenzie Island and consists of 3 cooling units, with no sediment interbeds. South of Mackenzie Island the cooling units are separated by lenses of ripple-laminated siltstone and mudstone or by flows of the Sparkplug Lake Member of the Echo Bay Formation. The cooling units fill broad paleovalleys and pinch out over local paleo high areas. On Vance Peninsula there are at least 6 cooling units, each less than 20 m thick, interbedded with arkosic sandstone and pebbly gritstone.

From Vance Peninsula north to Doghead Peninsula the Mackenzie Tuff is absent and its stratigraphic position is occupied by a thick pile (1 km) of sedimentary rocks. This sequence is interpreted as a series of braided stream, alluvial fan and lacustrine complexes. Hematitic, polymictic and polymodal conglomerate of mainly volcano-plutonic provenance dominate this interval. Locally, however, there are beds of conglomerate containing 90 per cent well-rounded orthoquartzite clasts. Volcanic lithic and feldspathic sandstones are planar or trough crossbedded and commonly contain mudchips. Ripple-laminated siltstone, sometimes with mudstone drapes, occur throughout the sequence. Local mudstones, occasionally with mudcracks may mark the sites of lacustrine sedimentation or in some cases, the distal ends of debris flows.

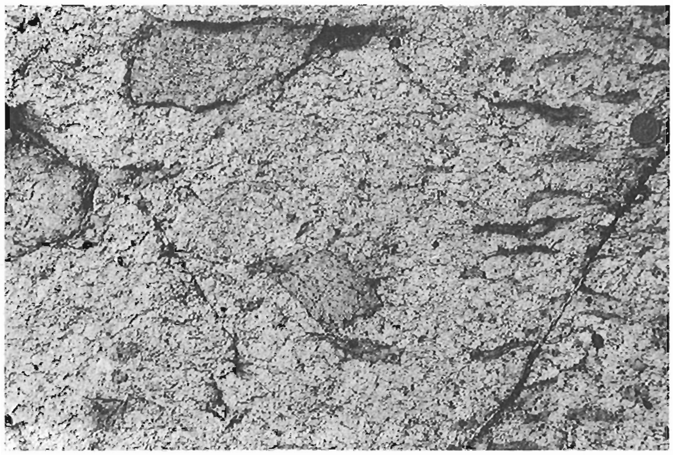


Figure 8.7. *Moderately-welded Mackenzie Tuff*

Figure 8.8. *Accretionary lapilli in the Mackenzie Tuff*

Devitrified ashstone beds (to 2 m) are common, especially on Vance Peninsula. Remnants of the beds, occurring as freestanding pinnacles of ashstone surrounded by sandstone, indicate they were channelled and eroded before deposition of the sandstones. The ashstone beds may represent coignimbrite ashes of the type described by Sparks and Walker (1977).

Directly overlying the Mackenzie Tuff west of Lindsley Bay is a 50 m coarsening-upward succession consisting of basal mudstone to crossbedded sandstones and pebbly sandstone, overlain by bouldery polymictic conglomerate. The entire sequence is capped by andesite lavas of the Sparkplug Lake Member of the Echo Bay Formation. The finely laminated mudstones, with lenses of fine grained sandstone, are locally mudcracked, and are likely lacustrine in origin. Sandstones overlying the mudrocks are medium- to coarse-grained and commonly gritty. Some beds are graded and contain imbricated pebbles that become smaller upsection. These beds are typically about 2 m thick and are overlain by trough and planar crossbedded sandstones. This part of the succession is interpreted as braided stream deposits. Clast-supported, crudely bedded bouldery polymictic conglomerates, that overlie the sandstones, probably represent alluvial fan deposits. The entire sequence is interpreted as a prograding alluvial fan complex, related to renewed volcanism from volcanic centres of the Echo Bay Formation, over lacustrine sediments.

Stevens Tuff Member

Stevens Tuff member consists of moderately to densely welded ash-flows that form one cooling unit characterized by large partly resorbed phenocrysts of quartz. Lithic fragments are ubiquitous near the base of the unit on Cornwall Island, Achook Island and Doghead Point, and commonly comprise up to 30 per cent of the rock. Pumice fragments are common, but in thick sections are obscured by alteration and welding. On Achook Island at least 75 thin ash-fall tuff beds underlie the Stevens Tuff (Fig. 8.9).

The tuff occurs throughout the belt from Echo Bay to Doghead Point. It is 20 m thick on Doghead Point and thickens gradually to the east-southeast. On Achook Island, the tuff is 400 m thick and farther east, on Cornwall Island, an incomplete section of several hundred metres outcrops in individual fault blocks. The Stevens Tuff thins drastically against a northeast-trending transcurrent fault on the eastern end of Cornwall Island. South and east of this fault, the tuff, which is less than 100 m thick, commonly appears to fill paleovalleys or is extensively channelled and eroded. North and west of the fault there is no evidence of a structural break or great topographic relief in the underlying sedimentary rocks, so it is unlikely that the fault was active before ash-flow tuff eruptions. The fault is interpreted to have been active during eruption of the ash-flows and later reactivated during strike-slip faulting.

It appears that the Stevens Tuff was deposited in a low-lying area that deepened to the southeast and was bounded by a major structural break, against which ash-flows ponded to a considerable thickness. The most probable explanation for these relations is that the Stevens Tuff was erupted concurrent with cauldron collapse.

As the central cauldron block appears to have been fault-bounded on only one side, it is reasonable to conclude that the central block subsided in a "trap-door" fashion; that is, bounded on one side by a large fault and on the other by a monoclinal flexure. Trap-door subsidence of central blocks in Cenozoic calderas has been documented by several workers (Seager, 1973; Seager and Clemons, 1975; Lambert, 1974; Steven and Lipman, 1976; Elston et al., 1976).

Achook Andesite Member

Amygdaloidal, sparsely-porphyritic lava flows, tuff, and breccia of andesitic composition that overlie Mackenzie Tuff from Echo Bay to Doghead Point are collectively termed the Achook Andesite. These flows and breccias contain abundant amygdules and sparse phenocrysts of altered plagioclase and amphibole. In these respects the Achook Andesite is different from the Echo Bay Formation which is sparsely amygdaloidal phenocryst-rich andesite. Lava flows in the Achook are generally less than 10 m thick, and commonly flow-banded. Amygdules are commonly mixtures of blood-red and snow-white chalcedony and in some flows are so common that they outline flow folds.

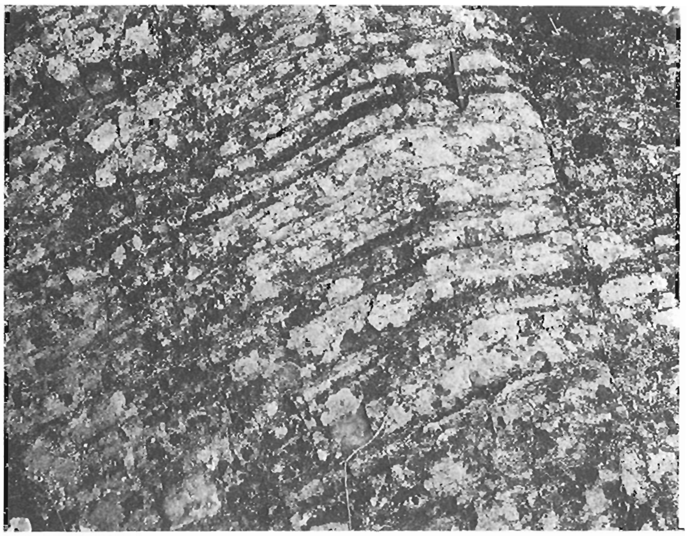


Figure 8.9. *Ash-fall beds at the base of Stevens Tuff. Note pen for scale.*

The Achook Andesite is intercalated with several ash-flow sheets (Fig. 8.3) which indicates that andesitic eruptions occurred sporadically over a time span sufficient to deposit several major ash-flow sheets, and that different volcanoes in the area were active concurrently.

The thickest sections (up to 1 km) of the Achook Andesite occur on Cornwall Island and the unit thins rapidly away from this area. Intensely altered andesite breccia several hundred metres thick on Achook Island may mark the site of an eruptive centre. The breccias, consisting of andesite blocks of varying sizes in a fine, comminuted matrix of andesite microbreccia and broken crystals, are interpreted as explosion breccias.

On Doghead Point lapilli tuff and ashstone contain normal and reverse graded beds. Contacts between these beds are commonly gradational. The beds are probably products of Strombolian-type eruptions. The lack of sharp contacts, coupled with the graded bedding, indicates that eruption and deposition went on more or less continuously. The graded bedding developed as eruptive strength waxed and waned and/or as wind velocity and direction fluctuated (Fisher, unpublished manuscript), or possibly as conduit size changed during eruption (Wilson et al., 1980).

Doghead Tuff

The Doghead Tuff is a single crystal-rich cooling unit that contains up to 30 per cent broken phenocrysts of highly altered hornblende, biotite, and plagioclase (Fig. 8.10). It is exposed only on Achook Island and Doghead Point. Most of the unit is very densely welded, with highly flattened pumice fragments near the base and top. Flattened blocks (to 50 cm) on Doghead Point contain inclined tension fractures, which indicate post-emplacement flowage of the tuff (Schmincke and Swanson, 1967). The orientation of the fractures indicates that movement was toward the northeast.

On Achook Island the tuff overlies an eastward-thickening wedge of bouldery, polymictic conglomerate and breccia, thin ash-flows with similar mineralogy to the Doghead Tuff, and andesite flows. Interbeds of thin ash-flows in the conglomerates indicate that eruptions began during conglomerate deposition.

Figure 8.10. *Densely-welded, crystal rich zone of Doghead Tuff.*

The Doghead Tuff is a minimum of 700 m thick on Achook Island. Both the tuff and underlying conglomerate pinch out eastward in less than 400 m against a series of closely-spaced syndepositional (?) faults which were subsequently reactivated during postvolcanic deformation (Fig. 8.11). The tuff thickens toward the west and northwest and is over 1 km thick on Doghead Point.

The above relations suggest that the Doghead Tuff was deposited within a depression and ponded against a topographic barrier. The exact nature and cause of the depression is unknown but a caldera origin is suspected.

Western Channel Tuff Member

The Western Channel Tuff consists of a single brick-red weathering cooling unit that varies from moderately to densely welded and displays spectacular eutaxitic texture (Fig. 8.12) and prominent columnar joints. The lower 2 m is everywhere drift or talus covered, which suggests the unit has an unwelded base.

Western Channel Tuff is exposed only on Doghead Point and Achook Island. It is everywhere porphyritic, but crystals of altered plagioclase, potassium feldspar, biotite and quartz together generally do not exceed 10 per cent of the rock, except near the top where they occupy nearly 20 per cent by volume. Plagioclase is absent in the lower third of the tuff, but becomes abundant in the upper two thirds.

The tuff is over 500 m thick on Doghead Point and thins to about 75 m on Achook Island. On Achook Island the Western Channel overlies a westward-thickening wedge of gritstone, sandstone, and bouldery polymictic conglomerate.

Rocher Range Tuff

Rocher Range Tuff is exposed only on Doghead Point where it is at least 300 m thick. The top of the member is not exposed. It is not present on Achook Island, only 3 km away. The tuff is densely welded, locally flow banded, and pumice seldom occurs, perhaps due to postdepositional recrystallization. The lower 30 m are clogged with andesite fragments of unknown provenance up to 1 m across. Phenocrysts form 15 to 30 per cent of the rock and are altered plagioclase, hornblende, and biotite.

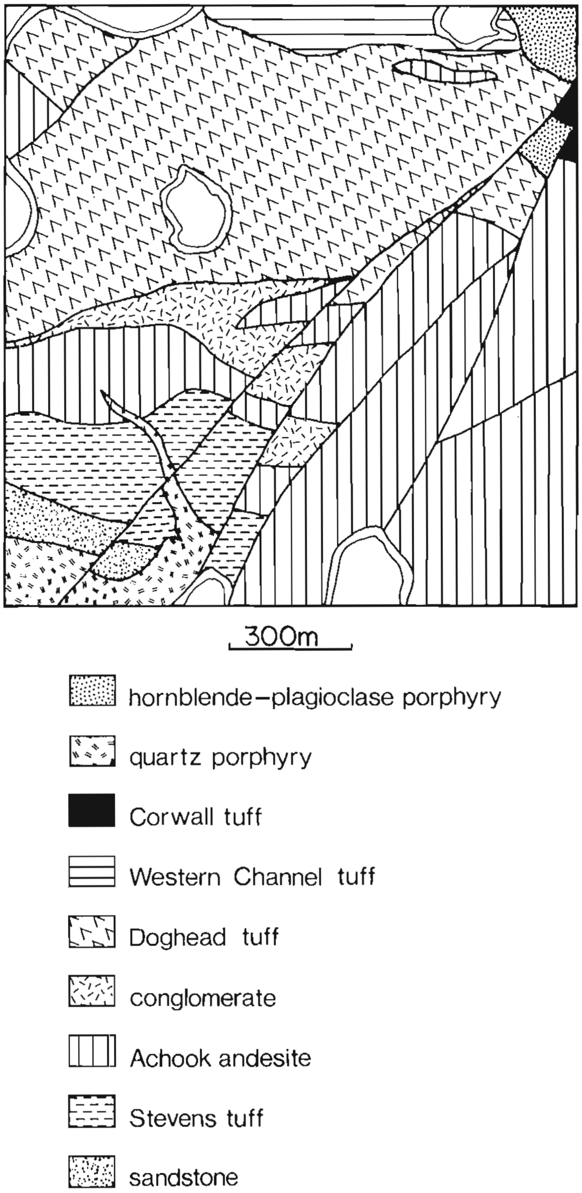


Figure 8.11. *Geological sketch map of north-central Achook Island illustrating relations at postulated cauldron margin. All units are dipping steeply to the north-northeast. Note thickness variations in the Doghead Tuff, believed to have been erupted concurrently with subsidence.*

Feniak Formation

The Feniak Formation occurs throughout the region from Vance Peninsula to Doghead Point. It is best exposed north of Stevens Island. As defined here, the unit includes all extrusive and sedimentary rocks between the base of the Cornwall Tuff and the Sloan Group. Contained within this interval are one major ash-flow tuff sheet (Cornwall Tuff), a thick, stubby dacite flow, and a diverse assemblage of waterlaid crystal tuff, devitrified ashstone, thin ash-flow sheets, fine grained epiclastic rocks, and rare beds of stromatolitic dolomite. It differs from the Cameron Bay Formation in that pyroclastic rocks (i.e. ashstone, crystal tuff and ash-flow tuff) make up the majority of the interval and coarse epiclastic rocks are relatively minor.

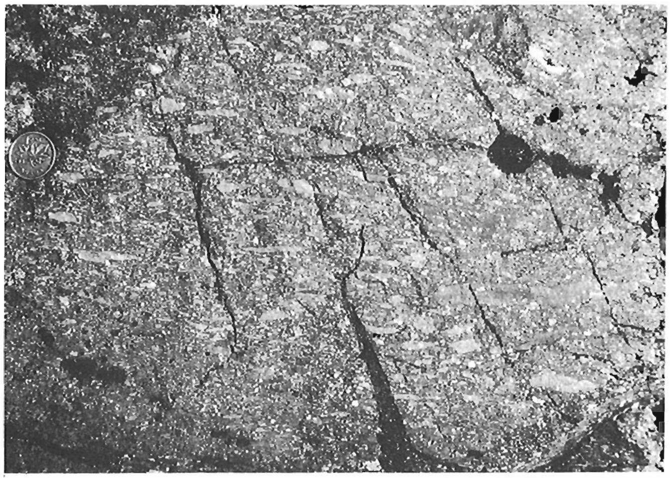


Figure 8.12. *Eutaxitic texture typical of the Western Channel Tuff.*

Cornwall Tuff Member

The lowermost unit of the Feniak Formation is the Cornwall Tuff Member, a non- to densely-welded composite ash-flow sheet containing 5 to 15 per cent altered plagioclase, hornblende, quartz, and potassium feldspar phenocrysts. The unit is well exposed on Achook Island and on Cornwall Island where it is over 1 km thick and highly propylitized. North of Stevens Island the tuff could be as thick as 1.8 km, but the central portion of the unit is not exposed and continuity cannot be demonstrated.

On Achook Island the Cornwall Tuff contains a 4 m thick, probably lacustrine, stromatolitic dolomite bed which suggests that the tuff at this locality is composed of at least 2 cooling units. On Doghead Point the Cornwall Tuff consists of three, or possibly four, thin cooling units intercalated with a thin sequence of diverse epiclastic rocks and a stromatolitic dolomite bed similar to that on Achook Island.

This epiclastic sequence consists, in its lower parts, of finely laminated sandstone and mudstone interbedded with thin beds of cryptalgal limestones, commonly with well-developed tepee structures. Numerous beds of devitrified ashstone also occur in this section. These weather various shades of pink, white and green and range from 30-70 cm thick. They are interpreted to be of airfall origin and may represent co-ignimbrite airfall deposits.

Fine grained arkosic sandstones and wedges of volcano-polymictic conglomerate, which pinch out or thicken at syndepositional faults are also present in this lower part of the section.

Clastic rocks in the middle part of the section contain numerous slump folds and lenses of water-laid crystal tuff. Overlying these beds are 100-150 m of interbedded crystal tuff and ashstone.

A 1 km thick dacite flow overlies the Cornwall Tuff on both Achook and Cornwall islands. It is generally highly altered but where alteration is low, it is plagioclase porphyritic and contains a flow-banded base.

The thickness of much of the Cornwall Tuff suggests that it is intra-cauldron facies tuff that ponded within a topographic depression created by the subsidence of a central block during the ash-flow eruptions. The thin, multiple cooling units preserved on Doghead Point are likely the remains of the outflow sheet.

Intrusive Rocks

A wide variety of intrusive rocks are exposed in the belt, but only the largest, geologically most significant, bodies are discussed here. For information regarding the intrusives not discussed in this paper, the interested reader is referred to Geological Survey of Canada Open File 709 (Hildebrand, 1980). Modal mineral proportions were estimated in the field and the nomenclature follows that recommended by Streckeisen (1973). The noun porphyry, as used in this paper, refers only to intrusive rocks which consist of phenocrysts in an aphanitic groundmass.

Cobalt Porphyry

Podiform to irregular-shaped intrusions of hornblende-plagioclase porphyry and microdiorite, collectively termed the Cobalt porphyry, are abundant at LaBine Point and cut only the Port Radium and lower Echo Bay formations. The Cobalt porphyries are of unknown age but as they are lithologically similar to the host andesite lavas of the lower Echo Bay Formation, they are interpreted as subvolcanic magma chambers from which some of the stratigraphically higher lava flows were erupted.

Brecciated zones up to 2 m wide occur within individual Cobalt porphyry bodies adjacent to the wall rocks. The matrix between the blocks consists of unbrecciated porphyry or finely brecciated and comminuted porphyry. Wall rocks near the contacts are also brecciated.

The brecciation of both the porphyries and the wall rock may have commenced before the porphyries had completely crystallized and could reflect the inflation and deflation that would result if these bodies were subvolcanic magma chambers that vented at the surface. As the chambers were emptied during eruption, solidified magma at their outer margins would be fractured and broken as the magma chambers collapsed. Alternatively, the breccias could be the product of steam explosions if the sediments were wet when the porphyries were intruded. There appears to be less brecciation where the porphyries intrude lava flows. Thus, the steam explosion concept may be of local importance, but the occurrence of breccias in both areas suggests that both mechanisms did occur.

Mystery Island Intrusive Suite

The Mystery Island Intrusive Suite comprises several (Fig. 8.4) semi-concordant sheets of medium grained diorite, quartz syenite, and granodiorite. They are widely distributed throughout the southern half of the map area and intrude both the Port Radium and Echo Bay formations. Characteristic of these intrusions are alteration haloes up to 2 km wide, comprising an inner bleached and albitized zone, a central zone of apatite-actinolite-magnetite pods, breccias, veins, and replacement, and an outer zone of chalcopyrite and pyrite gossan.

One member of this suite, the Tut pluton (Fig. 8.1), is likely contemporaneous with LaBine volcanism because it intrudes the Echo Bay Formation and conglomerate of the Cameron Bay Formation southwest of Lindsley Bay contains abundant clasts up to 1 m in diameter, of diorite and quartz monzonite identical in grain size, texture and lithology to phases of the Tut pluton. Furthermore, paleocurrents in associated sandstones show transport directions to the east, away from the pluton (Fig. 8.13). The conglomerate is overlain by the Stevens Tuff, indicating that the pluton was unroofed before the tuff was deposited.

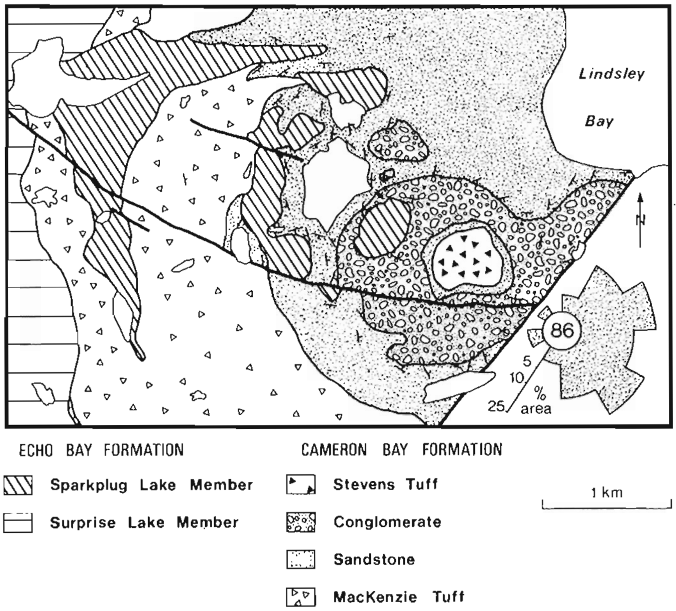


Figure 8.13. Geological sketch map of an area west of Lindsley Bay showing intercalation of the Echo Bay Formation with the Mackenzie Tuff. Note westward pinchout of sandstone and conglomerate. The Tut pluton is located 1 km west of this figure. A paleocurrent rose diagram for the sandstone underlying the conglomerate rich in Tut pluton clasts is also shown.

Subvolcanic Porphyries

Porphyries of varied compositions outcrop in the region. Most common are biotite-quartz and hornblende-plagioclase porphyries of unknown age which often intrude a thick conglomeratic horizon above the Lindsley Tuff. Another important group of porphyries, which Hoffman (1978) termed the Mulligan Porphyries, intrudes the Sloan-LaBine contact in several parts of the belt (Fig. 8.4). They are sill-like bodies of plagioclase-quartz porphyry believed by Hoffman (personal communication) to be partly coeval with Sloan volcanism.

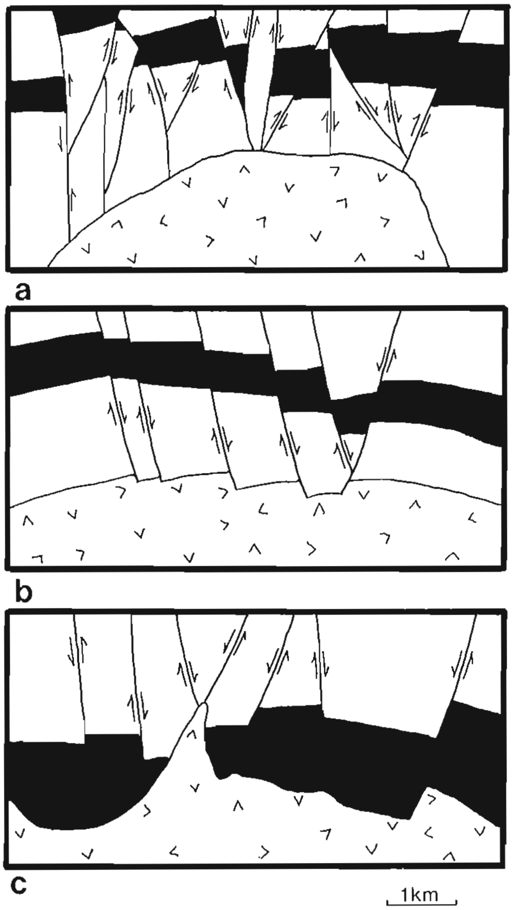
A distinctive plagioclase-potassium feldspar-quartz porphyry outcrops on Cornwall Island, where it intrudes and intensely alters conglomerate of the Cameron Bay Formation. The overlying Stevens Tuff locally contains up to 30 per cent lithic fragments identical to this porphyry. If they were derived from the porphyry, then the porphyry was intruded to within 1.5 km of the surface – the stratigraphic separation between it and the Stevens Tuff.

Hogarth Pluton

The Hogarth pluton intrudes volcanic and sedimentary rocks of the LaBine Group and is exposed from Vance Peninsula northward to Achook Island (Fig. 8.4). It consists of medium grained hornblende-biotite (chlorite-epidote), granodiorite and monzogranite. The granodiorite generally occurs in the upper portions of the pluton, while monzogranite dominates the lower part. Contacts with the wall rock are invariably razor-sharp and alteration is minimal. No miarolytic cavities were found. Xenoliths, of partly digested country rock up to 0.5 m across, are sparse.

A group of block faults that cuts rocks of the LaBine Group occurs above the roof of the Hogarth pluton on Achook Island, Cornwall Island and on Stevens Island. These faults typically have different trends than postvolcanic transcurrent faults or their splays and do not cut the Sloan Group except where reactivated by the younger transcurrent faults. The early faults must predate the Sloan Group because one is left laterally separated on Doghead Peninsula by another fault, probably dip-slip with west side down, which is overstepped by ash-flow tuff of the Sloan Group.

The faults are truncated by the Hogarth pluton near its apex but at deeper structural levels they penetrate the outer shell of the pluton. These relations are interpreted to indicate that the faults were active synchronously with emplacement of the Hogarth pluton and that magma near the margins of the lower part of the intrusion had already crystallized when the uppermost portions of the pluton were emplaced. If this interpretation is correct then the Hogarth pluton must predate the Sloan Group, and barring significant pre-Sloan Group erosion of the LaBine Group the maximum depth of emplacement of the pluton is approximately the stratigraphic thickness between its roof and the LaBine-Sloan contact – about 2.5 km.



a) a map view of the Cornwall cauldron (Hogarth pluton)

b) interpretive cross section of Valles caldera (Smith et al., 1970)

c) interpretive cross section of Timber Mountain caldera (Byers et al., 1976)

Figure 8.14. Comparison of cross-sections through the central portions of 3 large resurgent calderas. A stratigraphic unit in each area has been blackened to show the doming and development of the central grabens. Note the occurrence of both normal and reverse faults above the Hogarth pluton in a.

Interestingly, the faults are topographically coincident with the thickest and most altered parts of the Cornwall Tuff, suggesting that the tuff, faults and pluton are genetically related. Structural relations above the Hogarth pluton display striking similarities to resurgent domes of large collapse calderas in other volcanic fields. Blocks above its roof are jostled and lifted and there is a graben located in the central part of this uplift (Fig. 8.14). Similar relations are present in resurgent domes of Creede Caldera (Steven and Ratte, 1973; Steven and Lipman, 1973), Valles Caldera (Smith et al., 1970), Long Valley Caldera (Bailey, 1976; Bailey and Koeppen, 1977), the Timber Mountain Caldera (Byers et al., 1976), and many others. The lack of miarolytic cavities or associated pegmatites in the Hogarth pluton which intruded within a few kilometres of the surface, suggests that the pluton had already lost most of its volatiles before final emplacement. A possible mechanism for their loss appears to be voluminous ash-flow tuff eruptions which resulted when volatile pressure exceeded the containment capability of the roof.

Figure 8.15. *Outcrop near contact of granitic pluton showing abundant partly digested xenoliths and pegmatite-lined miarolitic cavities.*

Figure 8.16. *Contact of granitic pluton. Note leucocratic border phase.*

Later Granitoids

Several granitoid plutons that postdate the Sloan volcanics occur within the region covered by this paper. They are biotite-hornblende (chlorite-epidote) monzogranite and granite, typically with narrow alteration haloes and sharp contacts. These plutons were emplaced by block stoping and wall-rock assimilation. Xenoliths of partly digested country rock are common in some outcrops, most notably at LaBine Point, as are miarolytic cavities lined with pegmatite (Fig. 8.15). Contacts with the wall rock are invariably razor-sharp and leucocratic border phases are common (Fig. 8.16).

VOLCANIC EVOLUTION

The fine grained, locally mudcracked, volcaniclastics of the Port Radium Formation were deposited in a lacustrine environment and are interpreted as material from growing, but distant volcanoes. With further growth and development of the volcanoes, alluvial fan complexes, preserved as the Mile Lake Member of the Echo Bay Formation, prograded across the lacustrine beds and in turn were succeeded by thousands of metres of monotonous andesite flows erupted from at least two volcanic centres (Fig. 8.17). Similar facies relations related to growth and progradation of volcanoes have been described by Williams and McBirney (1979), Clemons (1979), Lipman (1975), and Smedes and Prostka (1972).

Andesitic volcanism had waned, but had not ended, when the first of several major ash-flow sheets was erupted and ponded within a steep-walled topographic depression. Of seven major ash-flow sheets, at least three can be related to cauldrons (Fig. 8.18). Cauldron subsidence coeval with ash-flow eruptions is demonstrated by the order of magnitude thickness variations of the ash-flow tuff sheets. However, the size and shape of the cauldrons are indeterminable because of post-eruptive tectonic complications, including two episodes of granitic plutonism, folding about northwest-trending axes, and separation by a multitude of northeast-trending transcurrent faults.

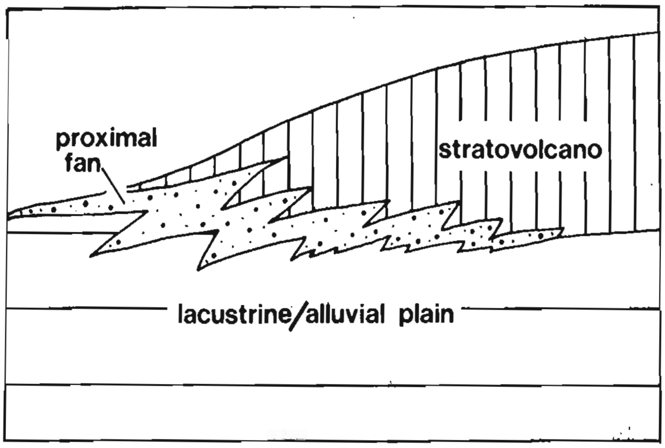
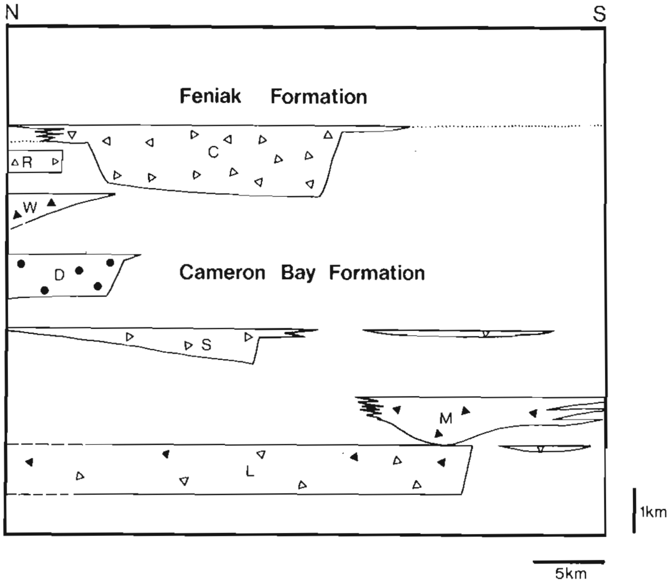


Figure 8.17. *Stratigraphic model for growth and progradation of stratovolcano.*



L = Lindsley Tuff
M = Mackenzie Tuff
S = Stevens Tuff
D = Doghead Tuff
W = Western Channel Tuff
R = Rocher Rouge Tuff
C = Cornwall Tuff

Figure 8.18. *Restored thickness variations of major ash-flow sheets (diagramatic and scale only approximate).*

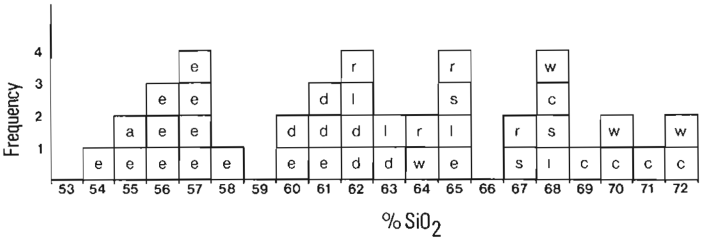
Several, and probably all, the ash-flow sheets are compositionally zoned. Typically, the earliest flows in each sheet are more siliceous, while later flows are more intermediate. This compositional zoning indicates that the source magma chambers for the ash-flows were compositionally zoned, with more differentiated upper portions (see Smith, 1979). These magma chambers are interpreted to have been individual plutons, such as the Hogarth, which probably coalesced at depth forming a batholith of regional dimensions.

The change from gas-poor andesitic volcanism to more highly gas-charged ash-flow eruptions could represent progressive differentiation of the batholith as it rose toward the surface, or perhaps it temporally reflects a higher degree of crustal input in the zone of magma genesis. Alternatively, the magmas may have scavenged volatiles during their rise to the surface with the andesites being erupted earlier, and from a deeper level.

CHEMISTRY

Volcanic rock petrochemistry is highly complicated by post-eruptive processes which modify the original magmatic composition. These processes include devitrification, deuteric processes, vapour phase transport and crystallization, fumarolic alteration, and hydration through interaction with ground water (Smith, 1960; Keith and Muffler, 1978; Lipman, 1965). Contact metamorphism and hydrothermal systems, related to contemporaneous or later events, may further modify earlier alteration making it difficult to determine the original magmatic composition.

As one might expect, the entire LaBine Group of the Echo Bay-Hornby Bay region is altered to some degree. Chemical analyses[1] were performed on the least altered rocks to ascertain their broad chemical affinities and for alteration studies in progress.



e = Echo Bay Formation
d = Doghead Tuff
l = Lindsley Tuff
r = Rocher Rouge Tuff
w = Western Channel Tuff
c = Cornwall Tuff
s = Stevens Tuff

Figure 8.19. *Histogram showing silica variation (recalculated H_2O free) in major stratigraphic units of the LaBine Group.*

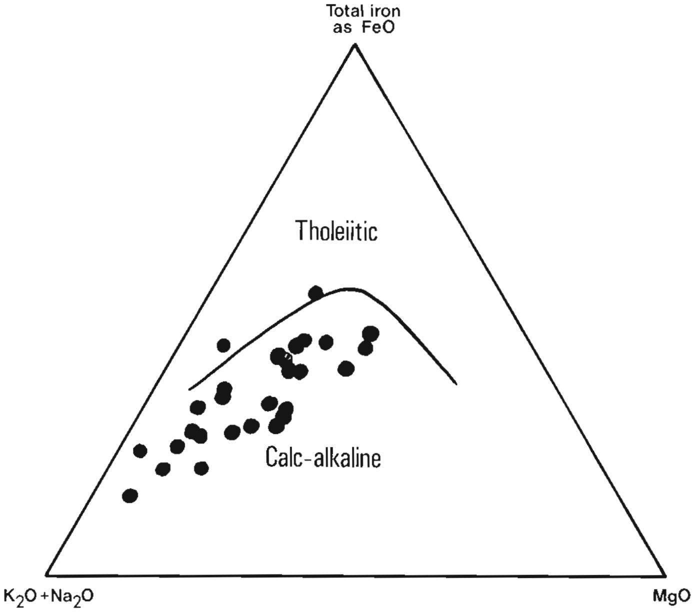


Figure 8.20. *AMF diagram for rocks of the LaBine Group. Tholeiitic-Calc-alkaline dividing line from Irvine and Baragar, 1971.*

In general, the LaBine Group is of intermediate composition with most SiO_2 values clustering between 55 and 68 per cent (Fig. 8.19), a chemical characteristic of calc-alkaline volcanic rocks (Green, 1980). Alkali and alkaline-earth variations indicate that these elements were extremely mobile during alteration and cannot be used for classifications although the suite shows no Fe enrichment trend on an AMF diagram (Fig. 8.20).

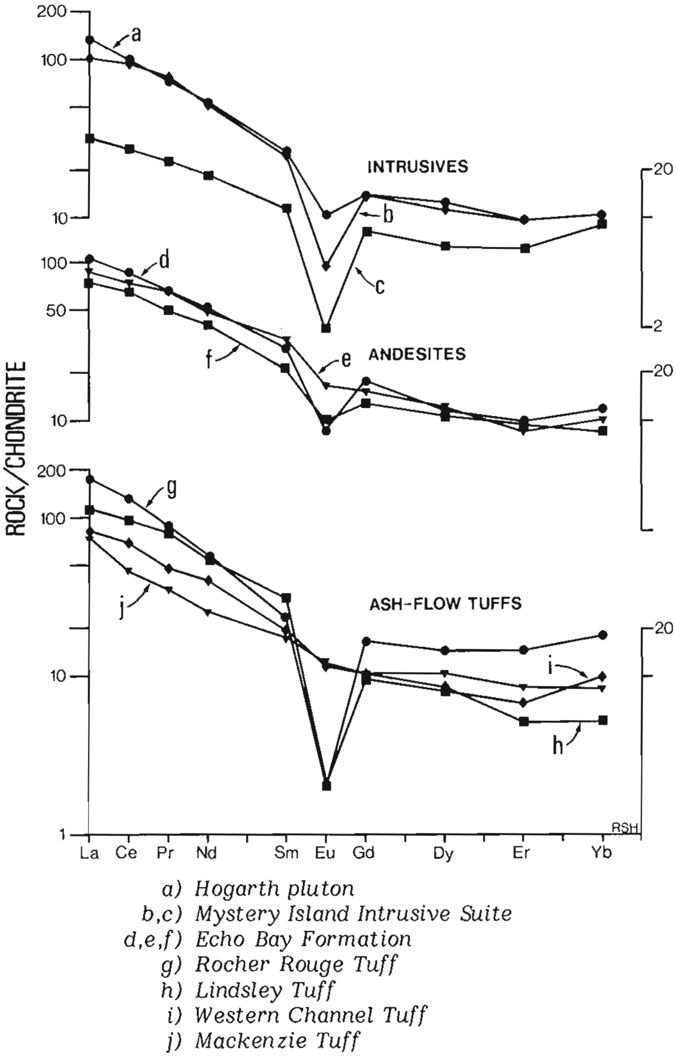
Titanium, while certainly mobile to some degree under appropriate conditions, may be less mobile than most other elements (Pearce and Cann, 1973). TiO_2 values for all rocks analyzed are less than 1.0 per cent. Intermediate rocks with low TiO_2 (<1.75%) dominate Tertiary-Recent volcanic provinces classified as orogenic (i.e. volcanic arcs) by Ewart and LeMaitre (1980). Green (1980) believed that typical TiO_2 values for island arc and continental arc rock series are less than 1.2 per cent. Furthermore, calc-alkaline extrusive rocks of continental arcs such as the Taupo Zone of New Zealand (Ewart et al., 1977; Cole, 1978, 1979), the Andes (for example: Kussmaul et al., 1977; Deruelle, 1978), Papua (MacKenzie, 1976) and the Pontid arc (Egin et al., 1979) nearly always have TiO_2 less than 1.0 per cent.

[1] Complete chemical analyses are available from the author on request.

Rare earth element (REE) analyses of rocks from the LaBine Group (Fig. 8.21) exhibit light REE enrichment patterns and the high overall abundances typical of high-K continental volcanic arcs such as the Chilean Andes (Thorpe et al., 1976, 1979), the Taupo Zone (Ewart et al., 1977; Cole, 1979), and Sardinia (Dupuy et al., 1979).

ALTERATION

The most prevalent alteration in the LaBine Group is pervasive potassium metasomatism in which potassium is enriched and soda depleted. While not yet studied in detail, many rocks contain greater than 6.0 per cent K_2O and less than 0.5 per cent Na_2O. In these rocks the plagioclase feldspars are completely replaced by an unidentified K-rich mineral(s) which is yellow-reactive to sodium cobaltinitrate, as is the groundmass. Trace elements such as Rb and Sr are also affected by this alteration and altered rocks with high K_2O/Na_2O ratios have Rb/Sr ratios greater than 10. Obviously, Rb-Sr ages obtained from the LaBine Group (Robinson and Morton, 1972) may not represent cooling ages but rather are related to hydrothermal events.



a) Hogarth pluton
b,c) Mystery Island Intrusive Suite
d,e,f) Echo Bay Formation
g) Rocher Rouge Tuff
h) Lindsley Tuff
i) Western Channel Tuff
j) Mackenzie Tuff

Figure 8.21. Representative rare earth element abundances of rocks occurring in the study area.

Alteration of the type described above has been documented in many volcano-plutonic terranes by numerous workers (for example: Ratte and Steven, 1967; Kisversanyi, 1972; Chapin et al., 1978; Wodzicki and Bowen, 1979). Fenner (1936) and Keith et al. (1978) described similar alteration of Recent age from shallow boreholes in the Yellowstone geothermal field and it has been widely recognized that hot spring waters are commonly depleted in potash relative to soda (Allen, 1935; Orville, 1963; Grindley, 1965; Nathan, 1976; Taylor, 1976; Sorey et al., 1978; Stauffer et al., 1980; Sammel, 1980; Parry et al., 1980; Rinehart, 1980). Thus, the LaBine Group is interpreted to have been affected by a fossil geothermal field in which hot springs were abundant.

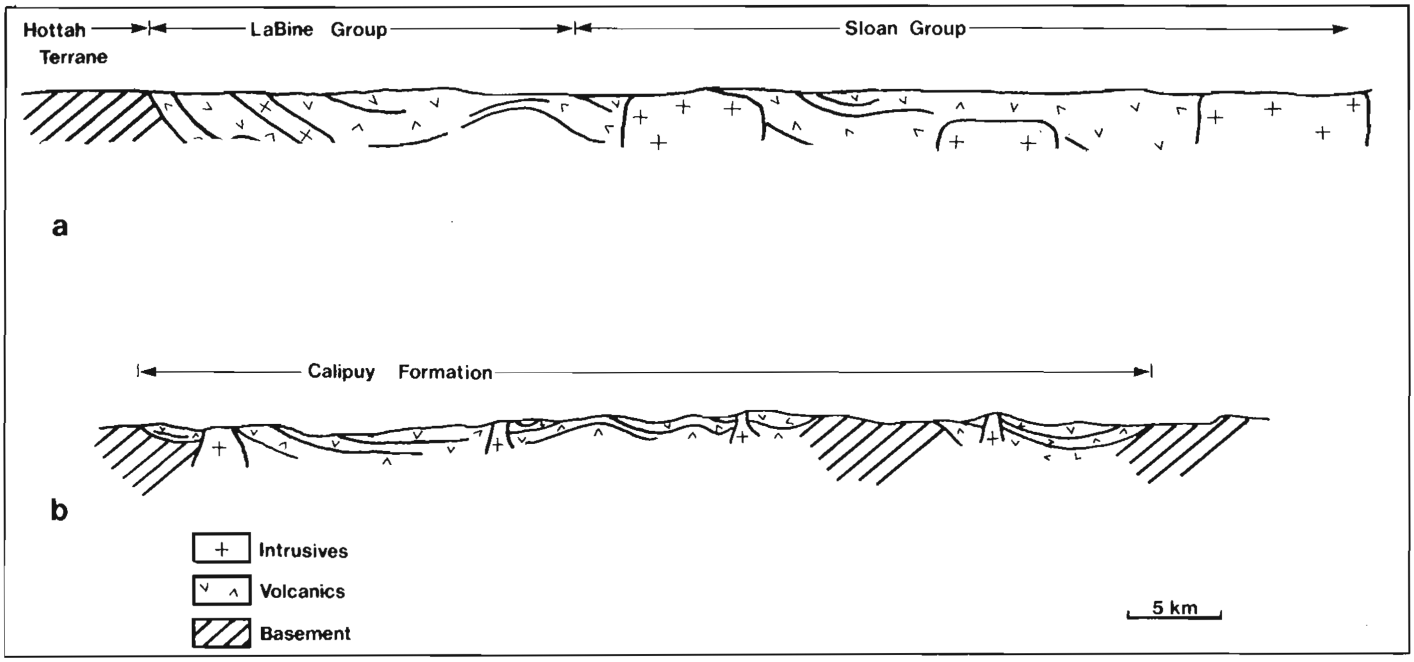
INTERPRETATION AND TECTONIC SETTING

Although alkali and alkaline earth metals were mobile during hydrothermal alteration, the original phenocryst mineralogy (quartz, potassium feldspar, biotite, hornblende, and plagioclase) coupled with SiO_2, TiO_2, and REE values indicate that the LaBine volcanic field is a high-K, calc-alkaline belt of mainly intermediate composition rocks that fall within the broad class of orogenic volcanic rocks (Ewart and LeMaitre, 1980). In detail, they are chemically similar to continental arcs related to subduction such as the Andes. In overall stratigraphy, mode of eruption, and mineralogy the LaBine Group resembles Cenozoic volcanic fields of the western United States such as the San Juan volcanic field (Steven and Lipman, 1976), the Datil-Mogollon volcanic field (Elston et al., 1976), and the Elkhorn Mountain volcanic field (Klepper et al., 1971). Cogent arguments have been made by several authors that the calc-alkaline volcanic rocks in those fields were related to oblique, low-angle subduction of the Farallon plate beneath the North American continent during the Eocene-Oligocene (Lipman et al., 1971, 1972; Elston, 1976; Coney and Reynolds, 1977; Lipman, 1980).

Although genetic details of volcanic arc magmatism are still controversial, there seems little doubt that arc magmatism is a multistage product of lithospheric subduction (Marsh, 1979). I see no compelling reason to invoke an ad hoc model to explain the origin of LaBine Group volcanic rocks as they have readily identifiable Cenozoic analogs. Therefore, I conclude that the LaBine Group represents a remnant of an early Proterozoic continental volcanic arc and that subduction, which may be the principal driving mechanism of plate tectonics (Forsyth and Uyeda, 1975; Richter, 1977; Chapple and Tullis, 1977), was occurring at least by about 1.9 Ga ago.

Stratovolcanoes are not likely to be preserved in the geologic record because they are topographically high-standing features, yet clearly there are tremendous thicknesses of andesite preserved in the LaBine Group. A probable explanation is that the LaBine Group developed in a basin which subsided concurrent with eruptions. The hypothesis that the Great Bear Volcano-Plutonic Belt was a region of subsidence during volcanism was first put forth by Hoffman and McGlynn (1977) who argued that the belt subsided in response to bending of a strike-slip fault.

Volcanic arcs often contain basins of various kinds. For example, grabens presently being filled with volcanics and related sediments are well-developed in the Cascades (Fyfe and McBirney, 1975), Nicaragua (McBirney, 1969), Ecuador (Williams and McBirney, 1979), and New Zealand (Ewart et al., 1977; Cole, 1979; Reyners, 1980). The Central American arc contains other types of basins besides grabens.



a. modified from Hoffman and McGlynn (1977)
b. modified after Hollister and Sirvas B (1978)

Figure 8.22. *Schematic cross-sections illustrating the similarity between the Great Bear Volcano-Plutonic Belt (a) and the Calipuy Formation (b).*

In Honduras, "intermontane tectonic troughs" developed during and after eruption of andesitic to basaltic lavas and breccias of the early Tertiary Matagalpa Formation, and many Miocene ash-flow sheets filled those, as well as other, broad, shallow basins (Williams and McBirney, 1969). Williams and McBirney (1969) also described a series of north-south trending, en echelon basins such as the Sula basin and the huge Comayagua Valley of Honduras. Furthermore, many individual Central American volcanoes, such as those found in Guatemala (Williams et al., 1964), are located within sags or depressions.

Yet another type of basin developed in arc terranes is found in northern Peru (Hollister and Sirvas B, 1978). There basaltic and andesitic volcanoes of the Calipuy Formation were erupted in a linear basin concomitant with folding of the volcanic and sedimentary basin-fill. Structurally the basin is strikingly similar to the Great Bear Volcano-Plutonic Belt (Fig. 8.22). Folds in both regions are en echelon with axes that are oblique to regional trends and to their respective outcrop areas.

Wilcox et al. (1973) showed how en echelon structures are related to wrench zones generated by horizontal shear couples. A given area in a wrench zone can undergo alternating periods of extension and compression because the stress regime at any particular place in the system depends on factors which change with time, such as bends and gaps in the braided fault system (Crowell, 1974a, b) or whether the system is one of parallel, divergent, or convergent wrenching (Wilcox et al., 1973). Crowell (1979), using the broad San Andreas transform system as an example, pointed out that wrench zones must be considered as complex moving systems in which local tectonic patterns, such as pull-apart basins, strike-slip faults, stretching, squeezing, dismemberment and rotation of individual fault-bounded blocks, are rapidly transformed as plate movement continues.

Wrench systems are not confined to transform margins but are also common in regions of oblique convergence (transpression) where the wrench system may appear in the magmatic arc (Fitch, 1972; Nakamura and Uyeda, 1980). There are numerous places where this situation exists with some of the more spectacular examples found in: New Zealand where the Taupo Zone and the Alpine and Hope Faults appear to be related to transpression (Sporli, 1980; Cole and Lewis, 1981); the northern Andes (Campbell, 1974), where the Dolores-Guayaquil Fault system formed in response to oblique motion of the northern portion of the Nasca Plate with respect to South America; Guatemala where Williams et al. (1964) interpreted conjugate sets of oblique faults to have been produced by strike-slip movements parallel to the long axis of the Central American Trench; and in Sumatra where the Sunda Arc is being folded and splintered by the Semangko fault system in response to oblique convergence of the Indian-Australian Plate with the Eurasian Plate.

The Semangko, or Barisan, Fault System of Sumatra exhibits most of the features typically found in wrench zones and is particularly interesting because it slices through the magmatic front (Fig. 8.23). Areas in the arc have undergone several periods of extension and compression leading to en echelon folding of basins filled with volcanic and sedimentary rocks (van Bemmelen, 1949; Westerveld, 1953). Topographic depressions have developed in extensional regimes along the fault itself (Page et al., 1979), especially near junctions of, and gaps between, en echelon fault segments (Tjia, 1978; Posavec et al., 1973). It is this type of environment (wrenched arc) that I envision for the LaBine Group because it satisfies all known constraints (i.e. arc volcanism, deposition in a basin, and en echelon folding). Although not touted in the literature, perhaps many exposures of ancient arc rocks represent the fill of wrench-generated basins related to oblique convergence, for this

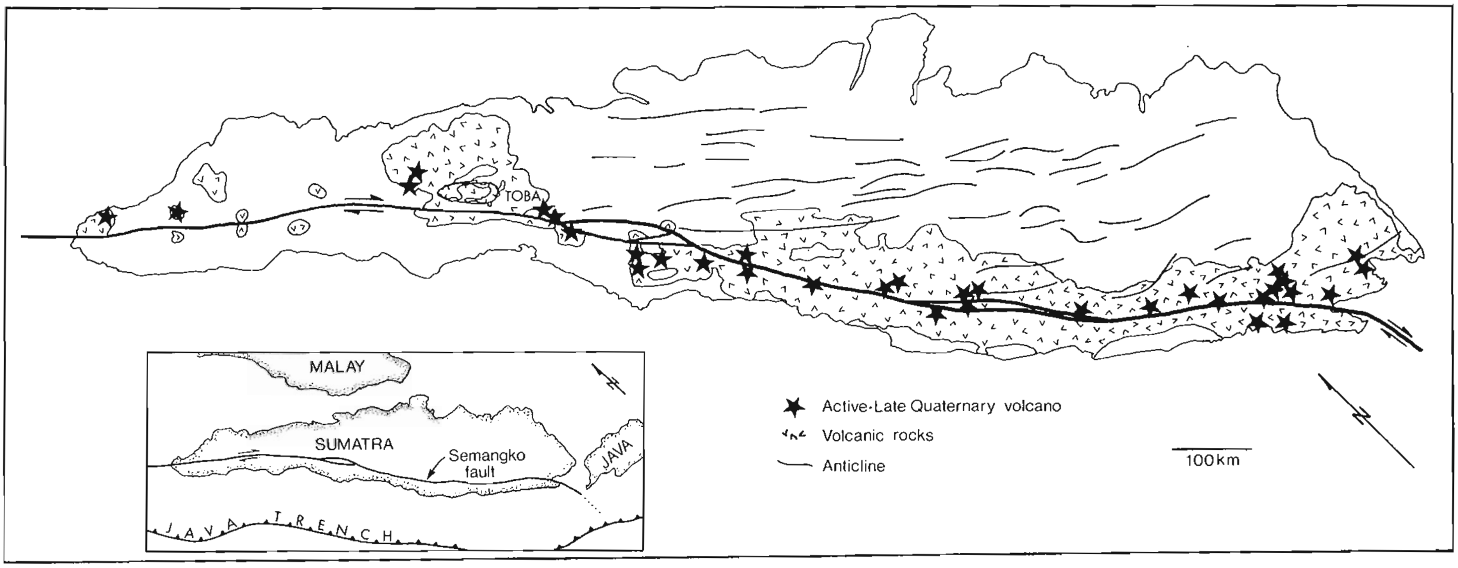


Figure 8.23. Generalized and schematic geological map of Sumatra showing relationship between arc volcanics, en echelon folds, and the Semangko Fault zone.

concept provides a simple and logical explanation for the preservation of high-level arc volcanoes which otherwise might be eroded to their roots.

TECTONIC MODEL

The tectonic model presented here is similar to that presented by Hoffman (1980a) but some refinements and modifications have been made in light of new geochronological and field data. The model is shown schematically in Figure 8.24.

In this model the Hottah Terrane is assumed to be allochthonous with respect to the Slave Craton and to be the remnant of a microcontinent or arc which collided with the Slave Craton over a westward-dipping Benioff zone (Fig. 8.24a). The collision resulted in accretion and deformation of the microcontinent and deformation of the western edge of the Slave Craton with its westward-facing passive margin sequence (Fig. 8.24b).

Continent-microcontinent or continent-arc collisions are by no means rare in the geologic record. Excellent examples of more recent continent-small plate collisions are present along the northwestern edge of the Australian continent where the edge of the Australian-New Guinea shelf is presently colliding with the Banda arc (Von der Borch, 1979). During the Miocene, an early Tertiary arc was accreted to the continent at New Guinea (Hamilton, 1979). Other examples of continent-microcontinent collision occur in the Eastern European Alpine System (Burchfiel, 1980) where several collisions are believed to have occurred from mid-Cretaceous to the Recent. In the northern Canadian Cordillera Tempelman-Kluit (1979) interpreted geologic relations in terms of a Late Jurassic-early Cretaceous continent-microcontinent collision.

In Wopmay Orogen the age of the collision is interpreted to have occurred between about 1.92 and 1.89 Ga. Metamorphic isograds, which postdate the major pulse of thrusting in the deformed passive margin sequence (Hoffman et al., 1980), are related to mesozonal S-type plutons (St-Onge and Carmichael, 1979) whose mean age is 1.89 ± 0.01 Ga[1] (Van Schmus and Bowring, 1980). Deformation of the Hottah Terrane must postdate a deformed pluton found at Hottah Lake dated at 1.92 ± 0.01 Ga (Van Schmus and Bowring, 1980). If deformation in both belts was related to the same event, as postulated here, then the age of deformation is bracketed between 1.92 ± 0.01 Ga and 1.89 ± 0.01 Ga.

The LaBine Group, which rests unconformably on the Hottah Terrane and lacks its penetrative fabric, must be younger than the microcontinent-continent collision. If the LaBine Group is a volcanic arc related to subduction, then it must have developed over an eastwardly-dipping subduction zone, as the ocean east of the microcontinent had already closed. This interpretation requires that following collision subduction changed from westward-dipping on the east side of the microcontinent to eastward-dipping on the west side (Fig. 8.24c).

Many examples of continent-arc or microcontinent collisions appear to have involved a reversal of subduction direction following collision. Hamilton (1979) presented evidence for incipient subduction reversal north of the island of Alor, as a result of collision between the Banda Arc and the Australian Continent. He also suggested that reversal of subduction direction occurred after arc-continent collision at New Guinea. The Miocene collision of the Apulian fragment with Euro-Russian continental crust was along a southward-dipping subduction zone while present day subduction under the Hellenic Arc is northward (Burchfiel, 1980). In the northern Canadian Cordilleran example of continent-microcontinent collision subduction is also believed to have stepped outboard of the accreted terrane and reversed direction (Tempelman-Kluit, 1979).

Independent support for an eastward-dipping subduction zone following collision in Wopmay orogen occurs in Athapuscow Aulacogen, located 300 km southeast of Port Radium (Fig. 8.1). There a group of calc-alkaline laccoliths, strikingly similar in composition, alteration and metalliferous deposits to the Mystery Island Intrusive Suite, are distributed axially over the length of the aulacogen, which trends normal to the Wopmay continental margin. The laccoliths exhibit compositional changes ranging from diorite in the west to quartz monzonite in the east (Hoffman et al., 1977).

[1] Age determinations by Van Schmus and Bowring are U-Pb zircon ages.

Badham (1978) considered this to be an oversimplification but stated that both potassium feldspar and biotite content in the laccoliths increased eastward.

The compositional trend in these laccoliths is similar to those of magmatic arcs (Moore, 1959, 1961; Ninkovitch and Hays, 1972; Kistler, 1974; Dickinson, 1975) – a similarity first pointed out by Hoffman et al. (1977) who suggested that the intrusions might be a result of subduction.

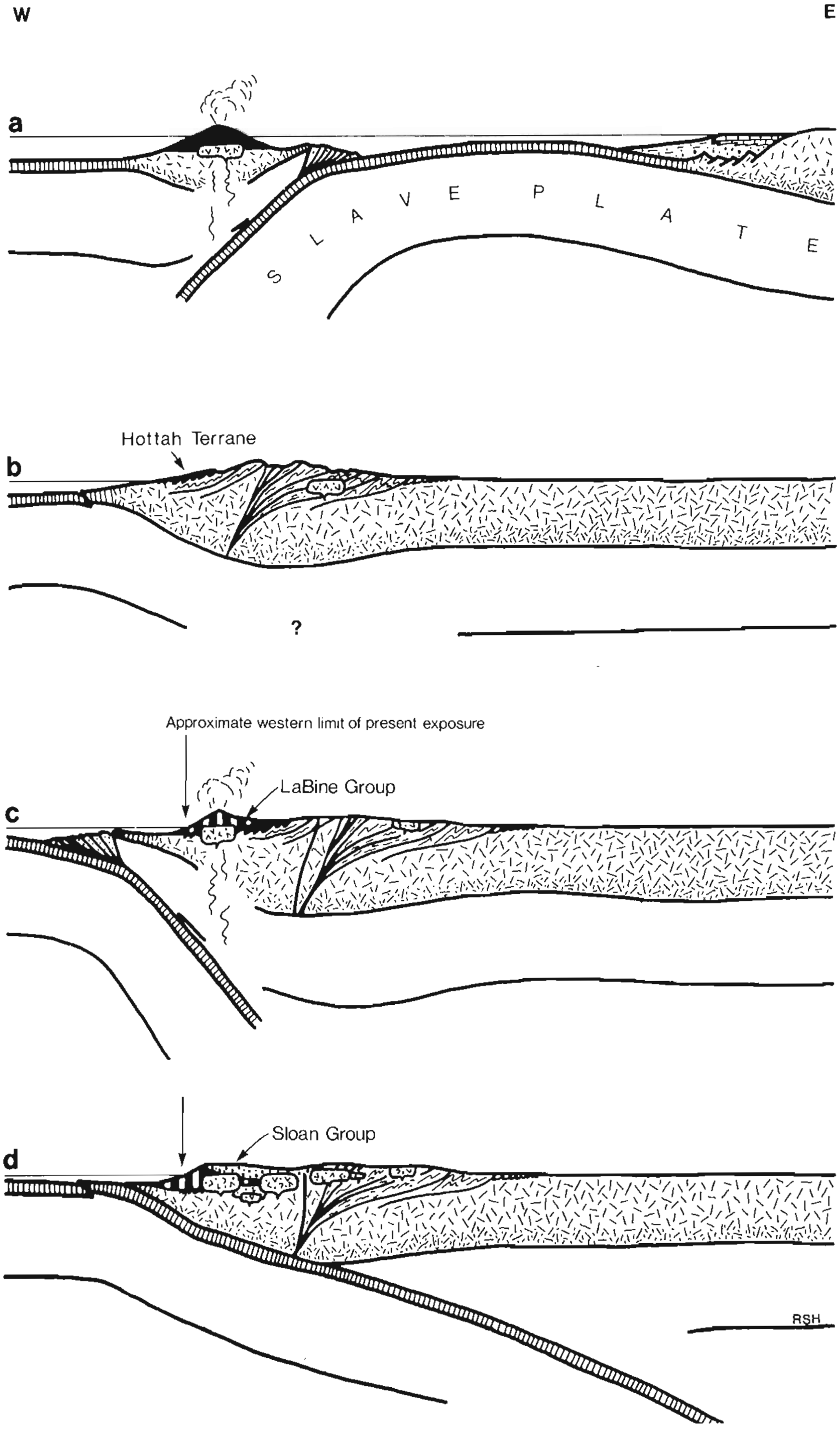


Figure 8.24. Proposed tectonic model for the origin of the LaBine Group and related rocks. See text for explanation.

The laccoliths postdate westerly-derived orogenic molasse presumably produced during collision and have an apparent age of 1.86 Ga ± .02 Ga (Van Schmus and Bowring, personal communication) – the same age or slightly younger than the LaBine Group. Thus, they support the concept of an eastward-dipping subduction zone that postdated the microcontinent-continent collision.

At the present time magmatism occurs above Benioff zones where they are about 100-200 km below the surface (see for example: Isacks and Barazangi, 1977). If this was also the case during the early Proterozoic then the Benioff zone postulated to have generated the laccoliths must have been fairly shallow, for they occur up to 250 km from the trench believed to have existed west of the accreted microcontinent.

A shallow Benioff zone might explain the conspicuous absence of similar magmatism in the Slave craton which should have resulted if a lithospheric slab was being subducted in an eastward direction. Perhaps the dip of the slab was so shallow that there was no asthenospheric wedge above the Benioff zone except under the aulacogen, where it presumably had upwelled during the initial rifting which created the Wopmay continental margin. The possibility that the presence of asthenospheric mantle above a Benioff zone is necessary for arc magmatism to occur has been proposed by Lipman (1980) and Dewey (1980). They both believed that extinction of magmatic activity in the Peruvian Andes is related to extreme flattening of the Benioff zone such that there is no asthenospheric mantle wedge present above it.

If this hypothesis is correct then why was there magmatism of the LaBine Group? I suggest that it may have been for one of three reasons: 1) possibly the subducting lithospheric slab was segmented, in much the same manner as modern slabs (Carr et al., 1979; Isacks and Barazangi, 1977) so that the segment dipping under the aulacogen was dipping at a shallower angle than the segment descending beneath the LaBine region, or; 2) if LaBine volcanism is slightly older than the laccoliths in the aulacogen, the dip of the downgoing slab could have decreased with time or; 3) the presence of thin lithosphere in the suture zone, which the LaBine Group likely buries.

It is the region of thickest and oldest lithosphere where, after collision, subduction would likely initiate because old lithosphere would tend to sink into the asthenosphere faster than young, hot lithosphere (Molnar and Atwater, 1978). With time, progressively younger lithosphere would be subducted resulting in a Benioff zone that becomes shallower with time. Assuming this, I speculate that the voluminous volcanism of the Sloan Group, located east of and stratigraphically above the LaBine Group, reflects progressive shallowing of the downgoing slab as younger, hotter and thinner lithosphere was subducted.

Burke et al. (1976) argued that during the Precambrian, convergence rates would have been greater, and Benioff zones more numerous, than in the Phanerozoic due to the greater thermal output of the earth at that time. If true, then Proterozoic Benioff zones would have been generally flatter than those of the Phanerozoic because the lithosphere would have been thinner and hotter during the Proterozoic.

It is likely that shallower subduction would lead to stronger coupling of the convergent plates (Dewey, 1980). When stronger coupling and oblique convergence occur together, wrench zones in arcs should be more common. Was this the case during the Proterozoic?

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