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GEOLOGY AND PETROCHEMISTRY OF THE ORDOVICIAN VOLCANO-PLUTONIC ROBERT'S ARM GROUP, NOTRE DAME BAY, NEWFOUNDLAND

H.H. Bostock

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Preface

The Middle Ordovician Robert's Arm Group is magnificently exposed on the coast of northern Newfoundland, and is located in the Dunnage Zone, one of four northeast-trending tectonostratigraphic zones recognized in this part of the Appalachians. Dunnage Zone is thought to contain the vestiges of Iapetus, an ocean that was the precursor of the Atlantic. The Robert's Arm Group probably developed in an island arc basin marginal to Iapetus and was deformed during the closure of this ocean.

Detailed mapping by Dr. Bostock has shown that the group is bounded and dissected by faults. Two petrochemical terranes have been identified: an older terrane of submarine tholeiitic basalts with small felsic centres and voluminous volcano-sedimentary debris, and a younger terrane characterized by calc-alkaline basalts with felsic centres.

Geochemical studies of this type are necessary when examining altered submarine volcanic rocks like those in the Robert's Arm Group, and are particularly important in relating volcanic rocks to models involving plate tectonics and the genesis of metallic mineral deposits. The region has a long history of mining and is characterized by numerous Cu-Zn-Pb-Ag-Au occurrences of the Buchans type. Ore mineralization was discovered on Pilley's Island in 1875, and was developed as a source of pyrite for sulphur in 1887. Mining for copper ore was first carried out in 1880 and there are still important copper reserves in the area.

R. A. Price
Assistant Deputy Minister
Geological Survey of Canada

Préface

De magnifiques affleurements du groupe de Robert's Arm de l'Ordovicien moyen se présentent le long de la côte nord de Terre-Neuve; ce groupe se situe dans la zone de Dunnage, l'une de quatre zones tectonostratigraphiques à orientation nord-est identifiées dans cette partie des Appalaches. La zone de Dunnage contiendrait des restes de l'océan Japet, ancêtre de l'Atlantique. Le groupe de Robert's Arm aurait pris forme dans un bassin d'arc insulaire, en bordure de l'océan Japet, et aurait été déformé au cours de la fermeture de l'océan.

La cartographie détaillée effectuée par M. Bostock montre que des failles entourent et dissèquent le groupe. Deux terrains pétrochimiques y sont identifiés: un terrain ancien de basaltes tholéiitiques sous-marins à petits noyaux felsiques qui contient une vaste quantité de débris volcano-sédimentaires, et un terrain plus récent caractérisé par la présence de basaltes calco-alcalins à noyaux felsiques.

Il est essentiel d'effectuer ce genre d'étude géochimique lors qu'on examine des roches volcaniques altérées d'origine sous-marine comme celles du groupe de Robert's Arm; ces études prennent encore plus d'importance lorsqu'il s'agit d'établir des liens entre les roches et les modèles établis en fonction de la tectonique des plaques et la genèse des gisements de minéraux métalliques. Cette région a une longue histoire d'exploitation minière et se caractérise par la présence de nombreuses venues de Cu-Zn-Pb-Ag-Au du type Buchans. Une zone minéralisée a été découverte dans l'île Pilley's en 1875 et on y a extrait de la pyrite comme source de soufre en 1887. Le minerai de cuivre a été extrait pour la première fois en 1880. D'importantes réserves de cuivre existent encore dans cette région.

R. A. Price, sous-ministre adjoint
Commission géologique du Canada

GEOLOGY AND PETROCHEMISTRY OF THE ORDOVICIAN VOLCANO-PLUTONIC ROBERT'S ARM GROUP, NOTRE DAME BAY, NEWFOUNDLAND

Abstract

The Robert's Arm Group is a Middle Ordovician, fault-bounded, spilitized, bimodal volcanic to shallow plutonic assemblage within the northern Dunnage tectonostratigraphic zone. On the north it is nonconformably overlain by Silurian Springdale Group redbeds, and both are separated from the Lower Ordovician Lushs Bight ophiolitic terrane by the Lobster Cove Fault. The group itself is complexly faulted and comprises an older terrane of tholeiitic to alkaline basalt slices overlain by one of more calc-alkaline slices. The tholeiitic basalts are interleaved with fine clastics of Cresent Lake Formation and with quartz-phyric felsites accompanied by substantial pyroclastics, whereas the calc-alkaline terrane includes quartz-amygdaloidal felsites with less common pyroclastics, concentrated in major centres that locally grade into granite. Erratic lithium enrichment of the basalts is spatially related to the basal fault contact of the group but spreads upward where deformation of underlying shales is strongest and disruption of the overlying basalts is greatest.

The Robert's Arm Group evolved at the outer edge of a back arc basin beginning with deep water eruption of tholeiitic basalts before obduction of ophiolite in western Newfoundland. Subsequent more calc-alkaline volcanism occurred in neritic to littoral environments likely about the time of continental collision. After southeastward thrusting of Robert's Arm Group and deposition of Springdale Group, the dips of both were steepened by Devonian tectonism. Oroclinal bending of the basalts accompanied late right lateral movements on the Lobster Cove Fault. Alkaline dykes of presumed Mesozoic age were emplaced during opening of the modern Atlantic Ocean.

Résumé

Le groupe de Robert's Arm est une suite de roches volcaniques bimodales spilitisées et de roches plutoniques mises en place à une faible profondeur qui se trouve à l'intérieur de la partie nord de la zone tectonostratigraphique de Dunnage. Au nord, le groupe est recouvert en discordance par les couches rouges du groupe silurien de Springdale; la faille de Lobster Cove sépare les deux groupes du terrane ophiolitique de Lushs Bight de l'Ordovicien inférieur. Le groupe de Robert's Arm a été faillé de façon complexe et comprend un terrane plus ancien de lambeaux de basaltes tholéiitiques ou alcalins sur lesquels repose un lambeau de composition plus calco-alcaline. Les basaltes tholéiitiques font voir des interelations de roches clastiques fines de la formation de Cresent Lake et de felsites microgranitiques accompagnés d'importantes quantités de matériaux pyroclastiques. Le terrane calco-alcalin comprend des felsites amygdaloïdes ayant moins de matériaux pyroclastiques et qui sont concentrés dans des grandes zones qui se transforment localement en granite. L'enrichissement erratique en lithium des basaltes est lié dans l'espace au contact de faille basal du groupe, mais se répand vers le haut là où la déformation des schistes argileux sous-jacents et où la rupture des basaltes sous-jacents sont les plus marqués.

Le groupe de Robert's Arm a évolué le long de la marge extérieure d'un bassin d'arrière arc; la formation du groupe a commencé par l'éruption en eau profonde de basalte tholéiitique qui a eu lieu avant l'obduction de l'ophiolite dans l'ouest de Terre-Neuve. Un volcanisme plus calco-alcalin a eu lieu par la suite dans des milieux néritiques ou littoraux, probablement à la même époque que la collision des continents. Suivant le chevauchement vers le sud-est du groupe de Robert's Arm et l'accumulation du groupe de Springdale, il y a eu raidissement des pendages des deux groupes au cours du diastrophisme dévonien. La courbure oroclinale des basaltes s'est produite en même temps que les mouvements latéraux le long de faille de Lobster Cove. Des filons alcalins vraisemblablement d'âge mésozoïque ont été mis en place au cours de l'évolution de l'océan Atlantique actuel.

Summary

The Robert's Arm Group is a Middle Ordovician, fault-bounded, spilitized, bimodal volcanic to shallow plutonic assemblage within the northern Dunnage tectonostratigraphic zone. On the west it is separated from late Precambrian-early Cambrian* basalt, gabbro and plagiogranite of the Hall Hill Complex by the Mansfield Cove Fault. On the north it is locally nonconformably overlain by Silurian redbeds of the Springdale Group, and both are separated from the Lower Ordovician Lushs Bight ophiolitic terrane by the Lobster Cove Fault. The southeast it is in fault contact with the Sops Head Complex, a tectonic zone along which Robert's Arm Group is thought to have been thrust over Ordovician to Lower Silurian, predominantly fine clastic sedimentary rocks of the Wild Bight Group, Shoal Arm, Sansom and Crescent Lake formations.

The group itself is complexly internally faulted and comprises an older terrane of tholeiitic to alkaline basalt slices overlain by a terrane of more calc-alkaline slices. Each terrane consists primarily of massive basalts, pillow lavas and pillow breccias with lesser but variable proportions of felsic volcanics and clastic sediments. Basalts of the two terranes are not generally distinguishable in the field, but thin section study indicates that clinopyroxene phenocrysts tend to be most common in the calc-alkaline terrane, whereas plagioclase phenocrysts are most common in the tholeiitic terrane.

Basalts of the tholeiitic terrane overlie and are interleaved with shale, chert and greywacke of the Crescent Lake Formation. Small felsic volcanic units in this terrane tend to be quartz-phyric and to have substantial associated pyroclastics in contrast to those of the calc-alkaline terrane, which are mostly quartz amygdaloida with less prominent pyroclastics, and are concentrated in major centres. Epizonal granite plutons were emplaced within and along the margin of the calc-alkaline terrane, after early deformation of the tholeiitic terrane but before calc-alkaline volcanism was complete. Felsic domes and some ash flows are contiguous with, and locally grade into, granite. Minor diatremes were also coeval with granitic plutonism.

Metamorphism of Robert's Arm Group is primarily of subgreenschist (prehnite-pumpellyite) grade. Electron microprobe analyses of four prehnites show increasing substitution of ferric iron for aluminum across Robert's Arm Group from tholeiitic to calc-alkaline terranes. Epidote-amphibolite facies metamorphic aureoles are present along unfaulted granite contacts, along the west (upthrown) sides of a number of faults which disect

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* New U-Pb zircon data, 479 + or- 3 Ma for Mansfield Cove plagiogranite (Dunning et al., 1987) suggest that this pluton is early Ordovoician, only slightly older than Robert's Arm Group.

Sommaire

Le groupe de Robert's Arm est une suite de roches volcaniques bimodales spilitisées et de roches plutoniques mises en place à une faible profondeur qui se trouve à l'intérieur de la partie nord de la zone tectonostratigraphique de Dunnage. À l'ouest, la faille de Mansfield Cove sépare le groupe de Robert's Arm des basaltes, gabbros et plagiogranites du Précambrien récent-Cambrien * ancien du complexe de Hall Hill. Au nord, par endroits, le groupe de Robert's Arm est recouvert en discordance par les couches rouges siluriennes du groupe de Springdale; la faille de Lobster Cove sépare les deux groupes du terrane ophiolitique de Lushs Bight de l'Ordovicien inférieur. Au sud-est, une faille a entraîné le groupe de Robert's Arm contre le complexe de Sops Head, qui est une zone tectonique le long de laquelle le groupe de Robert's Arm aurait chevauché les roches surtout sédimentaires, clastiques, fines, de l'Ordovicien et du Silurien inférieur du groupe de Wild Bight et des formations de Shoal Arm, de Sansom et de Crescent Lake.

Le groupe de Robert's Arm a été faillé de façon complexe et comprend un terrane plus ancien de lambeaux de basalte tholéiitique ou alcalins sur lesquels repose un terrane de lambeaux de composition plus calco-alcaline. Chaque terrane se compose surtout de basaltes massifs, de laves en coussins et de brèches en coussins, ainsi que de quantités inférieures mais variables de roches volcaniques felsiques et de sédiments clastiques. En général, il est impossible de distinguer les basaltes des deux terranes sur le terrain, mais l'étude de lames minces indique que normalement, des phénoblastes de clinopyroxène sont plus communs dans le terrane calco-alcalin tandis que des phénoblastes de plagioclase sont plus communs dans le terrane tholéiitique.

Les basaltes du terrane tholéiitique reposent sur le schiste argileux, le chert et le grauwacke de la formation de Crescent Lake et y sont intercalés. De petites unités volcaniques felsiques dans ce terrane ont une composition généralement microgranitique et sont associées à d'importantes quantités de matériaux pyroclastiques; par opposition, les unités volcaniques felsiques du terrane calco-alcalin sont surtout de nature amygdaloïde quartzeuse et contiennent des matériaux pyroclastiques moins proéminents; ces unités sont concentrées dans de grands centres. Des plutons granitiques épizonaux ont été mis en place à l'intérieur et le long de la marge du terrane calco-alcalin, après la première déformation du terrane tholéiitique mais avant la fin de la période de volcanisme calco-alcalin. Des dômes felsiques et quelques coulées de cendres se présentent contre le granite et par endroits, se transforment en celui-ci. De petits diatrèmes datent de la période de plutonisme granitique.

En général, le groupe de Robert's Arm a été métamorphisé presqu'à l'étape des schistes verts (prehnite-pumpellyite). L'analyse à la micro-sonde électronique montre que la substitution de l'aluminium par le fer ferrique devient plus marquée en travers du groupe, du terrane tholéiitique vers le terrane calco-alcalin. Des auréoles métamorphiques du faciès de l'épidote-amphibolite se trouvent le long des contacts granitiques non faillés, le long des marges ouest (soulevées) d'un certain nombre

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* La nouvelle datation du zircon U-Pb, 479 ± 3 Ma pour le plagiogranite de Mansfield Cove (Dunning et coll., 1987) suggère que ce pluton se situe au début de l'Ordovicien et qu'il est seulement un peu plus vieux que le groupe de Robert's Arm.

the calc-alkaline terrane, and in a zone of regional metamorphism which transects the southwest extremity of Robert's Arm Group. Robert's Arm Group is mostly steeply dipping and west-to northward-facing, but blocks of reverse facing directions are present in the southwest and northeast. In the southwest this deformation preceded emplacement of granite and related felsic volcanism, but in the northeast the felsic volcanics are folded. The deformation may be related to thrusting from the northwest (convex side) of Robert's Arm Group. Later northward tilting of Robert's Arm Group, indicated by northward overturning of Springdale beds along Lobster Cove Fault, appears to increase in intensity eastward. Spectacular, gently south-southeast plunging slickensides within Robert's Arm basalts, near the northeast extremity of the group, may have formed late in the period where back tilting was strongest. This deformation presumably occurred during Devonian-Acadian Orogeny when deformation of sediments farther east in Notre Dame Bay is thought to have occurred.

Chemical analyses of both clinopyroxene and whole-rock basalt samples confirm differences in original chemical composition of spilitic basalts in the two Robert's Arm terranes. Classification of clinopyroxene indicates that matrix grains from the tholeiitic terrane fall in the alkali to anorogenic tholeiite fields. Matrix grains from the calc-alkaline terrane fall mostly in the orogenic tholeiite to calc-alkaline fields. Direct comparisons of pyroxene chemistry indicate that FeOt, MnO and Na_2O are significantly high, TiO_2 may be high, and MgO may be low in grains from the thoeiitic terrane. Comparisons of whole-rock analyses from least altered slices of the tholeiitic terrane with those from the calc-alkaline terrane suggest that TiO_2 and FeOt are significantly enriched and P_2O_5 depleted in these rocks with respect to basalts of the calc-alkaline terrane. The most altered rocks of the tholeiitic terrane comprise a basalt-pillow lava-breccia slice that is uniquely TiO_2-rich (mean TiO_2 wt. % 1.74-1.93). They likely represent the faulted remnant of a small seamount.

Chemical alteration of the basalts occurred in at least two phases. Spilitization, involving variable but intimate carbonate addition and Si-Na-Ca mobility, was ubiquitous. Similar but more severe and localized alteration with mobility of some additional elements, occurred at sites of hydrothermal activity about Pilley's Island Mine, perhaps near the Crescent Lake Mine, and elsewhere. These alterations occurred during and soon after volcanism. Later alteration of basalts along the basal fault contact of Robert's Arm Group is suggested by enhanced but erratic lithium contents. This alteration is focussed where underlying shales in Sops Head Complex appear to be tectonically thickened, and it spreads upwards across major fault boundaries into overlying basalts. Its distribution suggests

de failles qui coupent le terrane calco-alcalin et dans une zone de métamorphisme régional qui traverse l'extrémité sud-ouest du groupe de Robert's Arm. La plus grande partie du groupe a un pendage brusque et une orientation ouest à nord; cependant, certains blocs au sud-ouest et au nord-ouest ont une orientation inverse. Au sud-ouest, cette déformation a précédé la mise en place du granite et le volcanisme felsique connexe, tandis qu'au nord-est, les roches volcaniques felsiques sont plissées. La déformation pourrait également être liée au chevauchement vers les nord-ouest (côté convexe) du groupe de Robert's Arm. Le déversement vers le nord des couches de Springdale le long de la faille de Lobster Cove révèle que plus tard, il y a eu basculement vers le nord du groupe de Robert's Arm; l'intensité du basculement aurait augmenté vers l'est. De spectaculaires miroirs de faille qui plongent doucement vers le sud-sud-est se trouvent à l'intérieur des basaltes de Robert's Arm, prêt de l'extrémité nord-est du groupe; ces miroirs de faille pourraient s'être formés vers la fin de la période lorsque le basculement vers l'arrière était plus marqué. Cette déformation aurait eu lieu au cours de l'orogène du Dévonien-Acadien, période pendant laquelle des sédiments plus à l'est dans la baie Notre-Dame auraient été déformés.

L'analyse chimique d'échantillons de clinopyroxène et de l'ensemble du basalte confirme l'existence de différences dans la composition chimique originale des basaltes spilitiques des deux terranes de Robert's Arm. La classification du clinopyroxène indique que les grains de la matrice provenant du terrane tholéiitique font partie de la gamme des tholéiites alcalins ou anorogéniques. Les grains de la matrice provenant du terrane calco-alcalin appartiennent surtout au domaine tholéiitique orogénique ou calco-alcalin. Une comparaison directe de la chimie des pyroxènes indique que la teneur en FeOt, en MnO et en Na_2O est relativement élevée, que la teneur en TiO_2 peut être élevée et que la teneur en MgO peut être faible dans les grains provenant du terrane tholéiitique. Une comparaison des analyses de l'ensemble des roches tirées des lambeaux moins altérés du terrane tholéiitique et ceux du terrane calco-alcalin porte à croire que ces roches sont très riches en TiO_2 et en FeOt et pauvres en P_2O_5 par rapport aux basaltes du terrane calco-alcalin. Les roches les plus altérées du terrane tholéiitique forment un lambeau de basalte-laves en coussins-brèche qui est riche en TiO_2 seulement (pourcentage en poid moyen du TiO_2 de 1,74 à 1,93). Ces roches représentent probablement les restes faillés d'un petit guyot. L'altération chimique des basaltes a eu lieu en au moins deux phases. La spilitisation, qui comportait l'addition intime de quantités variables de carbonate et le déplacement de Si-Na-Ca, a eu lieu partout. Une altération similaire mais plus marquée et localisée, caractérisée par la mobilité de certains autres éléments, a eu lieu là où il y a eu activité hydrothermale aux alentours de la mine de Pilley's Island, peut-être près de la mine de Crescent Lake et ailleurs. Ces altérations se sont produites au cours de la période de volcanisme et peu après. La présence de teneurs irrégulières mais plus élevées en lithium indique qu'il y aurait eu altération plus récente des basaltes le long du contact de faille basale du groupe de Robert's Arm. Cette altération a été concentrée là où les schistes argileux sous-jacents du complexe de Sops Head semblent avoir été tectoniquement épaissis; elle devient plus répandue vers le haut en travers des principales limites de faille jusqu'à dans les basaltes sus-jacents. Sa répartition porte à that it may have occurred during thrusting of Robert's Arm Group over Sops Head Complex.

Interpretation of the tectonic setting represented by Robert's Arm Group must be speculative until the fault movements, both within and along the margins of the group, are better understood. Possibilities involving major strike slip and zone-wide allochthony exist. Nevertheless there is evidence of internal consistency between Robert's Arm fault slices. In this interpretation the assumption is made that movement of more than a few tens of kilometres has not occurred either on these or upon the west and southeast boundary faults.

The Robert's Arm Group is thought to have evolved at the outer edge of a back arc basin analogous to that interpreted east of Topsails terrane on the west margin of Dunnage Zone farther south. Early deep water sedimentation and eruption of tholeiitic to alkaline basalts began shortly before obduction of the ophiolitic complexes of western Newfoundland. Subsequent more clac-alkaline volcanism occurred in a tectonically active environment under shallow water conditions, perhaps about the time of continental collision. Southeastward thrusting of Robert's Arm volcanics over the Upper Ordovician shale-greywacke basin, and stacking of Robert's Arm fault slices, was followed by Lower Silurian deposition of Springdale redbeds. Dips were steepened and Springdale beds overturned northwards during Devonian deformation. Eastward oroclinal bending of the basalts about a near vertical axis near Robert's Arm accompanied late, right lateral movements on the Lobster Cove Fault. Alkaline dykes of presumed Mesozoic age were emplaced during opening of the modern Atlantic Ocean.

croire qu'elle se serait produite pendant que le groupe de Robert's Arm a chevauché le complexe de Sops Head.

L'interprétation du milieu tectonique représentée par le groupe de Robert's Arm demeurera incertaine tant qu'on aura pas éclairci l'histoire des mouvements de failles à l'intérieur et en bordure du groupe. Il pourrait y avoir eu décrochement et allochtonie dans l'ensemble de la zone. Néanmoins, il existe des indications d'une uniformité interne entre les divers lambeaux de faille du groupe. Cette interprétation suppose qu'aucun mouvement de plus de quelques dizaines de kilomètres ne s'est produit sur ces lambeaux ou le long des failles limites à l'ouest et au sud-est.

Le groupe de Robert's Arm aurait évolué le long de la marge externe d'un bassin d'arrière arc similaire à celui qui aurait existé à l'est du terrane de Topsails, plus au sud sur la marge ouest de la zone de Dunnage. La sédimentation en eau profonde et l'éruption de basaltes tholéiitiques et alcalins ont commencé peu avant l'obduction des complexes ophiolitiques de l'ouest de Terre-Neuve. Une période subséquente de volcanisme calco-alcalin a eu lieu en eau peu profonde, dans un milieu tectoniquement actif, peut-être au moment de la rencontre des continents. Le chevauchement vers le sud-est des roches volcaniques de Robert's Arm sur le bassin de schiste argileux-grauwacke de l'Ordovicien supérieur et l'empilage des lambeaux de faille de Robert's Arm ont été suivis par l'accumulation des couches de Springdale du Silurien inférieur. Il y a eu raidissement des pendages et renversement vers le nord des couches de Springdale au cours de la déformation dévonienne. La courbure oroclinale vers l'ouest des basaltes autour d'un axe quasi vertical près de Robert's Arm a eu lieu en même temps que des mouvements latéraux récents le long de la faille de Lobster Cove. Des filons alcalins vraisemblablement d'âge mésosoïque ont été mis en place au cours de l'ouverture de l'océan Atlantique actuel.

INTRODUCTION

The Robert's Arm Group, with its numerous ore mineral occurrences and nearly continuous coastal exposure, provides a type area for the application of studies of physical volcanology, volcanic sedimentation, petrography and petrochemistry to Paleozoic volcanic belts of the Canadian Appalachians. This bulletin presents a final report covering a 1:50,000 scale mapping and sampling program within the Robert's Arm Group in 1974-77. It provides evidence that the Robert's Arm Group is divisible into two parts: 1) a lower basalt unit of tholeiitic affinity which is thought to form part of the floor of a back arc basin upon which 2) an upper prominently bimodal local unit of more calc-alkaline affinity was deposited. Similar studies of correlative centres along the chain, leading to both comparison and contrast with the Robert's Arm Group, would provide a better understanding of both the chain itself and of the basin within which it was deposited.

Location and access

The Robert's Arm project area (parts of NTS 2E 5, 2E 12, and 12H 8) is restricted on the south and north respectively by 49° 20' and 49° 32' N; and on the east and west by 55° 33' and 56° 06' W (see Fig. 2, in pocket). Geologically it encompasses those rocks previously considered to belong to the Robert's Arm Group including the Sops Head Complex as far south as the junction of Tommy's Arm River with the creek from Loon Pond, and it includes parts of the Hall Hill Complex, Lushs Bight Group, sediments southeast of Robert's Arm Group, Springdale Group, and plutons intrusive into these rocks.

Access to the area may be attained either from the sea or along the Robert's Arm highway (route 380) from the Trans Canada Highway at South Brook. All parts of the area are within a day's working distance on foot from these and local logging roads.

Most of the area is thickly wooded. Snow cover may persist on northwest-and north-facing slopes until the end of May or the first week in June. The local hunting season begins in early September. Figure 1 lists geographical names used in this report and indicates their location within the map area.

Previous work

Mining of copper ore from the Crescent Lake mine was carried out in 1880 (Murray and Howley, 1881) and again in 1924 (Espenshade, 1937). Numerous mining companies have since examined the Robert's Arm area but until recently the only published work consisted of a compilation map with marginal notes (Dean and Strong, 1976) based in large part on Dean's work with Noranda Exploration Co. Ltd. The first geological reports on the Robert's Arm region were by Murray and Howley (1881, 1918). These were concerned with examination of mineral occurrences and with the geographic character of the coastal area.

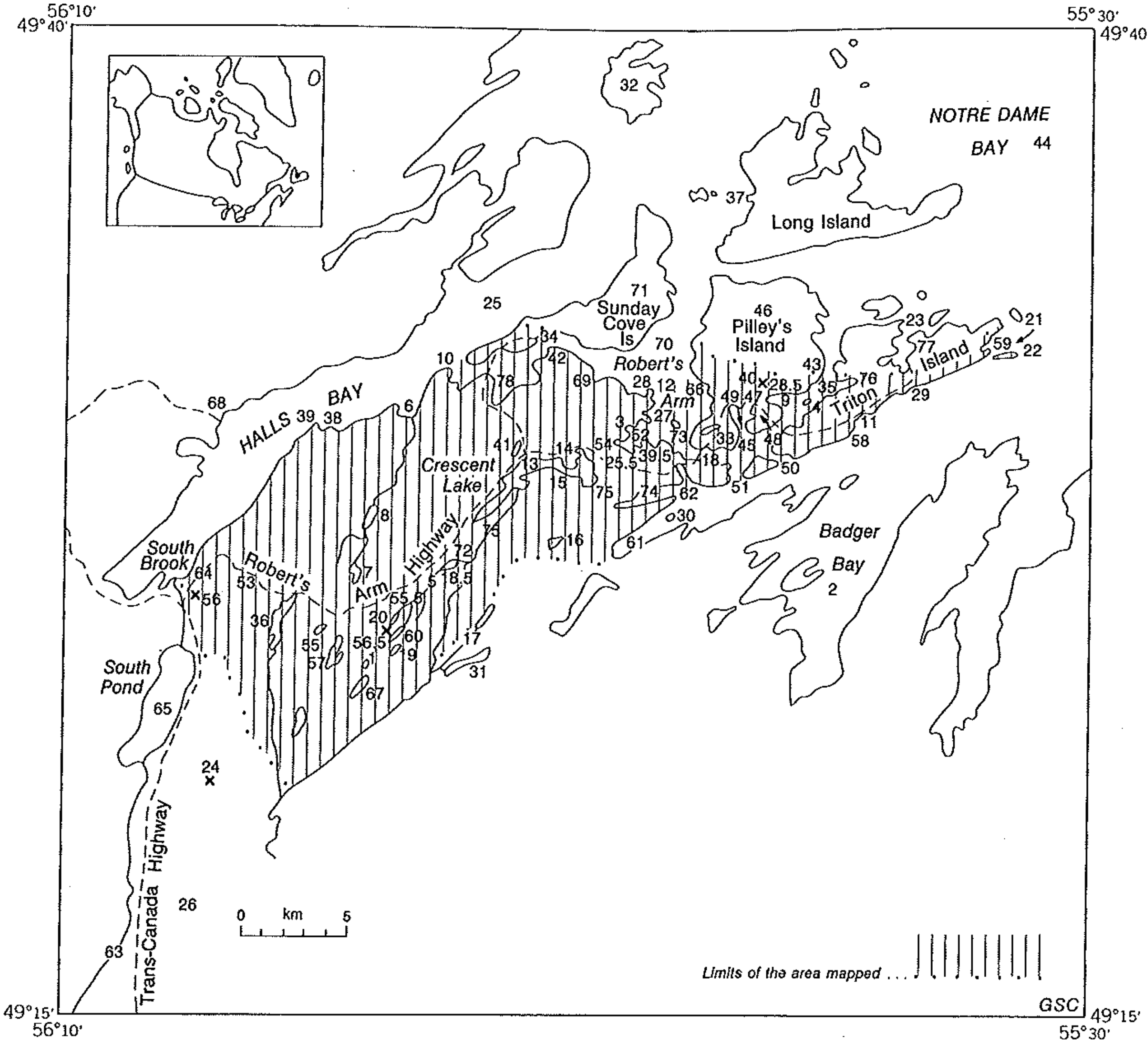
The first comprehensive mapping of the area was done by Espenshade (1937) between 1934 and 1936. He recognized the Lobster Cove lineament as a major fault and set up a stratigraphy which has only recently been modified. Espenshade's mapping was continued inland by Hayes (1951a, b) who recognized the existence of an important fault zone, extending southwest and south from the Sops Arm area, which he called the Burnt Creek fault zone. Williams (1962, 1964, 1969) integrated the work of earlier geologists in the Notre Dame Bay region and carried out reconnaissance mapping. His correlations provided the first comprehensive regional view of the geology of Notre Dame Bay.

Dean (1978) proposed that the Ordovician stratigraphy of the Central Mobile Belt is divisible into two volcanic arc sequences separated by a widespread Caradocian black shale marker horizon. This view, however, depends upon the assumption of continuity of stratigraphic sequence across a number of faults, and sits uneasily with radiometric Rb-Sr ages for the Robert's Arm Group of 455 Ma (Bostock et al., 1979), and of 447 Ma for the the Buchans Group (Bell and Blenkinsop, 1981). Dean suggested that rocks at Sops Head comprise a giant slump deposit initiated by tectonic disturbances resulting from the initiation of Robert's Arm volcanism.

Nelson and Casey (1979), Nelson and Kidd (1979), and Nelson (1981) examined coastal geology of central Notre Dame Bay from Sops Arm east. These authors considered that textures and structures in sedimentary rocks east of Robert's Arm Group indicate that some clastic sediments there were derived from the west or northwest. Nelson (1981) discovered conodonts of Llanvernian-Llandeilian age in limestone at Sops Arm which he believed to form allochthonous blocks within an olistostrome. In his view the limestone blocks were derived from a southeastward advancing Robert's Arm thrust sheet, and are analogous in stratigraphic position to the Cobbs Arm Limestone overlying Summerford basic volcanics on New World Island. This interpretation implies that the Robert's Arm Group is of minimum Llandeilian age in agreement with the age most likely on radiometric grounds.

Present work

Field work upon which this report is based was carried out with a single mapping team during the summers of 1974-77. Mapping was planned with traverses laid out perpendicular to regional strike at 800 m intervals, but where problems arose in the field, more thorough examinations were made. Emphasis was placed upon the search for indicators of stratigraphic sequence, particularly pillow tops, because it is clear that any attempt to understand the chemical stratigraphy of the basalts without first recognizing their correct stratigraphic sequence, is severely limited. Despite the resultant improvement in understanding of local structures it has still been necessary to assume stratigraphic relations across most of the more important bedding-plane faults in the area. A little



1. Anthony Pond
2. Badger Bay
3. Bear Cove
4. Big Island
5. Black Brook
6. Boot Harbour
7. Boot Harbour Pond
8. Boot Harbour Second Pond
9. Bumble Bee Cove
10. Burnt Head
11. Butlers Bight
12. Charley's Cove
13. Crescent Lake
14. Crescent Lake Mine
15. Crescent Lake Narrows
16. Fifields Pond
17. Five Island Pond Brook
18. Flat Rock Tickle
18.5. Fourth Pond
19. Fox Pond
20. Ghost Pond
21. Grand Dismal Cove
22. Great Dernier Island
23. Great Triton Harbour
24. Hall Hill
25. Hall's Bay
25.5. Hammer Cove
26. Hand Camp prospect
27. Hayward's Gull Island
28. Hayward's Head
28.5. Heads Pond
29. Jims Head
30. Kay Island
31. Kippins Pond
32. Little Bay Island
33. Loadabats Pond
34. Lobster Cove
35. Long Arm
36. Loon Pond
37. Lushs Bight
38. Mansfield Cove
39. Mansfield Head
39.5. Measles Cove
40. Mine Pond
41. Mud Pond
42. Nippers Harbour
43. Nogood Island
44. Notre Dame Bay
45. Penns Cove
46. Pilley's Island
47. Pilley's Island Mine
48. Pilley's Island village
49. Pilley's Tickle
50. Pretty Tickle
51. Raft Tickle
52. Robert's Arm
53. Robert's Arm Highway
54. Robert's Arm village
55. Rockey Pond
55.5. Round Pond
56. Rowsell Hill
56.5. Rust Pond
57. Sandy Pond
58. Sevier Point
59. Sisters Point
60. Ski Pond
61. Sops Arm
62. Sops Head
63. South Brook
64. South Brook village
65. South Pond
66. Spencer's Dock
67. Spot Pond
68. Springdale
69. Stag Cove
70. Sunday Cove
71. Sunday Cove Island
72. Third Pond
73. Tilley Cove
74. Tommy's Arm
75. Tommy's Arm River
76. Triton Island
77. Triton West village
78. Woodfords Arm

Figure 1. Map showing local place and topographic names.

more than one full field season was devoted to the collection of a representative sample of volcanic rocks of the Robert's Arm Group in five full and one partial section through the group. On Pilley's Island reconnaissance work suggested that the distribution of major map units as mapped by Espenshade (1937) is essentially correct. His work has therefore been incorporated in the present map with minor modifications.

Acknowledgments

Work was based from a cabin in the village of Robert's Arm, and the writer is indebted to Gerald Anthony, the proprietor, who provided advice on local matters and many services which contributed both to the comfort of the party and the success of the work. The writer was ably assisted in the field by Paul Code, Derek Wilton, David Scott, Marie Michaud, Bohdan Podstawskyi, Alain Leclair and Elizabeth Jull.

Analyses of rock samples were carried out by the analytical chemistry laboratory of the Geological Survey of Canada. Procedures used are outlined in Appendix 1.

Pleistocene geology

The northern part of the area is characterized by rounded rocky ridges reaching about 150 m above sea level. Drift cover is thin and discontinuous. Farther south the hills rise to over 200 m but are widely mantled by drift. This cover consists largely of pebbly to bouldery till with an abundant silty clay matrix that renders bush roads impassable soon after construction if adequate drainage is not provided. Characteristics of surficial deposits are displayed on surficial geology maps of the Robert's Arm and Springdale areas (Grant, 1973a, b).

Ice movement across the area during the Pleistocene was complex as shown by glacial striae (Fig. 3). The most common striae are north-northeasterly directed swinging to east-northeast in the northeast part of the area. Near Halls Bay a northwesterly trending set of striae appears to be superimposed on the common set at moderate to high acute angles. Farther east near Tommy's Arm River, striae of the two sets appear to converge. This may reflect a late drawdown of ice into the Halls Bay depression. On Sunday Cove Island the main striae have been found superimposed upon an earlier northwest-southeast-trending set that is less likely to be due to late drawdown into Halls Bay. Similar crossing striae, for which relative ages are not known, occur near Crescent Lake. It appears therefore that earlier ice may have moved across the grain of the country in a northwest or southeast direction.

Glacial erratics displaying a wide variety of lithologies, principally massive to gneissic hornblende gabbro, amphibolite, granites and volcanic rocks, are common. Counterparts to these lithologies outcrop widely in the Hall Hill Complex, in areas underlain by the Springdale Group and in the Lushs Bight terrane, that occur respectively to the south, west and north of the map area. Sedimentary rocks including lithologies similar to the Ordovician greywackes of the Exploits Group to the east and south appear less common. Occasional erratics of irridescent anorthosite, some weighing several tons, were observed along the shores of Tommy's Arm. These could have been brought in from the north by icebergs which commonly appear in Notre Dame Bay during the spring and early summer months. On the other hand they may perhaps have been transported by glaciers from the Long Range mountains where anorthosite is known to outcrop within the Grenville gneiss complex (Baird, 1959).

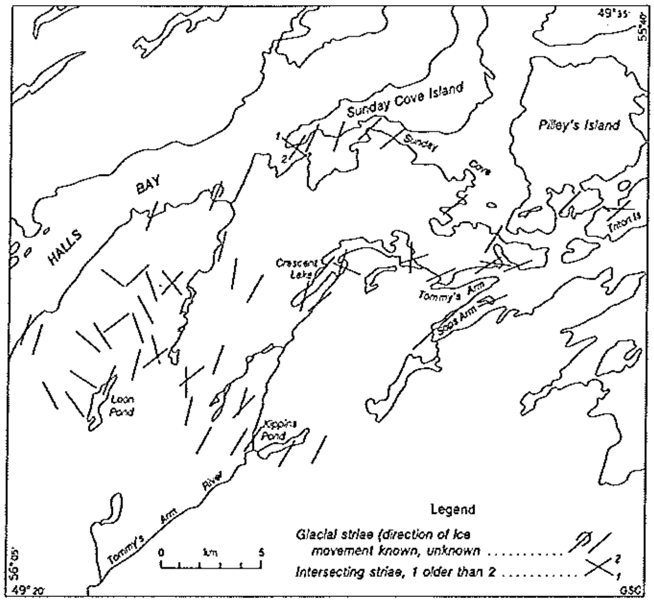


Figure 3. Sketch map showing glacial striae in the Robert's Arm Group Area.

The limited data suggest that northward-to eastward-moving ice was most effective in producing the striae that are preserved. Earlier ice transport of erratics from the west and northwest may be suggested by the occurrence of anorthosite boulders and may be responsible for some of the striae intersecting the main pattern. Ice movement from the southeast in the Crescent Lake and South Brook regions has been suggested by Lundqvist (1965) but no affirmative evidence of this movement has been collected during the present study. More thorough analysis of striae and drift will be necessary to fully establish the direction and sequence of ice movements in the Robert's Arm area.

GENERAL GEOLOGY

General statement

The Robert's Arm Group comprises an assemblage of mostly submarine volcanic rocks of Middle Ordovician age that lies at the northwest margin of the Dunnage tectonostratigraphic zone, a regional tectonic unit within the northern Appalachian orogen. The Robert's Arm Group (sensu stricto) is confined to a relatively well exposed local volcanic belt some 50 km long about Robert's Arm. Similar rocks of similar age, in somewhat similar settings are, however, exposed to the southwest to Buchans and beyond (Buchans Group, Thurlow, 1981), and as far east as New World Island (Chanceport Group, Strong and Payne, 1973), forming a discontinuous chain, the Robert's Arm belt (sensu lato), close to 250 km long. All of these belts of volcanics are fault bounded.

The oldest rocks* in the Robert's Arm region (late Precambrian, Bostock et al., 1979) comprise a heterogeneous assemblage, the Hall Hill Complex, including both volcanic and plutonic mafic rocks of tholeiitic affinity, and sialic rocks derived presumably from remelting, rifting and thinning of older crust. These rocks and their correlatives in the Hungry Mountain complex of the Buchans area (Whalen and Currie, 1983) to the south, contain very little sedimentary or metasedimentary material. They form a major component of the uplifted regional fault belt, which lies immediately west of Robert's Arm Group, and which, in attenuated form, likely contributes to the basement upon which the Robert's Arm Group rests. The Lushs Bight Group, ocean floor basalts, of possible Early Middle Ordovician age, are separated from the Robert's Arm belt in the north by the Lobster Cove Fault. Major movements occurred along this fault in post early Silurian time and hence the original relationship between Lushs Bight and Robert's Arm terranes is obscure. Age constraints and tectonic setting of Lushs Bight terrane indicate that it could have formed at a later date during the same era of sea floor spreading which began with emplacement of the Long Range Dyke Swarm and perhaps with evolution of the Hall Hill Complex and related rocks. Whether this spreading took place at a mid ocean ridge or within a marginal basin has been a matter of debate (Upadhyay et al., 1971).

The Robert's Arm Group of Middle Ordovician age, probably evolved initially as part of a back arc basin within which the later basalt eruptions took place in association with sialic plutonism and volcanism. Similar volcanic successions are known in the Cottrels Cove Group of central Notre Dame Bay (Strong, 1977) and possibly in the Chanceport Group of eastern Notre Dame Bay (Strong and Payne, 1973), intervening areas being covered by the sea. To the southwest bimodal volcanic rocks of the Buchans Group (Thurlow, 1981; Whalen and Currie, 1983) closely resemble the Robert's Arm Group and are of identical Middle Ordovician radiometric age. Although intervening areas are heavily drift covered, scattered occurrences of similar volcanics are known (Kalliokoski, 1953, 1955; Upadhyay and Smitheringale, 1972).

The southeastern margin of the Robert's Arm belt, where it is exposed, mostly lies along a regional tectonic zone (Sops Head Complex in the Robert's Arm region). Southeastward thrusting is thought to have been locally active along most of the belt. In places slices of older basement overrode the Robert's Arm belt, as at Buchans (Thurlow, 1981), whereas elsewhere Robert's Arm volcanics may have advanced as a thrust sheet eastward over the contemporary shale-greywacke basin to the southeast and shed coarse detritus into it (Nelson, 1981). This deformation occurred at approximately the same time as Middle Ordovician allochthony in western Newfoundland. It was followed by tilting, and by strike slip faulting of unknown magnitude, within the group.

The Springdale redbeds, extensively exposed to the west of the present map area, were deposited during Lower Silurian time, after uplift of Robert's Arm Group above sea level. They include clasts derived from contemporaneous volcanism as well as from sedimentary and plutonic terranes, and the emergent Robert's Arm Group. Within the mapped area it appears that the Springdale outliers, which locally include talus-like breccia beds, were deposited in a shallow water environment along a rugged shore line or fault scarp.

Following Middle Ordovician deformation, uplift, Early Silurian faulting and Springdale deposition, the Robert's Arm area and parts of Newfoundland farther east underwent regional Devonian (Acadian) orogeny. Steepening of earlier developed Robert's Arm thrust sheets likely occurred during this orogeny. Potentially significant for the Robert's Arm area was the emplacement of major mafic to granitic plutons in the Hodges Hill region to the south which are of Early Devonian age. Regional metamorphic grade in the Robert's Arm Group rises southwards toward these plutons; and their presence in the core of the prominent northwestward bulge in the Central Mobile Belt south of western Notre Dame Bay may have contributed to oroclinal bending of the group about this core.

The latest event recorded in the area is the intrusion of alkaline dykes and minor intrusive bodies of presumed Mesozoic age. These are thought to have been emplaced during rifting associated with expansion of the present day Atlantic Ocean.

TABLE OF FORMATIONS

Hall Hill Complex

The term, Hall Hill Complex was first used by Currie (1976) to apply to a heterogeneous assemblage composed mainly of basalt, amphibolite, gabbro and diorite to the west and south of Loon Pond. Following earlier workers (Hayes, 1951a; Kalliokoski, 1953), Currie (1976) believed that amphibolites about South Brook were correlative in part to the Robert's Arm Group. The Mansfield Cove block to the north was considered to constitute a fault bounded unit of older rocks. Dating of plagiogranite* within this block (Bostock et al., 1979) subsequently showed that the rocks are indeed at least partly late Precambrian (594 ± 10 Ma). The present work suggests that there is a still older component of metabasalt which forms an important constituent of both the Mansfield Cove block and the Hall Hill Complex as originally described, and that the rocks of both units are in large part related to late

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* New U-Pb zircon data, 479 + or-3 Ma for Mansfield Cove plagiogranite (Dunning et al., 1987) suggest that this pluton is early Ordovician, only slightly older than Robert's Arm Group, rather than Hadrynian.

<table>
<tr><th colspan="11">Table of formations</th></tr>
<tr><th>Era</th><th>Period</th><th colspan="4">Formation</th><th colspan="4">Lithology</th><th>Thickness</th></tr>
<tr><td>Cenozoic</td><td></td><td colspan="4"></td><td colspan="4">Glacial drift, sand, gravel</td><td></td></tr>
<tr><td colspan="11">Unconformity</td></tr>
<tr><td>Mesozoic</td><td></td><td colspan="4"></td><td colspan="4">Alkaline basalt dykes</td><td></td></tr>
<tr><td colspan="11">Intrusive contact inferred</td></tr>
<tr><td rowspan="18">Paleozoic</td><td>Lower Silurian</td><td colspan="4">Springdale Group</td><td colspan="4">Red beds: sandstone, siltstone, conglomerate, talus</td><td>180 m</td></tr>
<tr><td colspan="10">Unconformity inferred</td></tr>
<tr><td>Upper Ordovician or Lower Silurian</td><td colspan="4">Sops Head Complex</td><td colspan="4">Slate, greywake, siltstone, basalt, greenschist, breccia, conglomerate, minor limestone</td><td></td></tr>
<tr><td colspan="10">Tectonic contact</td></tr>
<tr><td rowspan="4">Upper Ordovician</td><td colspan="5">West</td><td rowspan="13">Tectonic contact</td><td colspan="3">East</td></tr>
<tr><td colspan="3">Formation</td><td>Lithology</td><td>Thickness</td><td>Formation</td><td>Lithology</td><td>Thickness</td></tr>
<tr><td colspan="5" rowspan="2">Removed by erosion</td><td>Sansom</td><td>Sandy greywacke, conglomerate</td><td></td></tr>
<tr><td>Shoal Arm (Caradoc)</td><td>Black slate</td><td></td></tr>
<tr><td rowspan="8">Middle Ordovician</td><td rowspan="8">Robert's Arm Group</td><td colspan="4">Limestone (Llanvern-Llandeilllan), preserved as allochtnonous blocks in the Sops Head Complex</td><td rowspan="8">Wild Bight Group</td><td rowspan="8">Greywacke, chert; minor basalt and intraformational conglomerate</td><td rowspan="8"></td></tr>
<tr><td rowspan="2">Boot Harbour terrane</td><td>"Calc-alkaline" regime</td><td>Basalt, pillow lava, felsite, breccia; some chert, tuff, greywacke, gabbro; minor ash flows, diatreme breccia limestone</td><td rowspan="2">5000 m</td></tr>
<tr><td>Loon Pond and Sunday Cove Granite plutons</td><td>Granodiorite, quartz monzonite; some quartz diorite</td></tr>
<tr><td colspan="4">Faulted contact</td></tr>
<tr><td>Mud Pond terrane</td><td>"Calc-alkaline" regime</td><td>Basalt, pillow lava, breccia; some chert, greywacke, tuff, gabbro; minor felsite</td><td>3000 m</td></tr>
<tr><td colspan="4">Faulted contact</td></tr>
<tr><td rowspan="2">Crescent terrane</td><td>"Tholeiitic" regime</td><td>Basalt, pillow lava, breccia; some chert, slate, greywacke, felsite, gabbro; minor limestone</td><td>1500 m</td></tr>
<tr><td>Crescent Lake Formation</td><td>Unit A: grewacke; some chert, siltstone
Unit B: chert, siltstone, shale; some grewacke</td><td>1500 m</td></tr>
<tr><td colspan="6">Faulted contact</td><td colspan="3">Not in contact</td></tr>
<tr><td>Lower Middle (?) Ordovician</td><td colspan="4">Lushs Bight Group</td><td colspan="4">Basalt, pillow lava, breccias; some greywacke, chert, greenschist; minor diatreme breccia</td><td></td></tr>
<tr><td colspan="11">Concealed faulted contact</td></tr>
<tr><td rowspan="6">Precambrian</td><td rowspan="6">Hadrynian</td><td colspan="8">Hall Hill Complex</td><td></td></tr>
<tr><td colspan="4">South Pond gabbro</td><td colspan="4">Gabbro, amphibolite, basalt dykes</td><td></td></tr>
<tr><td colspan="9">Intrusive contact</td></tr>
<tr><td colspan="4">Mansfield Cove plagiogranite</td><td colspan="4">Plagiogranite with local inclusions of basalt, amphibolite fine grained hornblende gabbro, and hornblende diorite</td><td></td></tr>
<tr><td colspan="9">Intrusive contact</td></tr>
<tr><td colspan="4">Rowsell Hill basalts</td><td colspan="4">Massive amphibolite, pillow lava</td><td></td></tr>
</table>

GSC

Precambrian igneous activity in a pre-oceanic setting. It is proposed therefore to modify the term Hall Hill Complex to include all of these related rocks and to employ separate names for the individual components. Thus the older amphibolitic basalts and pillow lavas will be called the Rowsell Hill basalts after the hill east of the village of South Brook where they are well exposed and least broken up by fracturing. The intrusive plagiogranite of the Mansfield Cove block will be called the Mansfield Cove plagiogranite after the cove where this pluton reaches the coast at its northern end; and hornblende gabbro, which apparently intrudes the Mansfield Cove plagiogranite will be called the South Pond gabbro, recognizing that although parts of this unit have not been mapped during the current work, it probably reaches its greatest extent immediately east of South Pond. One further unit comprising heterogeneous granitic rocks, which may include equivalents of both the Robert's Arm Group and the Mansfield Cove plagiogranite, occupies a triangular area of poor exposure near the southern limit of mapping and will be referred to as the "southern wedge".

South of the map area rocks potentially related to the Hall Hill Complex occur in the Hungry Mountain Complex (Whalen and Currie, 1983), and perhaps in poorly known dioritic rocks along the west side of South Brook. These plutonic rocks thus extend as a possibly semicontinuous zone near the west margin of the Central Mobile Belt, deep into the heart of central Newfoundland.

Rowsell Hill basalts

The Rowsell Hill basalts are extensively exposed in a triangular area southeast of Mansfield Head on Halls Bay, and farther south on Rowsell Hill east of the village of South Brook where the type section is located. They consist predominantly of massive dark green amphibolitic basalt, but locally remnants of pillow lava have been preserved. Along the coast near Mansfield Head the rocks are so fractured that only suggestions of pillows can be discerned, but farther south along the coast near South Brook and on Rowsell Hill pillows showing distinctive black margins due to crystallization of amphibole are present. On the east flank of Rowsell Hill the pillow lavas are somewhat lighter coloured and amygdule-like texture is locally present, but the rock is still amphibolitic. Unlike many pillow lavas within Robert's Arm Group, no chert or greywacke was found in pillow interstices or as thin beds between pillowed flows. Pillow lavas on the north spur of Rowsell Hill are distinctly plagioclase phyric with plagioclase phenocrysts up to 4 mm, whereas other pillow lavas appear more equigranular. Both amphibolitic basalts and pillow lava are abundantly intruded by irregular to dyke-like bodies ranging from equigranular basalt through plagioclase-phyric basalt to fine- and locally medium-grained gabbro. Felsite, aplite and granitic dykes are present locally and some of the felsic dykes are equigranular, some are plagioclase-phyric and some are both quartz- and plagioclase-phyric. Pillows on the north spur of Rowsell Hill face northwestward and those on the east flank of Hall Hill appear to dip about 70° westward. Pillow outlines exposed at low tide near the south contact of the Mansfield Cove plagiogranite appear also to face westward, but no other pillow top localities are known.

In thin section the pillow lavas consist primarily of green amphibole and intermediate plagioclase. Plagioclase phenocrysts showing strong normal zoning are common, but in the more altered specimens this texture is destroyed and two generations of amphibole may be present. Altered magnetite-ilmenite with associated grains of sphene is present in many specimens. Unlike pillow lavas of the Robert's Arm Group, chlorite is typically either absent or present only in traces, and epidote is only locally an important constituent suggesting that regional metamorphism of the Rowsell Hill basalts is higher grade (upper greenschist or amphibolite facies) than that in most of the Robert's Arm Group (prehnite pumpellyite to greenschist facies). Thin sections from most of the amphibolites examined resemble those of the pillow lavas but some contain mafic phenocrysts in which remnants of clinopyroxene are in varying degrees preserved within amphibole. Such specimens may have come from dykes whose contacts were not evident in the outcrops sampled. Thin sections from dykes intrusive into the Rowsell Hill basalts commonly contain similar remnants of primary clinopyroxene.

The contacts of the Rowsell Hill basalts are poorly exposed, however, individual outcrops show small bodies of plagiogranite intrusive into amphibolite, and inclusions of amphibolite are found within the Mansfield Cove plagiogranite. Pillow lavas along the southeast coast of Halls Bay are intruded by granitic veins. The plagiogranite is therefore believed to be intrusive into the basalts along their contacts.

Mansfield Cove plagiogranite

The Mansfield Cove plagiogranite pluton with type area at Mansfield Cove, is the principal component of the Hall Hill Complex north of Robert's Arm highway. It consists chiefly of white weathering, white to grey-green, medium grained, massive to foliated plagiogranite. Distinctive bluish quartz grains up to 5 mm in diameter, form 20 to 30% of the rock. Where the rock is foliated the quartz can locally be seen to lie in a lineation. Hornblende, which commonly forms up to 10% of the rock, is extensively chloritized, and epidote is present either disseminated or in veins at many localities. Inclusions of basalt, amphibolite, fine grained hornblende gabbro, and hornblende diorite can be found at various localities, and dykes of basalt and fine grained gabbro commonly intrude the plagiogranite. Quartz-phyric felsic rocks appear to be gradational to plagiogranite along the inland contact of the pluton southeast of Mansfield Head. Other plagioclase-phyric felsites and aplites, though less common, are intrusive into the plagiogranite. One outcrop along the shore of Halls Bay contains pink potasium feldspar in pegmatitic segregations.

In thin section the plagiogranite is hypidiomorphic with subhedral plagioclase showing altered cores and rims zoned from oligoclase to albite. Quartz forms discrete grains or polycrystalline aggregates. Hornblende is blue green and also forms polycrystalline aggregates with chlorite and locally biotite suggesting recrystallization. Epidote is a minor mineral in most thin sections and muscovite is present in some. Accessary minerals are magnetite, apatite and zircon. Pumpellyite was found locally in veins cutting the plagiogranite.

Microscopic textures in quartz-phyric felsites southeast of Mansfield Head, along the margin of the plagiogranite, are particularly interesting. Samples show grain size variations gradational to those of the plagiogranite. Quartz phenocrysts, like those in many hypabyssal felsites, show bipyramidal euhedral form with deep embayments, and late overgrowths. In some specimens bipyramidal quartz shows strain lamellae that are parallel within any one crystal but show random variation between crystals suggesting that the quartz was deformed prior to final emplacement. Grain size variations appear to suggest a chilled marginal zone but outcrops are not sufficiently numerous or continuous to demonstrate this. Alternatively, it is possible that the contact may be tectonic with the contact zone extensively lubricated by post-granite felsic intrusion, or the felsic rocks may have been remobilized during emplacement of late mafic (micro-gabbro) magmas.

The contact zone of the Mansfield Cove complex with the Robert's Arm Group is best exposed at Mansfield Cove, and is poorly exposed along the Robert's Arm highway near Loon Pond. At Mansfield Cove plagiogranite with interbrecciated mafic dykes and inclusions becomes highly fractured as the contact is approached. Brown, very fine grained felsite of the Robert's Arm Group to the east, is also fractured and the precise contact is hard to pin-point within a few metres because of this fracturing. A clearly demarked, steep fracture plane or fault, which trends 20°, cuts the felsite within a few metres of the contact. Farther west, near the southern corner of Mansfield Cove, basalt near the plagiogranite is highly fractured (Fig. 4) and it appears that the contact is a fault, possibly a splay from that farther east. Along the Robert's Arm highway the westernmost rubble-covered outcrops of Robert's Arm Group are cut by near vertical fracture zones up to 8 m across within which the rock is finely broken up. These zones trend about 170°. The nearest granitic outcrops are less fractured. These features and the difference in metamorphic grade (epidote-amphibolite vs subgreenschist facies) on either side of the contact north of Loon Pond indicate that the Mansfield Cove plagiogranite has been faulted against the Robert's Arm Group.

The south contact of the Mansfield Cove plagiogranite is poorly exposed but the pattern of outcrops suggest that it trends roughly northwesterly. Numerous basalt-amphibolite dykes and inclusions further complicate its definition. One contact, however, is exposed in the narrow canyon immediately south of the highway. There the plagiogranite is foliated (striking 40° and dipping 85° east) and shows no change in grain size, but adjacent hornblende gabbro is massive and fine grained with a 2 cm zone apparently chilled against the granite. The contact trends roughly 65° dipping 75° east. The plagiogranite is therefore probably intruded by the hornblende gabbro which forms a major component of the Hall Hill Complex farther south.

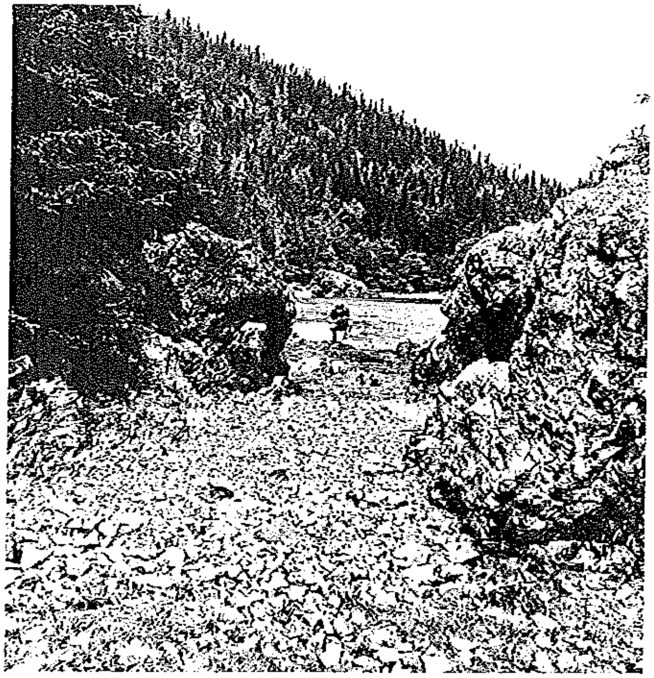

Figure 4. View west across Mansfield Cove showing fractured basalts of Hall Hill Complex (GSC 167141).

The contact between basalt and plagiogranite along the shore of Halls Bay south of Mansfield Head is complex. Near Mansfield Head the rocks consist of highly fractured basalt and micrograbbro containing a few broken up felsic dykes. Farther south more coherent breccias containing basalt, microgabbro, and locally felsite fragments in a microgabbroic matrix are present. In some of these breccias felsite occurs in amoeboid patches within a mafic matrix, possibly suggesting remelting of felsite. Still farther south fragments and irregular bodies of hornblende-epidote diorite appear in the breccias and these are cut by plagiogranite dykes that are themselves locally broken up in a basaltic matrix. In the vicinity of the contact these rocks merge into plagiogranite cut by basalt and micrograbbro dykes. Traverses inland show that the contact of the plagiogranite south of Mansfield Head is subparallel to the coast and that a discontinuous felsitic zone (possible chilled marginal phase) exists along this contact. This, and the brecciation farther within the wall rocks of the plagiogranite may indicate that the Mansfield Cove plagiogranite lies on its side with the Rowsell Hill basalts forming its roof. Such an hypothesis is consistent with the known westward facing pillow top determinations in the Rowsell Hill basalts.

South Pond gabbro

The South Pond gabbro is the predominant rock unit within a southward widening belt that lies between the Rowsell Hill basalts on the west and faults related to the Mansfield Cove fault on the east. Good exposures are present in a gulley just south of Robert's Arm highway and on the northwest face of one hill at the southern limit of mapping. The gabbro is dark green, medium grained and mostly massive. Basalt dykes intrude the gabbro, and some amphibolite bodies within it may represent inclusions of older basalt engulfed within the gabbro. Fine-and medium-grained gabbro dykes, presumably at least partly related to the South Pond gabbro, intrude the Rowsell Hill basalts.

In thin section the gabbro can be seen to consist of intermediate plagioclase and variably altered clinopyroxene with minor magnetite-ilmenite. Pyroxene tends to be severely altered to brown-green or blue-green hornblende. Minor amounts of epidote, chlorite and sphene are present in some specimens, and showed a cumulate texture with plagioclase-rich and pyroxene-rich bands.

Contacts of the South Pond gabbro are poorly exposed. Gabbro dykes penetrate the Rowsell Hill basalts and irregular patches of gabbro occur within the amphibolites near the contact. It therefore appears that the gabbro is intrusive along its west contact into the Rowsell Hill basalts. The west contact of the gabbro with the Mansfield Cove plagiogranite, exposed in the canyon south of Robert's Arm highway, appears chilled also indicating an intrusive relation. The east contact of the gabbro with basalts of the Robert's Arm Group is fixed within a few metres in the same canyon. Although the gabbro is little affected, the basalt shows a nonpenetrative foliation marked by chlorite slips as the contact is approached. Inasmuch as the contact lies close to the southward projection of the Mansfield Cove fault it seems likely that the South Pond gabbro is faulted against the Robert's Arm Group along its east contact. Farther south, some 1.6 km southwest of the south end of Loon Pond, a poorly exposed schistose zone exists within mafic rocks along the east margin of the metagabbro. Within this zone lenses of metagabbro up to 15 by 4 cm are elongated parallel to foliation in tough aphanitic greenschist. The schist zone is at least 3 m wide with schistosity striking north and dipping 75° east. Some 2 km farther south a second outcrop of greenschist lies about 100 m east of the easternmost gabbro outcrop. These occurrences of greenschist along the east margin of the gabbro provide a further indication that the contact is faulted.

Southern granite wedge

The southern granitic wedge is poorly exposed along the southeast side of the South Pond gabbro at the southern limit of mapping. It consists of fine- to medium-grained hornblende-bearing rocks of granitic to dioritic appearance with variable quartz and mafic contents. Some feldspar-phyric felsite megascopicaly resembling that of the Robert's Arm Group, is present on an isolated hill near the projection of Mansfield Cove Fault. Pink feldspar-bearing "granitic" rocks found in some outcrops proved to be leuco-quartz diorites. Because only a few outcrops were examined it is not known how typical these rocks are of the wedge as a whole.

In thin section both samples collected from the plutonic rocks are free of potasium feldspar and comparable in composition to the Mansfield Cove plagiogranite. Unlike most of the plagiogranite, however, textures vary from fine- to coarse-grained and one dioritic outcrop showed masses of hornblende clots roughly 1 cm in diameter.

Recent descriptions of the Handcamp prospect (de Ferriere, 1978), immediately to the south of the southern wedge, strongly imply that fine clastic sediments and volcanic rocks of the Robert's Arm Group host this deposit. The southern wedge is therefore most likely a fault-bounded wedge between Robert's Arm volcanics and Loon Pond pluton on the east, and South Pond Gabbro on the west. Within the wedge poorly exposed Robert's Arm Group may lie unconformably upon, or be faulted against, rocks of the Hall Hill Complex. The contact is not known to be exposed.

Mafic dykes

Mafic dykes intrusive into the amphibolites, plagiogranite, and gabbro are grey-green, fine-to medium-grained and mostly less than 3 m thick. Locally within the plagiogranite the host is foliated along their contacts, and chilled margins are evident within the dykes. In some dykes inclusions of plagiogranite are present, and a few contain epidote-chlorite-pyrite-bearing amygdules. In thin section the dykes are seen to be variably altered. All comprise plagioclase phenocrysts up to 2 mm and smaller mafic phenocrysts in a matrix rich in lathy plagioclase. In the less altered specimens plagioclase shows strong normal zoning about altered cores and original clinopyroxene has been only partly altered to hornblende-epidote-chlorite. In the more altered dykes clinopyroxene is absent, the zonal texture of plagioclase has been destroyed, and amphibole is locally present in more than one generation.

Dykes within the Mansfield Cove plagiogranite strike mostly from 2 to 90° and dip steeply northwest. Very shallowly dipping dykes do not appear to be present although such dykes might well be essentially invisible in the heavily drift covered terrain. The attitudes of 17 dykes taken from the shore of Halls Bay and cuts along the Robert's Arm highway are predominantly parallel to the margins of the plagiogranite. Steep dips likely indicate that the dykes which maintain their dyke-like form within the complex were emplaced primarily after it was tilted.

Chemical analyses

Samples of the Hall Hill Complex were collected at intervals of 150 m across the complex south of the highway, where outcrops of the mafic rocks are most numerous, as part of the chemical section sampling program for the

Table 1. Chemical analysis from the Hall Hill Complex

MAJOR ELEMENTS FOR ROCKS FROM THE HALL HILL COMPLEX

Station	Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2	S	F	Cl	FeO_t	Total
Pillow lavas																			
1082	A	49.90	2.10	16.40	4.30	7.20	.21	5.10	10.60	3.50	.26	.43	1.00	.10	.15	.04	.05	11.07	101.34
1117	A	48.90	1.77	14.30	4.00	8.30	.21	6.90	11.50	2.40	.44	.17	1.50	.10	.15	.02	.06	11.90	100.72
1115	A	48.90	1.63	14.90	2.60	8.40	.18	6.90	12.20	2.60	.30	.16	1.30	.09	.01	.02	.07	10.74	100.26
M		49.23	1.83	15.20	3.63	7.97	.20	6.30	11.43	2.83	.33	.25	1.27	.10	.10	.03	.06	11.24	
σ		.58	.24	1.08	.91	.67	.02	1.04	.80	.59	.10	.15	.25	.01	.08	.01	.01	.60	
Amphibolite																			
1029	B	45.20	2.05	13.50	3.30	9.10	.20	10.30	13.30	1.50	.23	.18	1.90	.01	.09	.03	.03	12.07	100.92
1030	A	51.10	.80	15.90	3.70	8.80	.20	5.90	8.60	2.90	.17	.06	2.10	.09	.11	.06	.04	12.13	100.53
1032	A	50.10	1.75	14.40	2.60	8.10	.20	7.60	10.40	3.60	.13	.18	1.10	.09	.11	.05	.04	10.44	100.45
1032	B	49.40	1.50	18.20	2.40	7.00	.17	5.60	12.30	3.10	.17	.14	1.10	.10	.19	.03	.04	9.16	101.44
1033	A	49.30	1.68	15.20	2.60	8.10	.21	7.70	10.80	3.10	.13	.17	1.30	.09	.02	.04	.06	10.44	100.50
1034	B	48.40	1.44	16.70	2.60	7.80	.17	6.90	13.00	2.00	.18	.14	1.30	.10	.02	.02	.04	10.14	100.81
1035	C	48.80	1.18	16.90	2.00	8.00	.17	8.10	10.90	2.60	.15	.19	1.80	.09	.22	.04	.02	9.80	101.16
1083	B	48.40	1.39	16.40	2.80	7.40	.18	6.70	14.00	2.30	.16	.14	1.30	.09	.07	.02	.10	9.92	101.45
1084	B	49.20	1.55	15.90	3.10	7.50	.20	7.20	12.00	2.60	.27	.14	1.20	.10	.01	.05	.11	10.29	101.13
1086	A	48.60	1.72	15.10	3.30	7.80	.21	8.20	10.60	2.80	.27	.17	1.40	.10	.03	.05	.08	10.77	100.43
1087	A	48.80	2.12	13.50	5.40	8.60	.23	7.40	10.70	2.80	.19	.27	1.30	.09	.08	.04	.07	13.46	101.59
1087	B	52.50	.55	17.10	3.70	6.00	.19	6.10	8.60	4.10	.29	.06	1.50	.10	.01	.02	.05	9.33	100.87
1088	A	50.00	1.75	15.50	2.60	8.30	.19	6.60	12.20	2.80	.17	.17	1.20	.09	.06	.03	.07	10.64	101.73
1088	B	45.20	1.20	14.40	1.80	7.80	.18	14.40	10.70	1.10	.12	.15	3.60	.09	.01	.02	.02	9.42	100.79
1089	A	50.60	.87	15.60	1.60	7.30	.17	7.80	12.10	2.00	.11	.08	1.60	.09	.07	.02	.01	9.24	100.52
M		49.04	1.44	15.62	2.90	7.87	.19	7.77	11.35	2.62	.18	.15	1.58	.09	.07	.04	.05	10.48	
σ		1.92	.45	1.33	.93	.75	.02	2.16	1.56	.77	.06	.05	.63	.02	.07	.01	.03	1.22	
Microgabbro																			
1031	A	50.20	2.36	14.20	3.90	8.90	.18	5.60	9.80	4.10	.15	.59	1.80	.09	.01	.03	.07	12.41	101.98
1034	A	46.20	.98	16.40	2.60	7.50	.19	9.30	11.00	2.10	.17	.26	3.20	.10	.06	.03	.02	9.84	100.11
1082	B	51.50	1.58	14.10	2.90	9.00	.20	6.70	9.20	3.30	.39	.33	1.70	.09	.07	.03	.07	11.61	101.16
1084	A	50.40	.95	17.40	2.60	7.60	.19	6.40	8.70	4.00	.48	.15	2.20	.09	.11	.02	.03	9.94	101.32
1118	A	49.70	2.38	13.50	5.20	9.10	.22	5.80	9.70	3.30	.39	.65	1.70	.09	.02	.05	.07	13.78	101.87
M		49.60	1.65	15.12	3.44	8.42	.20	6.76	9.68	3.36	.32	.40	2.12	.09	.05	.03	.05	11.52	
σ		2.01	.70	1.68	1.12	.80	.02	1.49	.86	.80	.15	.22	.64	.00	.04	.01	.03	1.68	
Gabbro																			
1029	A	44.30	3.54	14.40	6.10	11.50	.25	5.32	10.50	2.70	.17	.46	1.10	.01	.30	.04	.03	16.99	100.72
1035	A	48.90	1.78	15.30	2.80	8.30	.22	7.90	10.40	3.20	.27	.28	1.70	.10	.06	.03	.05	10.82	101.29
1116	A	51.30	2.25	14.60	4.00	9.30	.24	5.70	8.00	3.40	.34	.31	1.30	.10	.01	.02	.08	12.90	100.95
M		48.17	2.52	14.77	4.30	9.70	.24	6.31	9.63	3.10	.26	.35	1.37	.07	.12	.03	.05	13.57	
σ		3.56	.91	.47	1.67	1.64	.02	1.39	1.42	.36	.09	.10	.31	.05	.16	.01	.03	3.14	
Mafic dykes																			
1035	B	48.80	1.65	16.10	2.40	8.00	.18	7.20	11.80	2.40	.28	.18	1.20	.10	.07	.02	.05	10.16	100.43
1083	A	47.90	1.01	15.50	1.80	8.80	.18	8.60	12.50	1.80	.20	.09	2.10	.09	.19	.01	.03	10.42	100.80
1119	A	47.80	1.03	16.80	2.00	8.00	.14	9.80	9.40	2.20	1.31	.14	1.60	.09	.05	.03	.06	9.80	100.45
1119	B	52.00	.82	16.40	3.80	7.30	.19	5.70	5.90	5.40	.11	.08	2.20	.10	.23	.02	.03	10.72	100.28
1113	B	49.20	1.12	16.30	2.00	7.50	.18	9.00	9.00	3.20	.22	.13	2.70	.09	.07	.03	.02	9.30	100.76
M		49.14	1.13	16.22	2.40	7.92	.17	8.06	9.72	3.00	.42	.12	1.96	.09	.12	.02	.04	10.08	
σ		1.71	.31	.48	.81	.58	.02	1.62	2.61	1.44	.50	.04	.58	.01	.08	.01	.02	.55	
Plutonic and hypabyssal sialic rocks																			
1114	A	63.10	.85	14.50	5.30	4.90	.12	1.13	2.71	5.90	.45	.20	.90	.10	.01	.03	.03	9.67	100.23
1114	B	63.70	.87	15.70	4.80	5.00	.11	1.23	2.87	5.90	.44	.20	1.00	.09	.03	.03	.04	9.32	102.01
1090	A	68.80	.47	14.80	1.90	4.20	.13	.72	2.33	6.00	.25	.09	.70	.09	.01	.03	.04	5.91	100.56
1085	A	74.50	.32	13.60	.60	3.10	.05	.88	2.06	4.80	.35	.08	1.00	.09	.01	.03	.02	3.64	101.49
1091	A	74.40	.31	13.40	.50	2.70	.04	.65	2.50	4.40	.35	.07	.80	.10	.01	.03	.03	3.15	100.29
7427	B	65.00	.39	15.70	1.40	4.60	.12	2.08	4.10	4.60	.52	.07	2.20	0.00	0.00	0.00	0.00	5.86	100.78
7429	B	73.10	.24	13.70	.40	2.30	.05	.98	1.75	5.30	.55	.09	1.70	.20	0.00	0.00	0.00	2.66	100.36
7423	A	75.20	.20	13.60	1.10	1.30	.04	1.17	.76	5.50	.51	.06	1.20	0.00	0.00	0.00	0.00	2.29	100.64
4529	B	61.90	.67	17.40	.50	2.60	.12	.46	3.26	8.40	.27	.15	1.00	2.40	.09	0.00	0.00	3.05	99.22
4619	A	77.80	.11	11.70	.40	1.10	.02	.48	.97	4.80	.31	.02	.60	0.00	.04	0.00	0.00	1.46	98.35
4715	A	78.60	.19	11.40	.70	.60	.03	.23	.50	4.80	.35	.05	1.10	.20	.10	0.00	0.00	1.23	98.85
4864	B	72.90	.27	13.00	.70	2.50	.05	1.44	.75	5.80	.21	.03	1.40	.10	.04	0.00	0.00	3.13	99.19
M		70.75	.41	14.04	1.53	2.91	.07	.95	2.05	5.12	.38	.09	1.13	.28	.03	.03	.03	4.28	
σ		5.97	.26	1.71	1.71	1.50	.04	.51	1.13	1.07	.11	.06	.45	.67	.03	-	-	2.83	

TRACE ELEMENTS FOR ROCKS OF THE HALL HILL COMPLEX

Station	Sample	Li	Rb	Cs	Sr	Ba	V	Zr	Cu	Zn	Co	Ni	Cr
Pillow lavas													
1082	A	3	6	.1	287	115	364	177	64	70	52	40	68
1117	A	6	13	1.1	246	68	357	112	82	90	45	64	267
1115	A	6	8	1.6	293	56	329	139	66	80	49	80	246
M		5	9	.9	275	80	350	143	71	80	49	61	194
σ		2	4	.8	26	31	19	33	10	10	4	20	109
Amphibolite													
1029	B	10	6	.7	152	37	360	31	12	31	32	69	233
1030	A	3	3	.1	200	35	458	34	95	90	26	9	19
1032	A	2	1	.1	243	32	271	92	107	100	34	55	254
1032	B	2	3	.8	266	62	229	69	103	90	24	55	226
1033	A	6	2	1.2	235	35	224	73	119	100	26	45	221
1034	B	2	4	1.2	215	39	253	63	69	80	27	47	236
1035	C	10	4	.1	181	37	237	47	71	80	28	118	316
1083	B	3	4	.5	235	44	303	72	72	80	47	68	249
1084	B	3	7	.6	240	45	275	67	39	90	36	55	275
1086	A	3	3	1.2	195	51	336	120	76	90	60	56	160
1087	A	3	3	1.0	211	46	341	118	34	90	42	39	63
1087	B	3	6	1.0	228	67	310	44	20	70	44	9	4
1088	A	4	4	.7	202	44	324	105	100	100	45	42	247
1088	B	7	4	1.8	170	22	184	85	117	120	66	364	610
1089	A	5	3	2.1	168	62	280	67	91	60	42	79	204
M		4	4	.9	209	44	292	72	75	85	39	74	221
σ		3	2	.6	32	12	67	28	35	20	13	84	142
Microgabbro													
1031	A	3	2	.1	234	18	362	69	11	70	29	9	11
1034	A	5	5	1.0	212	57	202	40	89	80	20	78	200
1082	B	4	7	.2	201	98	314	100	274	60	37	43	55
1084	A	3	11	.8	252	176	230	43	68	90	30	23	31
1118	A	6	11	.6	220	116	429	209	53	60	40	41	50
M		4	7	.5	224	93	307	92	99	72	31	39	69
σ		1	4	.4	20	60	93	70	102	13	8	26	75
Gabbro													
1029	A	6	1	2.3	281	56	732	130	40	90	60	38	19
1035	A	5	5	.1	197	48	261	98	52	90	29	71	203
1116	A	3	8	.6	262	72	253	142	29	80	51	22	5
M		5	5	1.0	247	59	415	123	40	87	47	44	76
σ		2	4	1.2	44	12	274	23	12	6	16	25	110
Mafic dykes													
1035	B	8	1	.4	216	43	242	80	76	80	27	63	215
1083	A	5	6	.5	227	144	312	52	148	70	49	88	223
1119	A	10	15	1.6	235	85	256	147	113	80	38	69	243
1119	B	6	3	.9	75	23	285	73	52	100	30	9	7
1113	B	8	7	.1	207	141	244	84	109	80	37	108	121
M		7	6	.7	192	88	268	87	100	82	36	67	162
σ		2	5	.6	66	54	30	36	37	11	9	37	98
Plutonic and hypabyssal sialic rocks													
1114	A	3	9	.8	243	116	19	268	33	50	12	9	4
1114	B	4	9	.7	213	125	19	445	42	40	18	9	4
1090	A	4	4	.9	127	142	19	778	51	30	9	9	4
1085	A	5	6	.3	124	167	19	249	31	20	9	9	4
1091	A	3	8	.9	134	197	19	300	15	10	9	9	4
7427	B	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
7429	B	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
7423	A	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
4529	B	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
4619	A	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
4715	A	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
4864	B	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
M		4	7	.7	168	149	19	408	34	30	11	9	4
σ		1	2	.2	56	33	0	221	13	16	4	0	0

Note: M = mean
σ = standard deviation

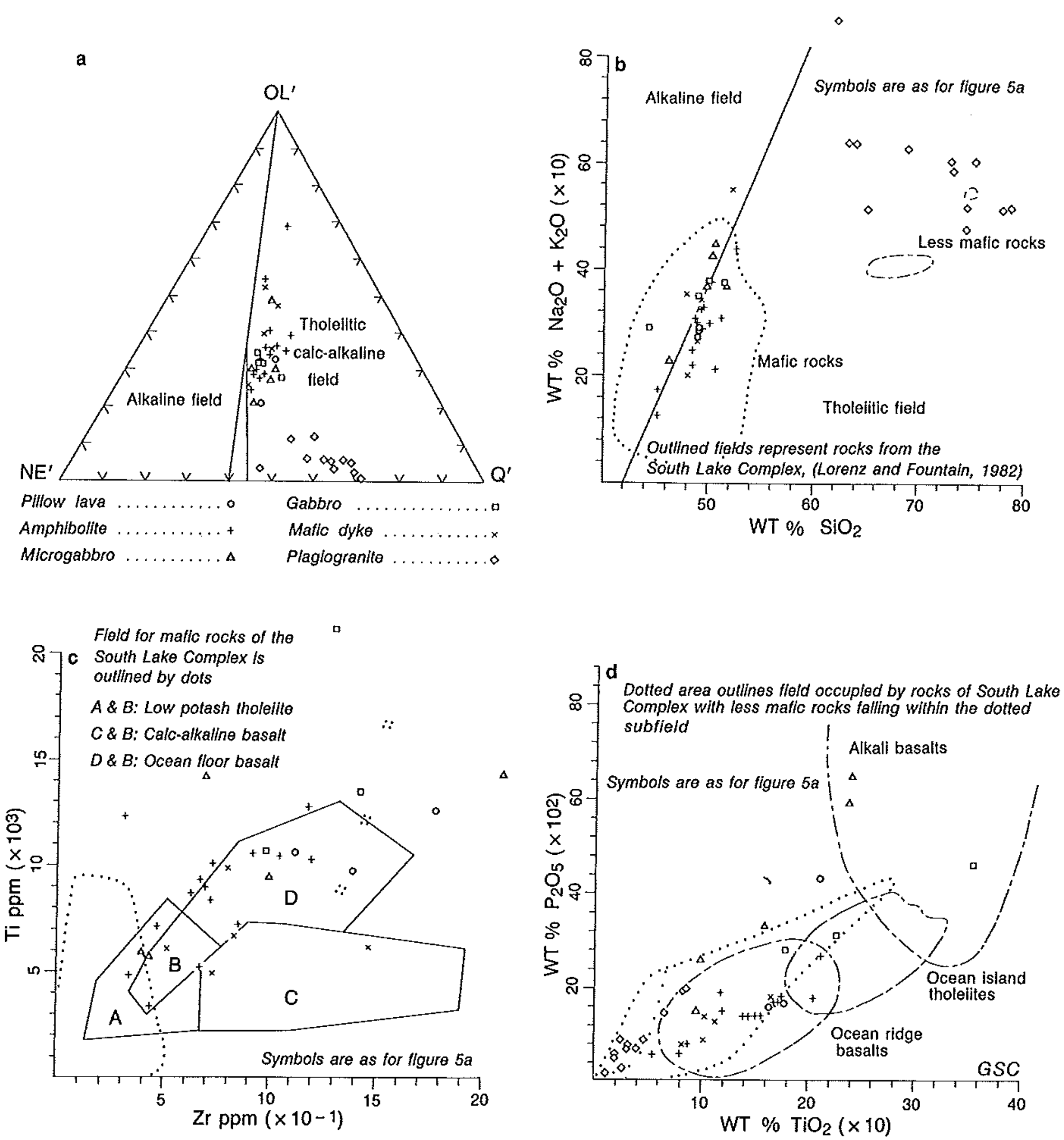

Figure 5. Rock classification, Hall Hill Complex. a. Nepheline'-olivine'-Quartz' diagram of Irvine and Baragar (1971) with tholeiitic-alkaline field boundaries. b. SiO_2 vs. Na_2O + K_2O plot showing MacDonald-Katsura (1964) alkaline-tholeiitic field boundary. Symbols are as for Figure 5a. Fields for mafic rocks (dots) and for less mafic rocks (dashes) from the South Lake Complex (Lorenz and Fountain 1982) are outlined. c. Zr vs. Ti plot showing fields of Pearce and Cann (1973). Symbols are as for Figure 5a. Field for mafic rocks of the South Lake Complex is outlined by dots. d. TiO_2 vs. P_2O_5 plot showing dashed field boundaries of Bass et al. (1973). Symbols are as for Figure 5a.Dotted area outlines field occupied by rocks of South Lake Complex with less mafic rocks falling within the dotted subfield.

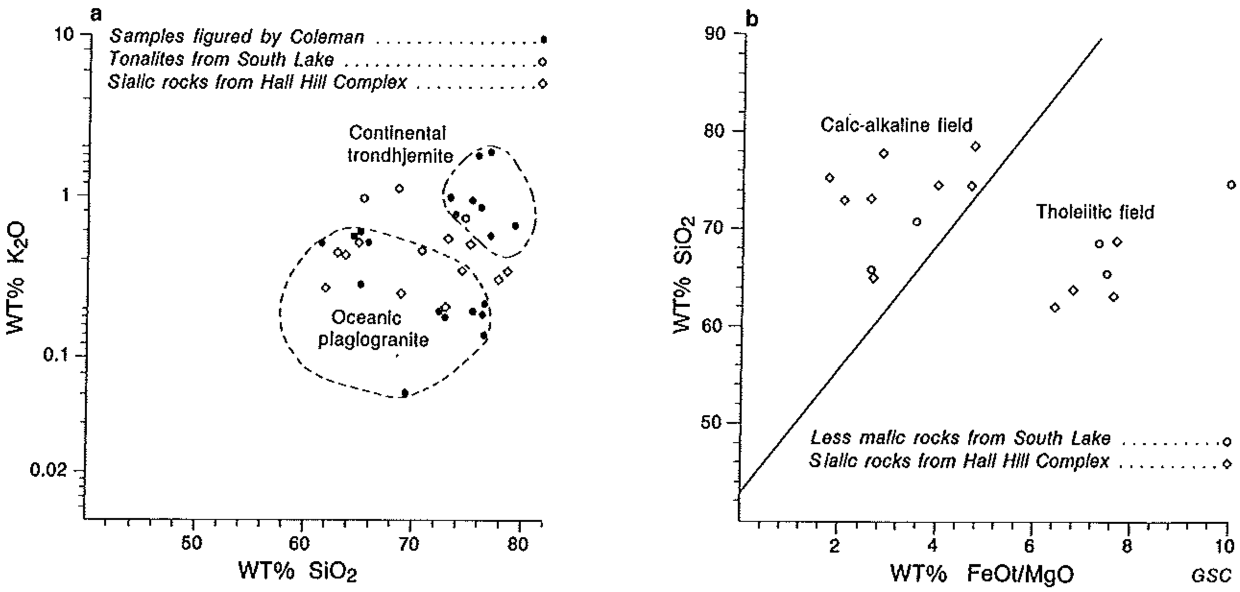

Figure 6. Mansfield Cove Plagiogranite. a. SiO_2 vs. K_2O plot with field boundaries of oceanic plagiogranite and continental trondhjemite of Coleman (1977). b. FeOt/MgO vs. SiO_2 plot showing the calcalkaline-tholeiitic field boundary of Miyashiro (1975).

Robert's Arm Group. Samples of the plagiogranite were collected mostly from highway cuts and from the shore of Halls Bay immediately to the west. This selection was augmented after completion of the field work, by analyses of hand specimens from felsic hypabyssal rocks intrusive into the complex, and by three analyses of plagiogranite provided by K.L. Currie of the Geological Survey of Canada. The location of the chemical section through the Hall Hill Complex is shown in Figure 37, and the results of the analyses are shown here in Table 1.

The samples can be divided into six lithological groups: 1) pillow lavas, 2) undivided amphibolites, 3) fine grained gabbro in small intrusive bodies, 4) medium grained gabbro, 5) mafic dykes, and 6) plutonic and hypabyssal sialic rocks. Rocks of the Hall Hill Complex have been raised to upper greenschist-lower amphibolite facies of metamorphism but the mafic rocks show less evidence of chemical alteration than do those of either the Lushs Bight or Robert's Arm groups. Unlike those of the Lushs Bight Group or Robert's Arm Group, corundum is rarely present in norms of the Hall Hill basalts.

Table 1 suggests that most of the various mafic lithologies of the Hall Hill Complex are not chemically distinct. Medium grained gabbros and the mafic dykes, the two most distinctive mafic members of the complex, have different TiO_2, P_2O_5, FeOt and Al_2O_3 contents, but other differences are not statistically significant.

Comparison of the mafic rocks of Hall Hill Complex with modern volcanic suites using various major element diagrams indicates that they are characteristically tholeiitic to intermediate (Fig. 5a and 5b illustrate this point). In Figures 5c and 5d, which involve relatively immobile elements least subject to possible effects of alteration, the mafic rocks fall in fields of ocean floor basalts and low potash tholeiites. In this respect, as will be seen, they are like the basalts of the southeastern and probably older part of the Robert's Arm Group, and are distinct from those in the more westerly and northerly parts of the group.

Chemical analyses of the Mansfield Cove pluton are plotted in Figure 6a (after Coleman, 1977) together with samples from South Lake Complex (Lorenz and Fountain, 1982). The figure illustrates the low potash content typical of plagiogranite in most of these rocks. A plot of FeOt/MgO ratios vs. SiO_2 (Fig. 6b) for rocks from both complexes suggests possible differentiation of the sialic rocks into two groups on this basis.

Age, correlation and tectonic setting

A late Hadrynian age (594 ± 10 Ma*) has been determined for the Mansfield Cove plagiogranite by zircon concordia (Bostock et al., 1979)*. The granite intrudes the basalts at Mansfield Head and at Rowsell Hill and is therefore at least somewhat younger than they are. Age relations with the South Pond gabbro are less clear but it appears that the gabbro intrudes both the basalts and the plagiogranite. Mafic dykes intrude both the basalts and the plagiogranite, and most are therefore younger than the plagiogranite, but some are probably older. The Hall Hill Complex is faulted against the Robert's Arm Group on the east, but the generally higher metamorphic grade of the mafic rocks suggests that they are older than the Robert's Arm Group, an indication born out by radiometric dating of the plagiogranite.

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* New U-Pb zircon data, 479 +or-3 Ma for Mansfield Cove plagiogranite (Dunning et al., 1987) suggest that this pluton is early Ordovician, only slightly older than Robert's Arm Group, rather than Hadrynian.

The Hall Hill Complex lithologically resembles the Hungry Mountain Complex which forms an older component of the Topsails terrane of central Newfoundland, and the two have been considered part of the same terrane (Whalen and Currie, 1983). Igneous activity of closely similar age* to that of Mansfield plagiogranite occurred in the Avalon Zone where zircon U-Pb ages of pre- to syntectonic granitic and volcanic rocks have been determined (Swift Current pluton 580 % 20 Ma and associated volcanics 590 % 30 Ma, Dallmeyer et al., 1981; Marystown ignimbrite 607 + 8.0 - 3.7 Ma, Krogh, 1983). These igneous events, coeval with Mansfield Cove plutonism, might represent the early accompanyment of rifting which ultimately separated them to either side of a developing (back-arc?) basin. They are, however, separated by a major tectonic boundary at the edge of the Gander Zone that may have been fundamentally active at a later date, and it is therefore not yet clear whether these distant terranes can be related in this way. Other possible correlations are more tentative, either because radiometric ages have not been determined, or because interpretation of available ages is uncertain. The South Lake Complex (Lorenz and Fountain, 1982), which occupies a horst block within the Ordovician stratigraphy of central Notre Dame Bay area some 25 km to the southeast of Robert's Arm Group, is in some respects lithologically similar to Hall Hill Complex, but is undated. Both complexes include a large proportion of tonalitic rocks along with basalt and gabbro. On the other hand, sheeted dykes, which have not been recognized in the Hall Hill Complex, have contributed to these authors' interpretation of the South Lake Complex as part of an ophiolitic basement that has been uplifted within the surrounding younger arc-related volcanics and greywacke.

Analogous to these rocks, the Hall Hill Complex occupies a fault wedge along the west margin of the Ordovician Robert's Arm Group and is possibly overlain by rocks of this group immediately south of the area mapped. These similarities lend particular interest to chemical comparison of the two complexes. In Fig. 5b, 5c and 5d fields occupied by South Lake lithologies are plotted along with individual samples of the Hall Hill Complex. The fields for major elements are mostly similar, but comparisons involving TiO_2 and FeOt/MgO ratio suggest contrasts with all the South Lake lithologies except the late dykes. In Figure 7 (FeOt/MgO vs. TiO_2) it can be seen that most of the Hall Hill samples follow an approximately linear trend characterized by relatively higher TiO_2 content for any given FeOt/MgO ratio. This may reflect higher contents of TiO_2 in the Hall Hill magmas, or higher oxidation potential leading to fractionation of magnetite in the South Lake magmas.

A late Hadrynian age, similar to that of Mansfield Cove plagiogranite, was reported for tholeiitic dykes of the Long Range dyke swarm (40Ar/39Ar 605 ± 10 Ma, Stukas and Reynolds, 1974a). This age superseded older K-Ar whole-rock data ranging back to 805 Ma (Pringle, 1971). It has not been tested by other methods, and there is therefore some possibility that the dyke swarm may be somewhat older. Following the interpretation of Strong and Williams (1972) emplacement of these dykes occurred during early rifting of the continental margin of North America that led to formation of Iapetus Ocean. Comparison of the chemistry of these dykes with basalts and amphibolites of the Hall Hill Complex suggests similarly high TiO_2 and P_2O_5 contents implying that some aspects of the setting in which these magmas evolved were similar.

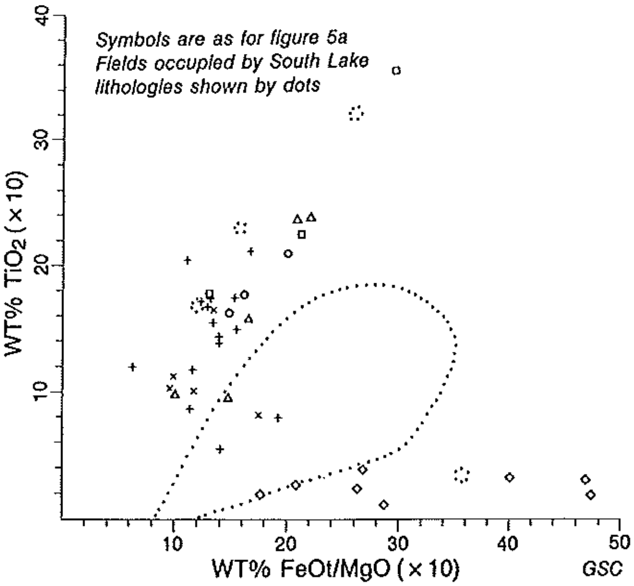

Figure 7. Hall Hill Complex. FeOt/MgO vs. TiO_2 plot with fields occupied by South Lake lithologies shown by dots. Symbols are as for Figure 5a.

A model for the development of the Topsails igneous terrane has been proposed by Whalen and Currie (1983) in which the central volcanic belt is envisaged as a back-arc basin with an east-dipping subduction zone beneath the Topsails. The surface intersection of the subduction zone was considered to follow the Baie Verte-Brompton line and to pass down Birchy and Grand lakes (between Hall Hill and the Great Northern Peninsula). The siliceous and potassic rocks of Topsails terrane imply that the source for the magmas forming these rocks was of continental character. Rifting of the proto-continent with which the Long Range dykes were associated marked a spreading phase which preceded plate consumption associated with this arc development; however, the similarity between Long Range dykes and the Rowsell Hill basalts suggests that similar magmatic conditions obtained. The Hall Hill Complex may therefore have evolved during early rifting which gave rise to the back-arc basin envisaged by Whalen and Currie (1983). Later spreading may have developed ophiolitic suites, such as South Lake Complex, deeper within the basin. Precise dating of the

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* The new radiometric data (footnote 1) suggest that the Rousell Hill basalts may be coeval with basalts of Lushs Bight terrane. They argue against the corellations made below with rocks of the Avalon Zone.

various Hadrynian-Cambrian mafic complexes and determination of their trace element characteristics will be required to substantiate the origin of these bodies; nevertheless it is upon this type of variegated tholeiitic terrane, perhaps involving magmas generated during more than one period of early distension, that the later Ordovician arc-related formations including the Robert's Arm Group may lie.

Lushs Bight Group

The name, Lushs Bight Group, was proposed by Espenshade (1937) for basic volcanic and pyroclastic, and some sedimentary, rocks exposed north of the Lobster Cove Fault mostly on Sunday Cove, Pilley's and Triton islands. In his usage the Lushs Bight Group together with the Cutwell Group to the north formed the Pilley's Series. Subsequent workers, noteably MacLean (1947) and Williams (1962), extended the name, Lushs Bight Group, to include similar rocks in Notre Dame Bay east and west of the original area north of the Lobster Cove Fault. Williams (1969, p. 22) proposed the term 'Headlands Group' to include "all the dominantly mafic volcanic assemblages that apparently form a continuous belt along the headlands and islands of Notre Dame Bay...". Horne and Helwig (1969) used the informal term 'Lushs Bight terrane' to apply to rocks of an area essentially the same as that underlain by the Headlands Group and bounded on the south by the Lobster Cove Fault Zone. Strong and Payne (1973) proposed the term 'Lushs Bight Supergroup' to apply to rocks of the Lushs Bight terrane "generally referred to as the Lushs Bight Group". In the Pilley's Island area this latter usage involves two established groups, one of which has the same name as the proposed encompassing supergroup. In the present study the term "Lushs Bight Group" is used in the original definition (Espenshade, 1937) with the Lushs Bight-Cutwell boundary as modified by Williams (1964, 1969). This accords with the usage of Dean and Strong (1977). The phrase "Rocks of the Lushs Bight terrane" will be used in preference to Lushs Bight Supergroup.

The Lushs Bight Group in the Pilley's Island area has been described by Espenshade (1937) and by Strong (1973), and is estimated by the latter to be 1500 m or more thick on Pilley's Island. Although the group is considered to be mostly southward facing, no continuous section through it has been recognized. In the present study only parts of the group close to the Lobster Cove Fault (up to a maximum of about 700 m north of the fault) on Sunday Cove, Pilley's and Triton islands have been examined.

On the west coast of Sunday Cove Island schistose pillow lava and metabasalt predominate with lesser amounts of green chloritic schists, schistose volcanic breccia, and minor greywacke and chert. Original bedding is rarely evident but was seen to strike east-southeast and to dip 80° south at one point. Mostly it has been obscured by an easterly striking, mostly steeply north dipping schistosity. Local mineral lineation and boudin axes plunge steeply, and kink bands, noted at one locality, trend 290° and plunge 85°.

On the west coast of Pilley's Island similar rocks are exposed but they are less sheared and altered (compare pillow lavas in Fig. 8 with those in Fig. 9). Nevertheless, deformation is still sufficient to prevent recognition of tops.

Figure 8. Highly sheared pillow lava of Lushs Bight Group on the west coast of Sunday Cover Island (GSC 167207).

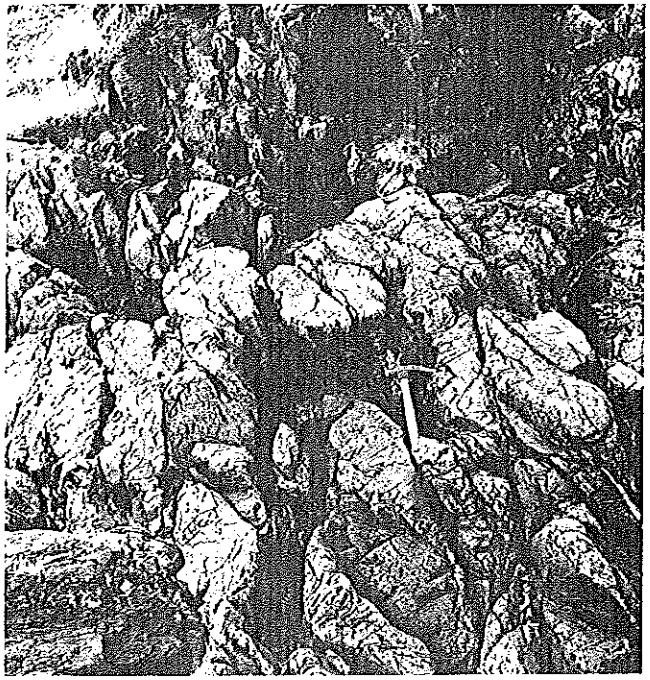

Figure 9. Moderately sheared pillow lava of Lushs Bight Group on the west coast of Pilley's Island (GSC 167101).

On central and eastern Pilley's Island deformation is still further reduced. Pillow lavas dip from 25 to 70° southward and with some pillow breccia form a continuous sequence some 600 m thick. Northwest of Nogood Island the pillow lava is brecciated and healed by epidote veins, and near the point north of this island the pillow lavas abut and are likely faulted against a sequence of hyaloclastites, chert, greywacke, breccia and basalt dykes. Only the southern 100 m of this sequence has been examined.

On Triton Island the Lushs Bight Group was examined locally for 300 to 400 m north of the Lobster Cove Fault. Pillow lava, basalt and some basaltic breccias are the dominant lithologies. Minor interbeds of chert and greywacke are most common on Long Arm and south of the village of Triton West. Hematite-rich beds up to 15 cm thick are present in the sediments on the point north of Long Arm. The rocks dip southward throughout the length of the Island at about 50° but steepen to near vertical along the Lobster Cove Fault. Pillows on a peninsula on the south shore of Great Triton Harbour strike northerly and dip gently westward (departing markedly from adjacent trends) suggesting that there may be a structural break along this inlet.

Thin section study shows that the basalts and pillow lava throughout the eastern part of the Lushs Bight Group are spilitic being composed of albitic plagioclase, clinopyroxene, epidote, chlorite, carbonate, pyrite, and magnetite-ilmenite. Quartz is common in minor veins and amygdules. Pumpellyite was found in one thin section. The pillow lava and basalt are commonly finely porphyritic with phenocrysts of plagioclase and locally clinopyroxene up to 3 mm but most are 1 mm or less. Matrices are lathy, microlitic or show quench textures. Volcanic sediments and breccias north of Nogood Island are distinctive in containing prehnite and more abundant pumpellyite than the basalts. Two dykes intrusive into these sediments were found to have fine grained gabbroic texture and consist of clinopyroxene with local fringes of blue-green amphibole in a matrix of intermediate plagioclase, minor epidote, chlorite, muscovite and opaques. Schists on Sunday Cove Island, likely derived from similar sediments, consist of fine grained plagioclase, quartz, sericite, chlorite, epidote, carbonate and minor magnetite. A single isolated outcrop of gabbroic appearance on the east coast of Pilley's Island proved to be a breccia consisting of fragments of clinopyroxene up to 4 mm, and inclusions of highly altered plagioclase-rich rock in a green chloritic matrix. Scattered small fragments of quartz-bearing felsite, and some mafic fragments containing abundant carbonate amygdules are present. The outcrop may constitute part of a minor diatreme.

The above descriptions indicate that rocks of the Lushs Bight Group immediately north of the Lobster Cove Fault and east of central Pilley's Island form a monoclinal southward-dipping, southward facing sequence consisting mainly of pillow lava, basalt, some breccia and minor chert and greywacke. Farther east they are largely unfoliated and of prehnite-pumpellyite metamorphic grade (subgreenschist facies). To the west, starting on central Pilley's Island they have a superimposed steeply northward dipping foliation. Pumpellyite and prehnite are missing and it appears that the rocks are of slightly higher (greenschist facies) metamorphic grade.

Age and correlation of the Lushs Bight Group

The Lushs Bight Group, low potash tholeiites, includes sheeted dyke-gabbro complexes such as the Brighton Gabbro which has been dated (40Ar/39Ar hornblende) at 495 ± 5 Ma. indicating an age of crystallization corresponding to Tremadoc-Arenig (Stukas and Reynolds, 1974b). The group has been interpreted as a part of the upper part of an ophiolite sequence which by correlation may include the Snooks Arm and Moreton Harbour Groups (Kean and Strong, 1975). The Lushs Bight terrane thus potentially underlies all of Notre Dame Bay north of the Lobster Cove Fault.*

The fossil age of the group, representing the depositional age of sediments which overlie and intertongue with the basalts that overlie the Brighton Complex, is only approximately known, but is consistant with the age determined for Brighton Gabbro. Fossils of definite Ordovician age, possibly early Middle Ordovician, were reported by Williams (1969) from the Cutwell Group on Little Bay Island. This age was supported, although not confirmed, by Strong and Kean (1972) on the basis of fossils found in the Cutwell Group on Long Island. MacLean (1947) reported a single brachiopod in the upper part of the basal pillow lava of the northwest Western Arm section northwest of the present study area. This brachiopod was interpreted as fairly definitely Canadian (early Ordovician), probably late Canadian.

Chemical analyses

A section through the southern part of the Lushs Bight Group was sampled at intervals of roughly 150 m for comparison with rocks of the Robert's Arm Group. The east coast of Pilley's Island was chosen for sampling because the section there is nearly perpendicular to strike and shows none of the foliation evident farther west. The lithologies analyzed may be separated into four groups: 1) pillow lavas, 2) massive basalt interleaved within the pillow lavas, 3) basaltic breccias and hyaloclastites, and 4) intrusive dykes. Means and standard deviations for each of these groups are given in Table 2.

Alteration of the Lushs Bight Group on Pilley's Island is suggested by higher H_2O and CO_2 than are present in the rocks of Hall Hill Complex. These characteristics along with sodic plagioclase are typical of spilitic alteration. Examination of silica values for the pillow lavas indicates that there is a progressive increase upward in the section (toward the Lobster Cove Fault). Quartz filled amygdules and fine silica veining were observed locally in the pillow lava in the vicinity of the Lobster Cove Fault (although these features were avoided in sampling), but

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* New radiumetric data, 479 + or- 3Ma for Mansfield Cove plagiogranite (Dunning et al., 1987) suggest that Rowsell Hill basalts, which the plagiogranite intrudes, may have been part of Lushs Bight terrane.

Table 2. Chemical analysis from the Lushs Bight Group

MAJOR ELEMENTS FOR ROCKS OF THE LUSHS BIGHT GROUP

Station	Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2	S	F	Cl	FeO_t	Total
Massive basalts																			
1043	B	53.90	1.18	15.30	3.20	7.10	.14	5.78	4.90	4.30	.66	.15	2.70	2.10	.01	.04	.02	9.98	101.48
1044	B	53.40	1.21	15.40	5.90	5.90	.21	4.24	7.80	3.10	.34	.13	.70	.90	.01	.04	.02	11.21	99.30
1045	A	51.30	1.13	15.30	2.40	9.70	.24	6.40	7.10	2.80	.01	.11	4.20	.70	.01	.04	.02	11.86	101.46
1045	B	55.00	1.21	14.30	2.60	7.30	.19	4.85	7.40	3.80	.06	.15	2.80	1.30	.07	.02	.02	9.64	101.07
1048	A	53.80	1.39	15.40	3.80	8.60	.36	5.80	3.00	5.10	.08	.12	2.70	.50	.01	.07	.03	12.02	100.76
M		53.48	1.22	15.14	3.58	7.72	.23	5.41	6.04	3.82	.23	.13	2.62	1.10	.02	.04	.02	10.94	
σ		1.36	.10	.47	1.41	1.46	.08	.86	2.04	.93	.27	.02	1.25	.63	.03	.02	.00	1.08	
Breccias																			
1047	A	50.60	1.30	15.60	1.70	9.90	.28	5.60	6.30	4.60	.07	.13	3.30	1.10	.01	.02	.03	11.43	100.54
1049	A	45.60	.64	14.80	2.00	8.00	.19	9.80	11.60	.80	.37	.08	4.50	2.30	.10	.02	.01	9.80	100.81
1050	A	48.20	.67	16.70	2.00	8.50	.19	7.13	7.30	1.90	.81	.13	4.90	1.50	.01	.02	.01	10.30	99.97
1051	B	48.20	.60	16.90	2.10	7.90	.21	9.30	8.30	1.50	.58	.10	4.70	.40	.01	.02	.02	9.79	100.84
1052	B	47.10	.58	18.20	2.30	7.50	.19	8.50	9.50	1.80	.64	.10	4.20	.10	.01	.02	.02	9.57	100.76
M		47.94	.76	16.44	2.02	8.36	.21	8.07	8.60	2.12	.49	.11	4.32	1.08	.03	.02	.02	10.18	
σ		1.83	.30	1.30	.22	.93	.04	1.71	2.05	1.45	.28	.02	.63	.88	.04	.00	.01	.75	
Pillow lavas																			
1042	A	59.90	1.16	14.50	1.40	8.30	.18	4.69	3.20	4.50	.16	.13	.90	.10	.01	.04	.02	9.56	99.19
1043	A	55.20	1.07	14.50	2.50	7.00	.14	4.59	7.00	4.50	.10	.13	3.00	.30	.01	.03	.02	9.25	100.09
1044	A	52.80	1.14	16.50	5.60	5.20	.16	3.62	5.80	5.60	.36	.13	3.30	1.20	.01	.04	.02	10.24	101.48
1046	A	50.70	1.77	13.80	1.90	7.10	.18	5.50	10.20	4.00	.09	.21	2.50	3.10	.17	.05	.02	8.81	101.29
1046	B	48.10	2.08	14.60	2.00	8.20	.19	6.30	9.70	3.90	.35	.22	3.10	3.00	.15	.05	.02	10.00	101.96
M		53.34	1.44	14.78	2.68	7.16	.17	4.94	7.18	4.50	.21	.16	2.56	1.54	.07	.04	.02	9.57	
σ		4.51	.45	1.01	1.68	1.25	.02	1.01	2.88	.67	.13	.05	.97	1.44	.08	.01	.00	.57	
Mafic dykes																			
1051	A	47.30	1.59	16.30	2.20	7.90	.16	8.00	12.10	1.40	.32	.22	2.50	.20	.06	.03	.02	9.88	100.30
1052	A	48.50	1.67	15.60	3.30	9.30	.22	6.20	9.70	2.70	.45	.42	2.90	.40	.14	.05	.03	12.27	101.58
M		47.90	1.63	15.95	2.75	8.60	.19	7.10	10.90	2.05	.39	.32	2.70	.30	.10	.04	.03	11.08	
Diatreme breccia																			
1048	B	51.10	1.47	16.10	2.20	10.80	.28	5.90	3.70	4.30	.19	.14	2.60	.40	.01	.05	.03	12.78	99.27

TRACE ELEMENTS FOR ROCKS OF THE LUSHS BIGHT GROUP

Station	Sample	Li	Rb	Cs	Sr	Ba	V	Zr	Cu	Zn	Co	Ni	Cr
Massive basalts													
1043	B	14	3	.1	155	26	279	50	53	110	18	9	4
1044	B	21	1	.3	161	76	387	74	91	90	28	10	4
1045	A	20	1	1.5	68	21	292	57	93	110	32	10	11
1045	B	9	1	.1	115	20	251	58	42	100	20	9	11
1048	A	10	1	.1	89	59	294	52	29	120	19	9	4
M		15	1	.4	118	40	301	58	62	106	23	9	7
σ		6	1	.6	41	26	51	9	29	11	6	1	4
Breccias													
1047	A	18	1	.2	104	39	286	69	83	110	25	9	4
1049	A	16	9	2.8	126	90	244	19	51	80	22	44	174
1050	A	23	11	1.7	150	272	268	37	111	100	22	31	28
1051	B	22	9	1.2	171	176	247	23	32	100	24	26	54
1052	B	19	11	1.4	213	201	219	19	73	90	17	23	54
M		20	8	1.5	153	156	253	33	70	96	22	27	63
σ		3	4	.9	42	92	25	21	30	11	3	13	66
Pillow lavas													
1042	A	16	3	.1	68	55	156	45	123	110	12	9	4
1043	A	18	10	.1	145	57	245	56	83	100	20	9	4
1044	A	8	6	.1	64	41	280	62	32	90	20	9	4
1046	A	14	1	2.1	126	21	256	82	33	90	25	9	7
1046	B	19	1	13.0	114	39	371	139	81	100	39	23	14
M		15	4	3.1	103	43	262	77	70	98	23	12	7
σ		4	4	5.6	36	15	77	37	38	8	10	6	4
Mafic dykes													
1051	A	17	2	1.4	229	123	232	92	95	70	33	108	250
1052	A	12	6	1.1	184	152	243	103	45	130	25	47	51
M		15	4	1.3	207	138	238	98	70	100	29	78	151
Diatreme breccia													
1048	B	13	1	.4	146	94	310	72	66	130	26	9	5

Note: M = mean
σ = standard deviation

there is a suggestion of some silicification in these rocks near the fault. As a similar progression is not evident in the massive basalts associated with the pillow lavas it is likely that this alteration of rocks close to the fault occurred on the seafloor rather than as a result of hydrothermal circulation after burial. Because the rocks have clearly been open to alkali-calcium migration and addition of H_2O-CO_2 they have been recalculated for plotting purposes on a H_2O-free calcite-free basis.

Comparison of the present results with those of Strong (1973) indicates potential differences in TiO_2 and possibly Al_2O_3, CaO, K_2O and FeO. For this reason six powders from the pillow lava-basalt group of the present study were reanalyzed but no significant variation was found. The differences observed may reflect the fact that the present study has concentrated on the upper part of the Lushs Bight Group whereas that of Strong (1973) probably ranged deeper within the group. Analyses by Smitheringale (1972) of Lushs Bight basalt are comparable to those of the present study for rocks of similar solidification indices.

Smitheringale (1972) and Strong (1973), and later authors have concluded that the Lushs Bight terrane is dominated by oceanic tholeiites. Evaluation of this conclusion using the Pilley's Island sample collection must avoid dependence upon alkali elements and calcium because of the high mobility of these elements and upon SiO_2 because of large absolute changes due to normalization. Neverthless the tholeiitic character of the suite is supported by the immobile trace and minor elements. The TiO_2 vs. P_2O_5 plot (Fig. 10) shows that all but one dyke sample plot in the field of ocean ridge basalts given by Bass et al. (1973). In the Zr vs. Ti plot (not shown) of Pearce and Cann (1973) the Lushs Bight samples fall in the fields of low potash basalt and ocean floor basalt. In these diagrams Lushs Bight rocks are very similar to tholeiites of the Hall Hill Complex supporting the view that they are of tholeiitic origin. Examination of the FeOt/MgO vs. TiO_2 distribution (not shown) suggests that they are intermediate between tholeiites of the Hall Hill and South Lake complexes but this comparison is suspect due to the effects of alteration on Fe/Mg ratios.

Robert's Arm Group

Introduction

The term, Robert's Arm volcanics, was used by Espenshade (1937) to apply to massive and pillowed basalt with intercalated red and green cherts that were placed at the top of his Badger Bay Series. Also included with these volcanics were the "purple and green rhyolite flows and tuffs" of Pilley's Island. Hayes (1951a) used a similar terminology but recognized basic volcanics south of the present map area (Mortons volcanics) as distinct from those mapped during the present study (Breakheart basalt). Both were included in his Robert's Arm Group. Williams (1964, 1969) used the name Robert's Arm Group to include both the Robert's Arm volcanics and the Crescent Lake Formation. Dean (1978) included the Sops Head Complex, Crescent Lake Formation, Robert's Arm volcanics and subvolcanic plutons at Loon Pond and Woodfords Arm within the Robert's Arm Group. Except for the exclusion of Sops Head Complex, his definition will be followed here.

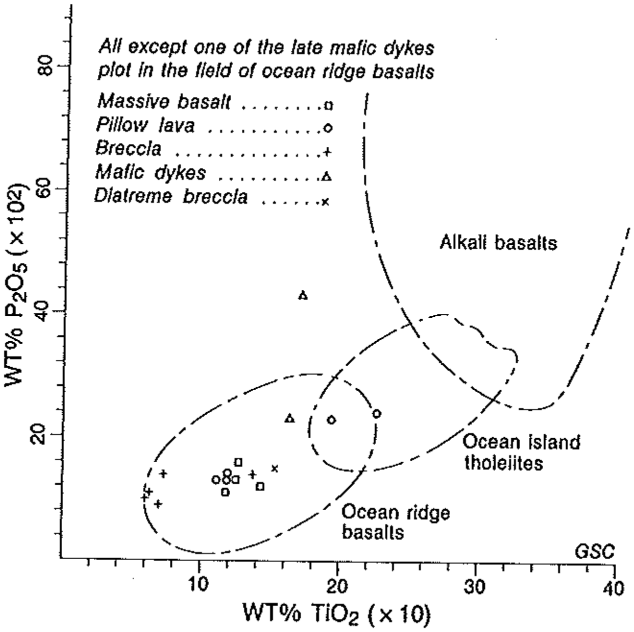

Figure 10. TiO_2 vs. P_2O_5 plot for Lushs Bight Group with field boundaries of Bass et al. (1973). All except one of the late mafic dykes plot in the field of ocean ridge basalts.

Bostock (1978) suggested the existence of three chemically distinctive fault belts within the Robert's Arm Group based on preliminary chemical analyses. The eastern belt including the Crescent Lake Formation and unnamed TiO_2-rich basalts, was thought potentially distinct from the Robert's Arm Group but the central and western belts were retained within it. Further investigations have suggested that these belts are not readily distinguished lithologically in the field, and the structures by which they are related are uncertain. Furthermore, additional chemical analyses provide evidence of only two chemically distinct belts. It therefore seems advisable to retain the Robert's Arm Group as a cover for all of these units. In the present study the Robert's Arm Group is defined to include both the sediments that have in part been assigned to the Crescent Lake Formation, and all the various volcanic and subvolcanic rocks limited by the Hall Hill Complex on the west, the Springdale and Lushs Bight groups on the north, and the Sops Head Complex on the southeast except for the few late, presumably Mesozoic, dykes.

Crescent Lake Formation

The Crescent Lake Formation comprises a number of isolated bodies of fine grained clastic rocks that occur in the southeastern part of the Robert's Arm Group. It is not known whether some of these clastic bodies were once continuous with the one another, or indeed whether some are even related to others. In particular, grey slaty rocks in the eastern parts of the formation may not be equivalent to predominantly red somewhat less deformed rocks in the western parts. Nevertheless, a common relationship seems the most likely interpretation. The name is established in the literature (Espenshade, 1937; Hayes, 1951a; Williams, 1969; Dean, 1978), and it will be continued here because the true situation is uncertain.

The Crescent Lake Formation as employed here occupies a long narrow belt which commences at its northeast end immediately south of Crescent Lake and extends southwestward near the northwest side of Tommy's Arm River to the southwestern limit of mapping for the present project. Similar sediments occupy faulted outliers at the east end of Crescent Lake and along Black Brook. Two additional large, lenticular southwestern outliers are more tenuously connected with the formation. These have distinct proximal volcaniclastic components of their own, but both include fine clastic sediments, like rocks in the Crescent Lake Formation, which may have been derived from the same source. All of these rocks lie within the same major fault belt and all are included in the Crescent Lake Formation in this report on the basis that they may have been interconnected. Sediments similar to those in the eastern part of the formation occur along the northwest margin of the Sops Head Complex, which likely in part represents a sheared fault repetition of the Crescent Lake Formation. Clastic sediments that occur within the basalts in the central and western parts of the Robert's Arm volcanics are separated from the Crescent Lake Formation by major faults and occur mostly in small disconnected bodies. The largest of these, that east of Boot Harbour Second Pond, coarsens northeastward unlike the main sedimentary belt. These rocks are therefore excluded from the Crescent Lake Formation, but the difference might merely reflect the building up of the Robert's Arm submarine volcanic edifice above its basin floor at an accelerated rate. Greywacke at the southwest end of the formation reaches about 1500 m thick but both contacts are likely faulted so the true maximum thickness is unknown.

The Crescent Lake Formation is divisible into two lithological units comprising greywacke with subordinate interbedded chert and siltstone (Unit A); and chert, siltstone and slaty shale with subordinate greywacke (Unit B). The greywacke occurs mostly in the southwest whereas the finer clastic unit with a few mappable greywacke lenses is predominant in the central and northeast parts of the map area.

Unit A: greywacke

Greywacke in the large body west of Kippins Pond is typically grey-buff weathering, grey-green to olive or purplish and fine grained. Scattered clear quartz grains in a cloudy feldspathic matrix are present in most specimens examined. Chert chips up to a few centimetres diameter are present locally and basalt fragments a few millimetres in diameter are less common. Graded beds mostly only a few centimetres thick with tops northwest were found locally. Interbeds of siltstone up to 1 m thick are common. Greywacke in the large lens southeast of Sandy Pond and at Ski Pond is similar except that scattered grains of pink feldspar were seen in several places, and grey felsic rock fragments were observed locally, particularly close to felsites at the southwest end of the Sandy Pond lens. Greywacke in the isolated lens on Tommy's Arm River near Crescent Lake weathers brown, and is pale green. Grain size is about 2 mm, but 5 mm sand is present in beds up to 30 cm thick locally. Some finer beds superficially resemble basalt except for the presence of scattered quartz grains.

Figure 11. Banded cherty siltsone of Crescent Lake Formation north of Tommy's Arm River (GSC 167251).

Unit B: chert, siltstone and slate

Fine clastic sediments and cherts characterize most of the northeastern two thirds of the Crescent Lake Formation (Fig. 11). Grey-green slates with strong paper-thin cleavage, local cherty beds and rare greywacke are typical of the outlier on the south side of Tommy's Arm River at the east end of Crescent Lake. At the northeast end of the main belt along upper Tommy's Arm River the formation consists of both grey-green and red slates with a large component of chert. Farther southwest red to purplish slaty siltstones show fine buff-white weathering, contorted lamination. Laminated intervals occur in larger units commonly 3 m or more thick. Red cherty siltstones along Black Brook have a substantial greywacke component along their west margin, and those in the outliers through Anthony and Sandy ponds are interbedded in almost equal proportions with greywacke. Siltstones on the northeast side of lower Tommy's Arm River are red like those in the main part of the Crescent Lake Formation and unlike those on the opposite southwest side of the river.

Cleavage and beds within the main part of the Crescent Lake Formation along Tommy's Arm River show parallel trends with steep dips on either side of vertical. Twenty-five minor fold axes measured within the formation show a maximum near vertical plunge with northeast-southwest dispersion in the plane of foliation. Among these folds both left- and right-handed displacements are indicated.

Earlier workers (Espenshade, 1937; Hayes, 1951a; Dean, 1978) considered that the Crescent Lake Formation mostly underlies the Robert's Arm Group. Pillow lavas within the Robert's Arm Group along the northwest contact of the main belt of sediments indicate this to be true. Basalts beneath the main part of the Crescent Lake Formation along Tommy's Arm River also face northwestward, but a single, isolated, notably undeformed showing of rudely bedded purple and grey greywacke, in contact with basalts on the southeast side of the river, shows scour and fill apparently indicating top to the southeast. If this facing direction is valid it may represent only a restricted fault wedge. A prominent lineament projecting from the southeast contact of the sediments along Tommy's Arm River northeast through the basalts to Crescent Lake suggests that the bottom contact of the Crescent Lake Formation is faulted. Similar mostly red cherty, slaty siltstones occur with some greywacke on the northeast shore of lower Tommy's Arm River suggesting that the upper part of the Crescent Lake Formation may possibly be correlated on either side of Crescent Lake (across the Crescent Lake Fault). Slaty rocks in the larger outlier on the south shore of lower Tommy's Arm River are mostly grey and perhaps more closely related to similar rocks in the Sops Head Complex. Grey to pink, orange weathering, friable siltstones in the small body at the narrows between east and west Crescent Lake mostly do not closely resemble either red or grey slaty rocks in the Crescent Lake Formation, but are of more volcanic aspect like some beds within the Robert's Arm volcanics seen along the highway southwest of Crescent Lake.

Facies variations within the main part of the Crescent Lake Formation are consistent with those of a section obliquely approaching a felsic volcanic shoreline from the northeast. Thus the preponderance of quartz-bearing greywacke in the southwest may reflect proximity to a river delta whereas lenses of coarser greywacke within the cherts and siltstones farther northeast reflect more distal submarine channels. Darker, grey to greenish slates in the northeastern part of the formation and within the Sops Head Complex perhaps reflect an environment more remote from this shoreline.

No fossils have been found in any part of the Crescent Lake Formation. An upper limit for its age is probably set by the Rb-Sr isochron age of felsic volcanics in the upper part of the Robert's Arm Group at about 455 Ma. (Bostock et al., 1979).* Interpretation of fossiliferous limestone blocks within Sansom greywacke as having been deposited on top of Robert's Arm basalts (Nelson, 1981), suggests that it may be of Middle Ordovician (pre-Llandeilian) age.

Robert's Arm volcanics

The Robert's Arm volcanics are in fault contact with the Hall Hill Complex in the west along the Mansfield Cove Fault, and are separated by the Sops Head Complex (part of a complex tectonic zone) from volcano-sedimentary rocks of central Notre Dame Bay on the east. Within the volcanics good marker horizons are lacking and the main subdivisions are delineated by faults which separate basalts of differing general character such as abundance of associated felsite or type and proportion of phenocrysts in the more coarsely porphyritic flows. The southwestern part of the group occurs in three major, predominantly west- to northwest-facing, fault-bounded belts. They will be called the Crescent Lake, Mud Pond, and Boot Harbour fault belts (Fig. 12). The fault belts are separated by the Sunday Cove Fault through Woodfords Arm in the west, and by the Crescent Lake-Tommy's Arm Fault in the east. In the northeastern part of the map area the Robert's Arm Group is bent eastward and crumpled, thus complicating eastward projection of the fault belts. Nevertheless it appears that the Crescent belt is faulted out along Tommy's Arm, and much of the Boot Harbour belt has been truncated across central Pilley's Island by the Lobster Cove Fault. The division between Mud Pond and Boot Harbour belts may project eastward from the Sunday Cove Fault near Woodfords Arm along a lineament which divides felsite-bearing basalts on the northeast from felsite-free basalts of the Mud Pond belt to the southwest. At its west end this lineament forms the south boundary of a structurally discordant rotated block, and is therefore believed to be a fault. It will be called the Robert's Arm Fault. Near its east end the Robert's Arm Fault is intersected by a splay from the Crescent Lake-Tommy's Arm Fault, and it is not known whether the former continues to the east through Robert's Arm, through Bear Cove, or has been faulted out altogether by displacement of the south boundary of Boot Harbour belt all the way south to the east branch of the Crescent Lake-Tommy's Arm Fault. In the area east of Robert's Arm the Mud Pond and Boot Harbour fault belts are therefore undivided (Fig. 12).

Geographic reference is also required for terranes of chemical and petrographic variation within Robert's Arm volcanics because the volcanic lithologies transgress across fault belts in the southern part of the area. The **Crescent terrane** is defined to include all the Crescent fault belt plus the inverted rocks at the south end of Boot Harbour belt. The **Mud Pond terrane** is coextensive with the Mud Pond fault belt; and the **Boot Harbour terrane** corresponds to the Boot Harbour fault belt except for the inverted rocks at its southern end. East of Robert's Arm the Mud Pond and Boot Harbour terranes are undivided,

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* New U-Pb zircon data, 473 + or-2 Ma for rhyolites from Robert's Arm Group (Dunning et al., 1987) suggest that the Group is somewhat older Ordovician than the earlier Rb/Sr isochrons had suggested.

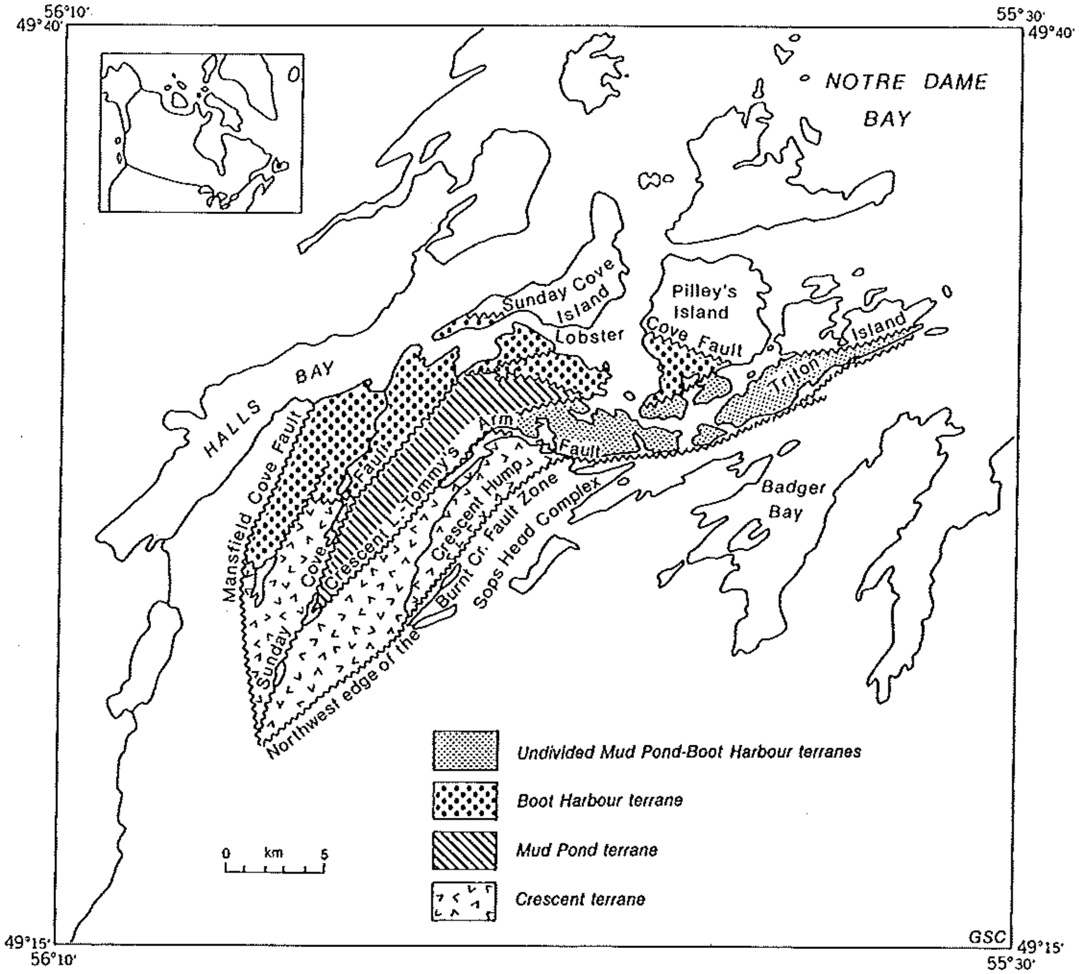

Figure 12. Fault belts and terranes of the Robert's Arm Group.

but a "minimum" Boot Harbour terrane can be defined to include the rocks on central Pilley's Island north of the prominent lineament through Loadabats Pond. Because of the above uncertainities these two latter terranes will be combined for many purposes as the **Mud Pond — Boot Harbour terrane**. One further subdivision has been suggested within Crescent terrane by certain chemical contrasts, by distribution of breccias, and by scarcity of interleaved felsites and sediments. **Crescent Hump** on the northeast, is separated from the **Southwest Crescent Block** on the southwest by an oblique fault lineament that follows the base of the major western body of Crescent Lake Formation near upper Tommy's Arm River. These terranes are also illustrated in Figure 12.

The Robert's Arm volcanics are divided into several lithological map units, namely:

1. Basalt, pillow lava, and small bodies of gabbro, some pillow breccia, tuff, chert, greywacke and siltstone, minor limestone;
2. Pillow breccia, mafic to polymict volcanic breccia;
3. Felsic volcanic rocks;
4. Submarine ash flows, some greywacke and siltstone;
5. Chert, siltstone, greywacke;
6. Minor mafic intrusions;
7. Diatreme breccias.

The volcanic rocks have everywhere been subject to spilitic alteration and have locally been raised to epidote amphibolite facies metamorphic grade. Thick accumulations of felsite occur discontinuously in the upper part of the northwest fault belt and similar rocks are present as smaller bodies in other parts of the volcanics. These accumulations are here referred to as felsic volcanic centres with an appropriate geographic name for clarity of reference. This is not meant to imply that all the felsic rocks of each centre were necessarily derived from one volcanic vent, or that two or more centres could not have been derived from the same vent, connecting areas having been covered by the sea.

Unit A: basalt and pillow lava

Basalts of the Robert's Arm Group are pale to dark green or locally grey, aphanitic to medium grained and equigranular to porphyritic. Porphyritic basalts are distinctly more common and show larger phenocrysts in the Boot Harbour-Mud Pond terranes than in the Crescent terrane. Phenocrysts are of plagioclase (altered to albite during spilitization) or both plagioclase and clinopyroxene and in places reach 5 mm in length. Amygdules are common to abundant in many flows and are composed mostly of carbonate, but epidote, chlorite, pumpellyite and less commonly prehnite are widely present. In pillow lavas amygdules are commonly concentrated in several zones about the periphery of pillows and especially on the upper side providing an indication of stratigraphic sequence (Fig. 13). Red to grey or greenish chert is widely present in the intersticies between pillows (Fig. 14) and commonly thin bands of finely bedded chert, siltstone and greywacke separate flows. Stratigraphic sequence may be discerned where cut and fill structures are present and where the unconsolidated sediment has been forced upward into contraction cracks in overlying massive basalts. More rarely small lava flows of pillow-like section suggesting flow directions are present (Fig. 15).

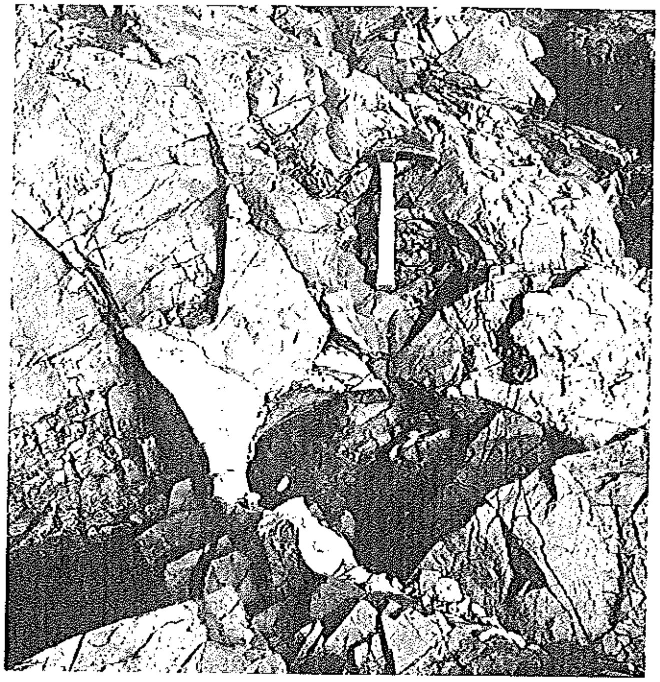

Figure 14. Pillow lava of Robert's Arm Group, Boot Harbour terrane, showing pillows (dark) within basalt formed along a chert band 0.8 m thick (GSC 167097).

Figure 13. Pillow lava of Robert's Arm Group, Boot Harbour terrane, showing amygdule concentration at pillow tops.Local bedding is parallel to pocket knife and faces toward the upper left (GSC 167146).

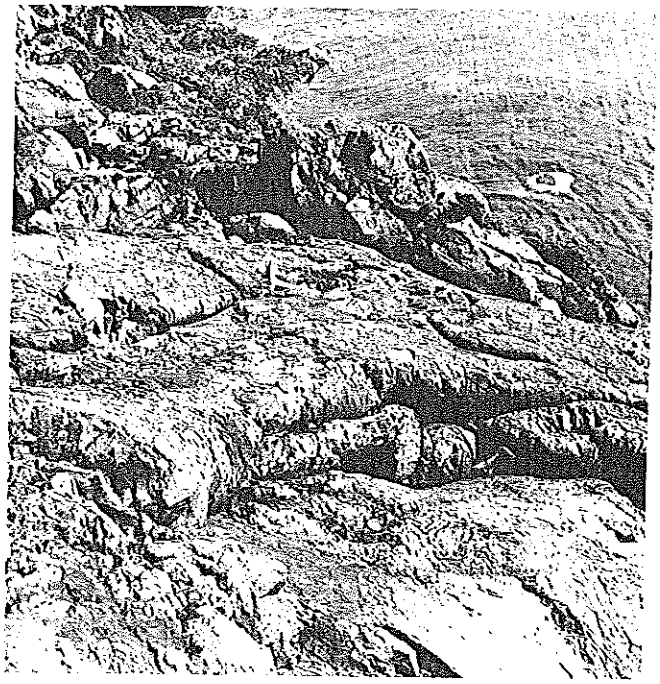

Figure 15. Minor lava flow on Pretty Island shows dispersal at flow foot indicating flow direction (towards shore line; GSC 167286).

Table 3. Petrographic contrasts within the Roberts Arm mafic volcanics

A. LITHOLOGY

Subunit	Breccia	Basalt	Andesite	Amphibolite
1	0/0	29/100	0/0	0/0
2	0/0	51/100	0/0	0/0
3	5/3.2	152/96.8	0/0	0/0
	(4/6.0)	(63/90.4)		
4	21/17.6	85/71.4	2/1.7	11/9.2
	(22/10.5)	(174/83.3)	(2/1.0)	(11/5.3)

B. AMYGDULES

None	Few	Many
21/72.4	3/10.3	5/17.2
32/62.7	9/17.6	10/19.6
39/24.8	29/18.5	89/56.7
(17/25.4)	(11/16.4)	(39/58.2)
40/33.6	15/12.6	64/53.8
(62/29.7)	(33/15.8)	(114/54.5)

C. MATRIX GRAIN SIZE

Subunit	<0.1 mm	0.1 to 0.5 mm	>0.5 mm
1	23/79.3	6/20.7	0/0
2	15/29.4	27/52.9	9/17.6
3	73/46.5	77/49.0	7/4.5
	(45/67.2)	(21/31.3)	(1/1.5)
4	69/58.0	46/38.7	4/3.4
	(97/46.4)	(102/48.8)	(10/4.8)

D. PHENOCRYST SIZE

Subunit	Absent	<1 mm	1-2 mm	2-4 mm	>4 mm
1	25/86.2	4/13.8	0/0	0/0	0/0
2	43/84.3	7/13.7	1/2.0	0/0	0/0
3	112/71.3	24/15.3	18/11.5	2/1.3	1/0.6
	(46/68.7)	(9/13.4)	(10/14.9)	(1/1.5)	(1/1.5)
4	48/40.3	25/21.0	27/22.7	17/14.3	2/1.7
	(114/54.5)	(40/19.1)	(35/16.7)	(18/8.6)	(2/1.0)

E. MICROPHENOCRYST MINERALOGY

Subunit	Absent	Plag	Pyrox	Both
1	20/69.0	9/31.0	0/0	0/0
2	28/54.9	23/45.1	0/0	0/0
3	66/42.0	48/30.6	22/14.0	21/13.4
	(31/46.3)	(16/23.9)	(16/23.9)	4/06.0
4	28/23.5	37/31.1	16/13.4	38/31.9
	(63/30.1)	(69/33.0)	(22/10.5)	(55/26.3)

F. LARGE PHENOCRYST MINERALOGY

Subunit	Absent	Plag	Pyrox	Both
1	26/89.7	3/10.3	0/0	0/0
2	43/84.3	7/13.7	0/0	1/2.0
3	112/71.3	15/9.6	19/12.1	11/7.0
	(46/68.7)	(8/11.9)	(8/11.9)	(5/7.5)
4	49/41.2	14/11.8	24/20.2	32/26.9
	(115/55.0)	(21/10.0)	(35/16.7)	(38/18.2)

(Note): Numerators indicate number of samples, and denominators indicate percentage of the respective subunit. For Mud Pond and Boot Harbour terranes the initial value given is based on minimal size of Boot Harbour terrane with boundary on Pilley's Island at the fault through Loadabats Pond. The value in brackets beneath is for maximum Boot Harbour terrane with the Mud Pond terrane east of Robert's Arm removed by faulting.

Subunits: 1. Crescent Hump, 2. Southwest Crescent Block, 3. Mud Pond terrane, 4. Boot Harbour terrane.

Thin sections of the basalts show that somewhat less than 50% are porphyritic with either or both plagioclase and clinopyroxene phenocrysts. Plagioclase phenocrysts have been completely albitized but clinopyroxene commonly appears unaltered. In a few sections phenocyrysts possibly pseudomorphic after olivine, but now composed of chlorite and carbonate, are present. Matrices commonly show quench textures in pillow lavas and, more rarely in some apparently massive, structureless basalts. Massive basalts are more normally ophitic to gabbroic and locally basalt sills show cummulate textures. Patches of chlorite suggesting original glass are common. Evidence of alteration is ubiquitous taking the form of varying proportions of epidote, chlorite, pumpellyite, prehnite, sericite and clinozoisite. Magnetite persists in some specimens but in many, magnetite-ilmenite has been altered to white opaque leucoxene-like patches and grains. Amygdules are common particularly in basalts of the Boot Harbour belt. These are mostly filled with calcite but epidote, chlorite, prehnite, pumpellyite, albite and quartz fillings are common. Pale yellow andradite appears rarely with carbonate in amygdules and as an alteration product in a few sections (Table 7).

Where the rocks have been raised to higher metamorphic grade amphibole 'whiskers' appear within chlorite patches particularly where these are in contact with pyroxene, and prehnite and pumpellyite are absent. With more advanced metamorphism the basalts are converted to amphibolite composed primarily of blue-green amphibole and plagioclase. One amphibolite, found in the valley 0.6 km north of Sandy Pond and probably emplaced as a fault sliver during movement along the Sunday Cove Fault, consists mostly of altered brown-green hornblende, plagioclase and minor garnet.

Megascopic and microscopic characteristics of the basalts were recorded in conjunction with chemical analyses for computer assisted statistical studies. Values were assigned to lithology, colour, matrix size, phenocryst size, phenocryst mineralogy and amygdule concentration. Tables were then constructed for each variable comparing its values within each of the terranes using the procedure, Crosstabs from, Statistical Package for the Social Sciences (Nie et al., 1970).

Table 3 indicates that there is an increase in proportion of breccia to basalt and possibly in the proportion of rocks judged in the field to be intermediate in composition between basalt and felsite, northwestward in the progression from Crescent through Mud Pond to Boot Harbour terrane. Table 3 for amygdules shows that the rocks of Crescent terrane tend to be less amygdaloidal than those of the other two. Most basalts have a matrix size less than 0.1 mm (quench textures were automatically included in this category in spite of the length of some crystals). Coarsest grain sizes are most prominent in the Southwest Crescent Block, and if the maximum extent of Boot Harbour terrane is assumed, there is an increase in grain size in basalts of Boot Harbour terrane over those of Mud Pond terrane. Phenocryst size indicates a progressive increase in size of phenocrysts from Crescent Hump to Boot Harbour terrane which is strongest if minimal extent of Boot Harbour terrane is assumed. Phenocryst mineralogy indicates that there is a distinct increase in proportion of phenocrysts to matrix in progression from Crescent Hump to Boot Harbour terrane. Plagioclase phenocrysts predominate in Crescent terrane whereas pyroxene phenocrysts are more common in Mud Pond — Boot Harbour terrane. There is a suggestion that the proportion of pyroxene to plagioclase phenocrysts increases northwestwards (upwards) if minimal Boot Harbour terrane is assumed. Colour counts (not illustrated) suggest decreasing alteration upwards because somewhat paler green basalts tend to predominate in Crescent Terrane whereas the proportion of grey basalts is greatest in Boot Harbour terrane.

Pillow lavas were found to be more or less evenly distributed throughout the terranes of Robert's Arm Group. Comparison of the chemistry of pillow lavas with that of massive basalts indicates that the former tend to be slightly more mafic than the latter (see Rock chemistry of Robert's Arm Group). This suggested a comparison of the distribution of pyroxene phenocrysts between pillowed and massive basalts (illustrated in Table 4). The data indicate that the proportion of pillow lavas bearing large clinopyroxene phenocrysts in Mud Pond terrane is slightly lower than the proportion of massive basalts with the same characteristics. In Boot Harbour terrane the relationship is strongly reversed indicating that the pillow lavas are predominantly pyroxene-phyric. Consideration of microphenocrysts suggests that there is little difference between basalts and pillow lavas in Mud Pond terrane, but in Boot Harbour terrane the pillow lavas are again predominantly pyroxene-phyric. Speculation as to the origin of this change can better be made after consideration of chemical contrasts between basalt lithologies in the section on rock chemistry.

Table 4. Distribution of clinopyroxene phenocrysts between basalt and pillow lava

		Large Phenocrysts	Micro Phenocrysts
Mud Pond terrane	Massive basalt	21.4 (22.2)	27.7 (26.7)
	Pillow lava	15.0 (16.7)	27.5 (38.9)
Boot Harbour terrane	Massive basalt	37.3 (28.0)	37.2 (32.2)
	Pillow lava	72.3 (50.0)	75.0 (53.4)

Note: Numbers represent the percentage of samples of the stated lithology that contained clinopyroxene phenocrysts. The upper number for each category provides the percentage within minimum Boot Harbour terrane assumed whereas the figure in brackets provides the percentage with maximum Boot Harbour terrane assumed.

Increasing phenocryst size likely reflects retention of magmas for progressively longer periods in the intratelluric phase. This may be due to increasing buildup of Robert's Arm volcanics above the basin floor and hence increasing height of magma column. This phenomenon, together with increasing proportions of breccia and increasing vesicularity, suggests shallower environments of eruption during the later phases of volcanism. These changes tend to take place in succession across the fault belts from southeast to northwest implying that the terranes are related by progressive buildup and are not composed of fault wedges assembled in random fashion from widely dispersed source terranes.

Unit B: mafic volcanic breccias

Volcanic breccias are mostly pillow breccias made up of angular fragments of green and purple pillows some 30 cm or less in diameter in a matrix of chloritized glass chips of variable size, commonly with more or less abundant carbonate (Fig. 16). In places basalt clasts are rounded and amygdaloidal with chilled margins and are smaller than normal pillows; in places hyaloclastite beds with basalt fragments variably abundant or of small size are present (Fig. 17), and more rarely breccia beds show sorting and grading (Fig. 18). Some breccias are composed of a few per cent of scoreaceous basalt globs in a larger proportion of fine grained more friable chloritic volcanic detritus.

The breccias occur in beds up to several metres thick throughout the Robert's Arm Group but they are concentrated in large bodies in the Boot Harbour fault belt where up to 600 m of breccia with some intercalated basalt are present locally. Local association of these large breccia bodies with felsitic centres and the fact that some breccia bodies are slightly discordant with the adjacent lavas may indicate that some of them developed on slopes

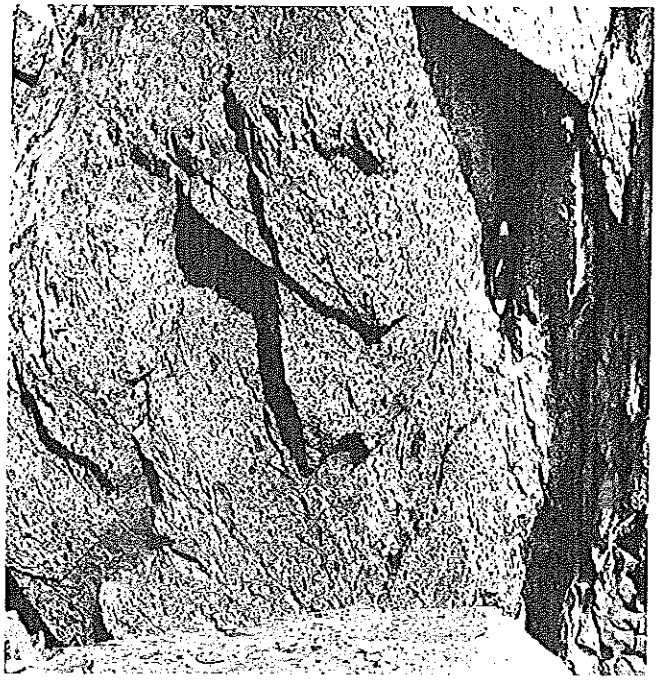

Figure 17. Fine hyaloclastic breccia in Robert's Arm Group on the south coast of Triton Island (GSC 179727).

Figure 16. Massive poorly sorted pillow breccia with hyaloclastic matrix in Robert's Arm Group north of Loon Pond (GSC 167178).

Figure 18. Bedded pillow breccia in Robert's Arm Group north of Loon Pond. Pillow fragments show within bed sorting and are graded in some beds (GSC 167174).

adjacent to local uplift that preceded or accompanied felsic volcanism. Examples of breccias composed of scoriaceous globs in more friable volcanic detritus occur in association with unpillowed or sparsely pillowed basalts on the west coast of Pilley's Island and at the head of the large bay southwest of Flat Rock Tickle where they may reflect spatter debris from a barely emergent volcanic terrane. Elsewhere pillow breccias containing rounded basalt masses with chilled margins like those of pillows resemble isolated pillow breccias of Quadra Island (Carlisle, 1963). Such breccias are concentrated in large bodies in the Crescent terrane south of Long Lake and northwest of Kippins Pond. Both of these latter breccia masses occur in association with siltstones of the Crescent Lake Formation, perhaps indicating that they are related to the margins of an extensive sea mount-like basalt accumulation within the Crescent Lake terrane. This basalt structure is characterized by flows that are more TiO_2-rich, but also more altered, than the rest of the Robert's Arm Group. As it is smaller than a typical sea mount and its origin can only be inferred it will be called "Crescent Hump".

Unit C: felsites

Felsitic rocks (keratophyres) of the Robert's Arm Group are particularly rare in Crescent Hump, but are common as minor bodies throughout the Southwest Crescent block. They are less common in Mud Pond terrane but are abundant in the upper part of Boot Harbour terrane where they form large volcanic centres which interleave laterally with the basic volcanics.

The felsites are fine grained to aphanitic, or in places glassy, and invariably contain albite phenocrysts mostly up to 1 or 2 mm in length, that are widely visible in hand specimen. Quartz phenocrysts are present in most of the small felsite bodies that occur within the Crescent terrane and fragments of quartz-phyric felsite are common in the associated greywackes, but a few of these felsite bodies have only plagioclase phenocrysts. In the remainder of the Robert's Arm Group the felsites are mostly devoid of quartz phenocrysts but are characterized by more or less abundant quartz-filled amygdules. This distinction appears to be accompanied in a general way by changes in the amount of volcanogenic sediments associated with the felsite. Thus in the centres outside Crescent terrane the proportion of felsite substantially exceeds that of greywacke, tuff or ash flow depsoits in the adjacent environment. In contrast the centres of Crescent terrane and Sops Head Complex commonly, although not always, possess aprons of sediment and ash flow material that may substantially exceed the volume of recognizable flows. The Loon Pond felsites, and felsites in the Pilley's Island Mine area, may be intermediate in this respect because both quartz-plagioclase-phyric and plagioclase-phyric examples have been found among them; and because, although all the other large centres of Boot Harbour belt are plagioclase-phyric and have little associated volcanic sediment, the Loon Pond centre has conspicuous accumulations of quartz-phyric volcaniclastic debris and ash-flow material in its general vicinity. Felsites in the Pilley's Island Mine area have associated breccias containing fragments up to about 15 cm and important tuffaceous horizons are described in reports of detailed examinations of the region.

The absence of quartz phenocrysts in some of the felsites suggests either that intratelluric cyrstallization never reached the cotectic in the $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O system (Bowen and Tuttle, 1958) or quartz phenocrysts have been resorbed completely as a result of shifts in the cotectic with changing volatile vapour pressure. The common presence of abundant silica-filled amygdules in quartz-aphyric felsites possibly favours the latter hypothesis. This, and the association of quartz-aphyric felsites in the same fault belt with shallow granite magma chambers may indicate that the presence of quartz phenocrysts has been controlled by the volatile composition and evolution in different types of magma chambers and conduits through which the magmas passed. Alternatively, there is some evidence in the chemistry of felsites that those from Crescent terrane, which are commonly quartz-phyric, are enriched in SiO_2 with respect to felsites in the major centres of Boot Harbour belt.

In thin section the felsites are seen to consist primarily of finegrained, unfoliated quartzofeldspathic matrix with minor finegrained chlorite, epidote and locally magnetite and pyrite. Accessory apatite is evident in some samples. Grain size varies but is mostly less than 0.8 mm. Traces of circular to ovoid structures, which locally cross matrix grain boundaries, suggest recrystallization of perlitic cracks, implying that many felsites were originally glassy. Albite phenocyrsts are euhedral to fragmental and twinned but unzoned. They are typically 1 to 2 mm in length, but in some specimens may exceed 4 mm. Coarsegrained quartz is common in amygdules in the Boot Harbour belt, and as corroded to fragmented phenocrysts in the felsites of the Crescent terrane. Spherulites are common in some felsites about the Pilley's Island Mine, and Grimley (1968) has described collapsed vesicles and flattened fragments which appear to have been moulded over other fragments.

Most felsites occur in massive structureless apparently tabular bodies up to 10 m or more thick which may be separated by thin basaltic pillow lava or by beds of sediment. Only rarely can they be seen to intrude the enclosing beds. In places breccias composed of greenish to brownish fragments mostly less than 10 cm in diameter occur in pink or orange felsitic matrix (Fig. 19). These breccias grade into more common mottled pink and green felsites in which the darker fragments are no longer distinct. Similar breccias were found in zoned felsite dykes on the southwest coast of Sunday Cove Island where outer zones of brownish felsite grade into pink cores containing brown fragments in varying stages of assimilation. These breccia dykes suggest that the brecciated to mottled structures seen in the larger tabular bodies may also be of hypabyssal rather than surficial origin. The mottled breccias are quite distinct from breccias seen about Pilley's Island Mine in which fragments and matrix are very similar.

Figure 19. Mottled felsitic breccia in Robert's Arm Group near Burnt Head. Green (dark) fragments with amoeboid to angular outlines are set in a pink felsitic matrix. "Fragments" in most mottled breccias are gradational into matrix (GSC 167200).

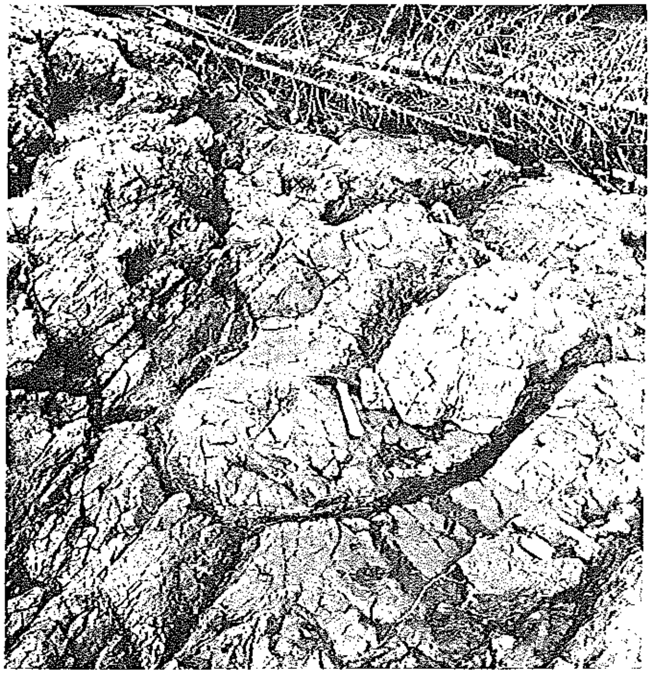

Figure 20. Felsitic pillow lava in Robert's Arm Group west of Haywards Head showing large pillows with altered rims surrounding a zone rich in white quartz amygdules (GSC 167094).

In a few places brown to purple, dense, glassy felsite forms large amoeboid or linguoid lenses in finegrained greenish, friable, thoroughly altered matrix. These felsites perhaps resemble the proximal part of a section through the distal region of a Precambrian submarine flow near Noranda, Quebec, described by Dimroth et al. (1979), but no transition to extreme distal or upper clastic facies was found. Locally near the margins of some felsite centres, dark brownish quartz-amygdule felsites of intermediate chemical composition show pillow-like structures commonly 2 to 2.5 m in diameter (Fig. 20). Only on Pilley's Island was flow banding seen in the felsites (Fig. 21).

The massive unbrecciated character of most felsite bodies, the suggested hypabyssal origin of the common mottled breccia structure, and the low proportion of other felsite breccias and felsite debris associated with the felsites, suggest that most felsite bodies were emplaced as dykes and shallow sills of low volatile content. For the same reasons the thick felsite body of limited lateral extent at the north end of Loon Pond may have been emplaced as one or more endogenous domes.

Unit D: submarine pyroclastic flow deposits

Distinctive buff-weathering green to pinkish rocks thought to be submarine pyroclastic flow deposits are most abundant southwest of Boot Harbour Second Pond. They also occur along the highway at the north end of Loon Pond, and on the east shore of Rocky Pond. The rocks are massive, vaguely foliated or bedded, and in places include lenses of fine breccia and beds of siltstone. Quartz grains up to 3 mm in diameter form up to several per cent of the rock. Rock fragments in the breccias

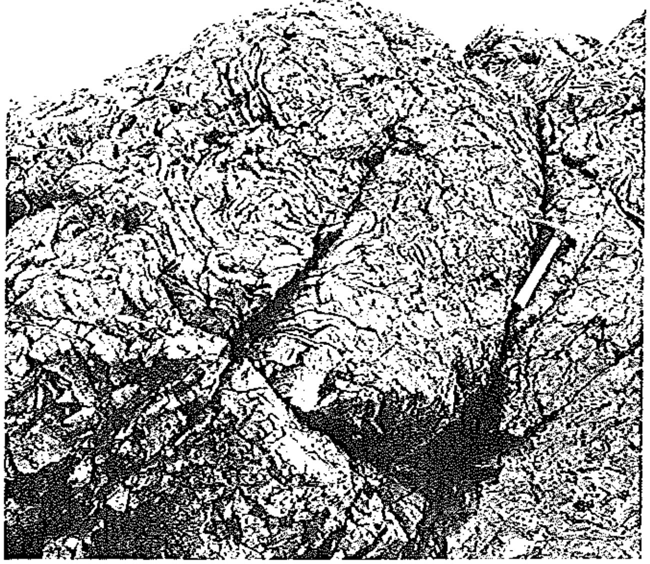

Figure 21. Flow banded felsite in Robert's Arm Group on Pilley's Island, near Spencer's Dock (GSC 167131).

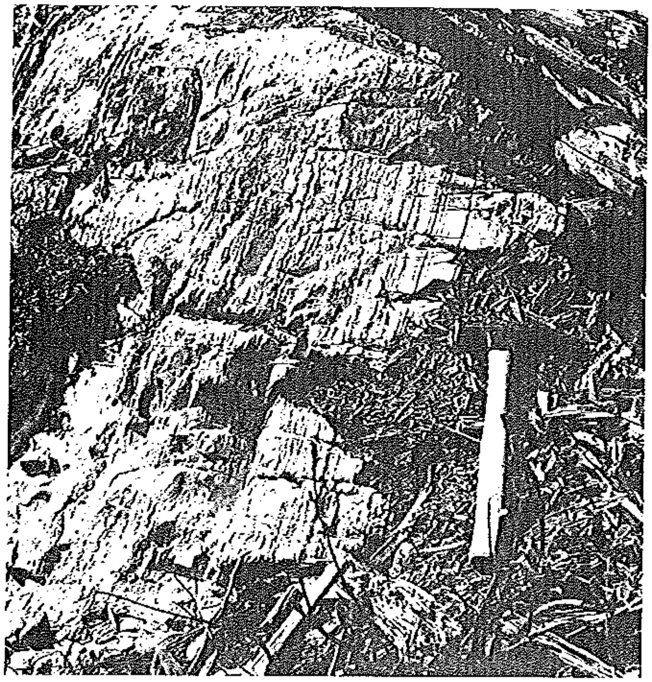

Figure 22. Felsitic banded tuff in Robert's Arm Group at Rocky Pond (GSC 179693).

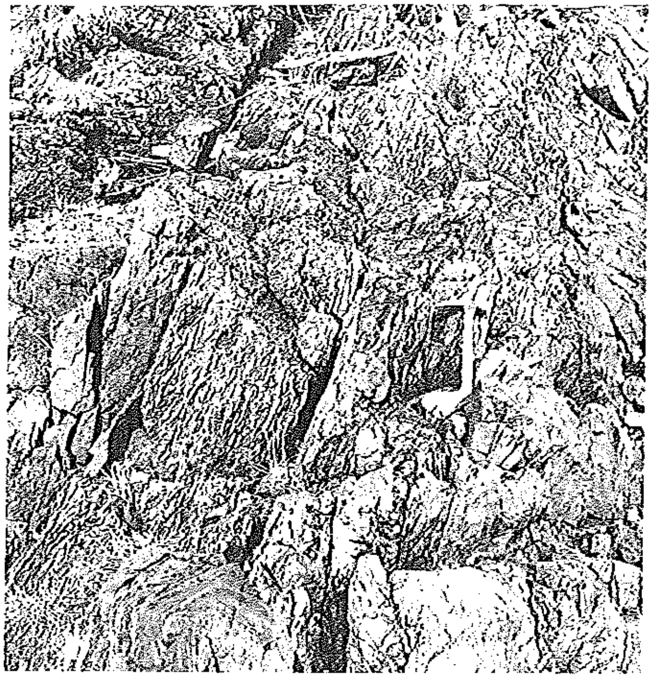

Figure 23. Siliceous-calcareous beds between basalt flows in the Robert's Arm Group west of Haywards Bight (GSC 167095).

include felsite and chert chips. In places in the more massive rocks small chloritic patches suggest the original presence of glass. In thin section the rock is seen to be composed of angular fragments or rounded corroded quartz grains up to 3 mm, plagioclase as subhedral fragments or glomerocrystic clusters, and chips of chert and felsite in a fine grained siliceous chloritic and epidote-bearing matrix. Some quartz grains are partly enclosed by fine grained quartz in parallel optical orientation resembling halos about quartz typical of some volcanic rocks. A few outcrops of banded felsic tuff (Fig. 22) may be distal equivalents of similar rocks.

Unit E: interflow sediments

Interflow sediments consisting of thin beds of chert, siltstone and greywacke occur widely within the Robert's Arm volcanics. The cherts are multicoloured in shades of red brown to salmon pink, buff cream, blue, green yellow, or black but the red-brown and cream cherts are the most common. Locally they contain scattered pyrite euhedra. The greywackes are mostly fine grained but in places display quartz grains up to 3 mm in diameter. Pink altered feldspar grains and chert chips commonly displaying bleached rims are present locally. Locally quartz seen in thin section is of volcanic origin. Some beds appear to be gradational into pyroclastic deposits, and most are probably submarine sediments of felsic tuffaceous origin.

Minor beds of limy sediments occur at the west side of Haywards Bight, on Haywards Gull Island, on Pretty Island, and southwest of Kippins Pond. At the first locality a band of cherty, pink-weathering, carbonate-rich sediment, 7.5 m thick lies between pillow lava flows (Fig. 23). Carbonate forms only about 30% of most beds but in a few it forms over 50% and some lenses of nearly pure carbonate are present. On the south shore of Haywards Gull Island brown weathering carbonate lenses up to 10 cm thick occur in red-brown cherty siltstone. A ten-foot limestone bed was reported by Dean and Strong (1976) on the northwest coast of Pretty Island. Foliated siliceous grey limestone occurs in a small outcrop between exposures of greywacke on a lone ridge west of Tommy's Arm River and southwest of Kippins Pond. Fragments of basalt and feldspar up to 3 mm are present within the limestone. No microfossils have been found in samples from any of these localities.

Unit F: minor intrusions

Dykes and sills of basalt, felsite and fine grained gabbro are intrusive into the Robert's Arm volcanics along the coast, and similar intrusions are less well exposed inland. The basalt dykes are typically fine grained, green to grey and locally amygdaloidal, closely resembling the basaltic country rocks. Those examined in thin section are mostly altered like the basalts, but a few (including dykes less than a metre thick) consist of euhedral to acicular pale brown-green amphibole in megacrystic habit, in a matrix of altered plagioclase with or without remnants of clinopyroxene, chlorite, epidote, magnetite-ilmenite and carbonate. These dykes presumably reflect local hydration of basalt magma.

Attitudes of 85 basalt dykes were measured, mostly along the sea coast. Because the rocks in which these dykes occur bend sharply across the top of the Sunday Cove pluton, the dykes were divided into two groups: one

Figure 24. A layered columnar basalt sill in the Robert's Arm Group at Burnt Head (GSC 167195).

south and west of Woodfords Arm (26), and the other on the mainland and Sunday Cove Island to the north and east (59). Mafic dykes are also concentrated about Robert's Arm, but measurements of these and dykes elsewhere were found to be too few and scattered to provide meaningful plots. In the southwestern region the dykes are nearly perpendicular to bedding and would have been striking in approximately the same northwesterly direction if rotated the necessary amount about the strike of bedding to return it to horizontal. Dykes north and east of Woodfords Arm show more scatter but are present in two maxima, one approximately perpendicular to bedding and one nearly parallel to it. One set of crosscutting relations suggests that the dykes which are nearly parallel to beds may form a younger set, but this younger set is also cut by felsite dykes and is therefore probably not appreciably younger than the first set. The apparent distribution and age relations of the dykes are consistent with the view that emplacement was facilitated by deformation that accompanied intrusion of the Sunday Cove pluton.

Small sill-like bodies of grey-green, medium- to fine-grained gabbro are interleaved locally with the Robert's Arm volcanics and are probably contemporaneous with them. Some are layered and in one columnar body at Burnt Head 44 layers showing alternate gradational and sharp contacts were counted (Fig. 24). Each layer is about 15 cm thick. Unlike other bodies in this group a well formed columnar structure is developed.

Somewhat larger, more irregularly shaped, and slightly coarser grained gabbro bodies intrude the Robert's Arm volcanics just north of Crescent Lake, about 2 km west of Crescent Lake narrows, and along the coast of Pretty Island. These bodies become finer grained at their margins and appear to interdigitate with the surrounding basalts. The gabbro is typically dark grey green, medium- to fine-grained and altered with locally prominent lathy plagioclase. In thin section the gabbro north of Crescent Lake is composed of medium- to fine-grained heavily saussuritized plagioclase and clinopyroxene remnants surrounded by chlorite-epidote patches. Magnetite-ilmenite grains are partly altered to fine grained leucoxene-like products, and the rock is cut by fine epidote veins. The Pretty Island gabbro is most highly altered along the southeast coast of the island where pyroxene is at least locally completely altered to pale green-brown amphibole forming interlocking prisms within recrystallized sodic plagioclase. Scattered patches of epidote are present. Farther north along Pretty Tickle thin sections of the gabbro show it to be distinctly less altered. There, medium grained, abundantly poikilitic clinopyroxene anhedra contain medium- to fine-grained intermediate plagioclase laths. Large magnetite-ilmenite grains showing altered exsolution intergrowths are present. Patches of chlorite-pumpellyite alteration form some 20% of the rock and are responsible for its green colour. For many of these gabbros their altered condition suggests that they are not much younger than the Robert's Arm volcanics, which they intrude; and it is possible that they represent small pools of intrusive magma beneath local volcanic orifices some of which presumably fed the superjacent flows. On the other hand, the poorly exposed gabbro body north of Crescent Lake may have been emplaced athwart part of the Crescent Lake-Tommy's Arm Fault system. It could thus be younger than at least some of these fault movements, or else movement could have been contemporary with volcanism.

Felsite dykes, lithologically similar to the felsites of the major centres, are scattered through the Crescent terrane, are rare in the Mud Pond terrane, and are scattered over most of the Boot Harbour terrane. They are concentrated beneath the felsites that overly the Sunday Cove granite pluton. A few dykes were observed about the margins of Loon Pond granite pluton, but the major felsite accumulation there appears gradational directly into the granite.

Attitudes for 39 felsite dykes were measured south and west (18), and north and east (21) of Woodfords Arm where the greatest concentration of dykes is evident. Like the basic dykes, both sets show diffuse maxima approximately parallel and approximately perpendicular to bedding, but the felsite dyke maxima are rotated slightly counterclockwise with respect to the basalt maxima. This suggests that the two types of dykes were related to similar stress patterns which may perhaps have developed at slightly different times.

In order to consider the combined dyke structure about Woodfords Arm, it is necessary to rotate the near vertical beds northeast of Woodfords Arm by about 30° counterclockwise about a vertical axis to bring them into approximate parallelism with beds striking southward into central Newfoundland. Execution of this rotation produces a diffuse maximum of steeply dipping northeast striking dykes subparallel to beds, and a sharper maximum of subvertical dykes approximately perpendicular to bedding strike. This maximum is not altered by subsequent rotation of bedding to horizontal because its poles are subparallel to the rotation axis. The data suggest that magma from the Sunday Cove pluton was intruded along northwest-trending fractures that may have reflected either northwest elongation of uplift over the pluton, or an independent fracture pattern due to compression perpendicular to the dykes.

Unit G: intrusive breccias

At least four small bodies of distinctive polymict breccia are poorly exposed on the western and southern flanks of the prominent hill about 2 km north-northeast of Loon Pond. Crosscutting relations were observed at one locality but the structure of the remaining showings, which reach up to at least 8 m in diameter, is unknown.

The breccias are distinctive in consisting of angular fragments up to 3 cm diameter of grey weathering dacite or andesite, pink or white quartz and plagioclase-phyric felsite, red chert, and locally amphibolite. The matrix varies in aspect from that of fine grained, tough, grey-green basalt to quartz-bearing grit. In thin section the matrix of the breccia is invariably of low metamorphic grade indicating that amphibolite fragments were metamorphosed elsewhere. Magmatic matrices are trachytic and plagioclase-rich. Quartz bipyramids, epidote chips, glass fragments and chlorite chips were observed in gritty matrices.

The unique lithology and clustering of these breccias within a single limited area suggest an unusual environment of origin. One interpretation is suggested by the fact that the area in which they occur comprises the northwestern tip of the inverted (southeast-facing) basalt block lying east and northeast of Loon Pond pluton. This part of the block may have occupied the present position of the Loon Pond pluton and may have been pushed northeastward in front of the advancing granite during its intrusion. In this scenario the breccias are interpreted as diatremes which formed in the plug during or shortly before its ejection.

Chemistry of some basalt minerals

Chemical analyses of several minerals occurring in the Robert's Arm basalts have been made for specific purposes. Pyroxenes and plagioclase representative of the various fault belts have been analyzed to see whether they could be used to characterize the individual terranes; and in the case of pyroxenes, to see if information relating the basalts to specific tectonic environments could be obtained. The pyroxene data, although limited by the few analyses of material from the Crescent terrane, suggest that this belt may contain a different pyroxene population from that present in the Mud Pond and Boot Harbour terranes. The plagioclase proved to be entirely albite except where the rocks have been raised to epidote amphibolite metamorphic grade. All plagioclase was found to contain minor Fe and K. Ferric iron, which substitutes for Al, is high in the most calcic (remetamorphosed) plagioclase within the aureole of the Sunday Cove granite, and in some albites from the Crescent Lake fault belt.

Several prehnites were analyzed because many of the prehnite occurences appeared to have lower than normal birefringence. Prehnite from the Mud Pond and Boot Harbour terranes were found to be unusually iron-rich, whereas a prehnite with normal birefringence from the Crescent terrane was found to have low iron content typical of most prehnites.

Garnets were found at five localities in the Robert's Arm Group and one was selected for analysis. The composition shows that it is an andradite probably derived from low grade metamorphism of calcareous material within the basalt.

Mineral grains analyzed were obtained from thin sections of samples taken for rock analysis from the Mansfield, northern Crescent, northern Pilley's sections, and in the case of garnet from the southern Robert's section. All mineral analyses were carried out by laboratory staff at the Geological Survey of Canada using an electron microprobe under conditions specified in Appendix 1.

Augite

Pyroxene crystals analyzed were selected chiefly from the Mansfield Cove section (Tables 5A, B, C). Probe data were reduced first to 12 charges and then to two cations by oxidation of iron. Both equigranular and porphyritic basalts were included. Where both phenocrysts and matrix grains occurred together, several separate analyses were made of matrix grains, phenocryst cores and phenocryst rims. None of the rock samples from the Crescent terrane contained pyroxene phenocrysts and only two contained matrix grains sufficiently unaltered for analysis. One of these samples contained a mixture of clear grains and slightly bluish-grey grains. These two types have distinct compositions and have been treated as separate samples (Nos. 41 and 941). Zoning is evident in many of the pyroxene phenocrysts studied but is not always obvious in thin section depending partly on the crystal orientation.

The pyroxene compositions indicate a trend from crystallization of early phenocryst material of restricted composition toward more iron-rich phenocryst rims as might be expected at the end of the intratelluric phase (Fig. 25). This phase was commonly followed by resorption of phenocrysts shown by some rounding and absence of phenocrystic material of matrix grain composition. Such resorption may have accompanied upward surges of new magma that preceded eruption and crystallization of matrix grains. If so the tendency of matrix grains to be iron-rich with respect to phenocryst rims suggests that differentiation continued though this phase of magma evolution which did not involve simple mixing of more primitive magmas into those that were erupted. The

Table 5. Analysis of clinopyroxene

A. Matrix grains

Section	Mansfield															Crescent			Pilley's
Terrane	Crescent			Mud Pond					Boot Harbour							Mud Pond		B.H.	N.Pil
Sample No.	50*	41*	941*	12	14	16	21	25	29	36	69	72	972	103	120	83	86	116	61*
SiO_2	44.96	50.61	46.96	50.83	51.81	51.37	46.26	49.85	50.42	51.61	46.83	49.91	50.16	46.62	46.11	49.62	50.19	50.48	50.66
TiO_2	2.88	0.69	1.72	0.42	0.35	0.35	2.20	0.66	0.45	0.37	1.07	0.75	0.75	1.54	1.09	0.50	0.72	0.55	0.43
Al_2O_3	6.67	2.90	5.59	3.60	2.83	3.28	7.51	4.06	3.38	3.24	7.96	5.01	4.36	6.80	8.05	5.27	5.21	3.17	3.67
Cr_2O_3	0.08	0.11	0.06	0.20	0.10	0.19	0.12	0.00	0.05	0.08	0.17	0.21	0.01	0.03	0.00	0.12	0.13	0.08	0.14
FeO_t	11.28	11.39	12.57	6.29	6.88	7.98	11.20	9.76	8.72	6.66	8.09	7.70	10.58	11.27	9.03	6.61	7.99	9.33	6.65
MnO	0.25	0.29	0.25	0.15	0.15	0.21	0.15	0.25	0.25	0.13	0.13	0.13	0.24	0.24	0.07	0.16	0.18	0.25	0.11
MgO	10.56	15.92	12.83	16.72	16.57	17.05	11.10	14.59	14.99	16.74	13.87	15.45	15.67	13.45	13.39	14.69	15.17	15.46	15.92
CaO	22.32	17.61	19.27	20.85	21.25	19.37	22.02	20.80	21.24	21.18	21.59	21.49	18.75	20.55	21.97	22.47	20.72	20.66	21.99
Na_2O	0.36	0.40	0.49	0.13	0.07	0.08	0.14	0.07	0.10	0.04	0.16	0.09	0.27	0.15	0.02	0.20	0.30	0.15	0.09
Total	99.36	99.92	99.74	99.19	100.01	99.88	100.70	100.04	99.60	100.05	99.87	100.74	100.79	100.65	99.73	99.64	100.61	100.13	99.66
Si	1.712	1.878	1.766	1.875	1.902	1.888	1.733	1.852	1.875	1.891	1.732	1.826	1.842	1.730	1.715	1.832	1.838	1.866	1.867
Ti	.082	.019	.049	.012	.010	.010	.062	.018	.013	.010	.030	.021	.021	.043	.030	.014	.020	.015	.012
AlIV	.288	.122	.234	.125	.098	.112	.267	.148	.125	.109	.268	.174	.158	.270	.285	.168	.162	.134	.133
AlVI	.011	.005	.014	.032	.024	.030	.065	.030	.023	.031	.079	.042	.031	.027	.068	.061	.063	.004	.026
Cr	.002	.003	.002	.006	.003	.006	.004	.000	.001	.002	.005	.006	.000	.001	.000	.004	.004	.002	.004
Fe_3	.136	.104	.156	.074	.057	.062	.085	.087	.083	.059	.136	.091	.103	.167	.158	.089	.076	.107	.085
Fe_2	.223	.250	.240	.120	.154	.183	.266	.216	.188	.145	.114	.145	.222	.183	.122	.115	.168	.182	.120
Mn	.008	.009	.008	.005	.005	.007	.005	.008	.008	.004	.004	.004	.007	.008	.002	.005	.006	.008	.003
Mg	.599	.881	.719	.919	.907	.934	.620	.808	.831	.914	.765	.843	.858	.744	.742	.809	.828	.852	.875
Ca	.911	.700	.777	.824	.836	.763	.884	.828	.846	.831	.856	.842	.738	.817	.875	.889	.813	.819	.868
Na	.027	.029	.036	.009	.005	.006	.010	.005	.007	.003	.011	.006	.019	.011	.001	.014	.021	.011	.006

* Samples in which only matrix clinopyroxene was found.

Note: B.H. = Boot Harbour terrane sector of Crescent section.
N.Pil = Boot Harbour terrane sector of Pilley's section.
Samples 41 and 941 represent distinctly clear and bluish grey grains from the same thin section.

B. Phenocryst rim zones

Section	Mansfield								Crescent	
Terrane	Mud Pond		Boot Harbour						M.P.	B.H.
Sample No.	14	25	29	36	69	972	103	120	83	116
SiO_2	50.52	50.22	51.10	51.25	51.05	49.61	49.87	48.74	51.15	50.58
TiO_2	0.59	0.42	0.23	0.28	0.29	0.59	0.55	0.69	0.34	0.52
Al_2O_3	4.11	3.58	2.44	3.35	3.80	4.66	4.16	5.89	4.34	3.38
Cr_2O_3	0.04	0.05	0.04	0.35	0.54	0.05	0.14	0.03	0.22	0.17
FeO_t	7.99	7.90	7.83	5.22	5.24	8.17	8.71	7.59	5.26	9.00
MnO	0.12	0.20	0.23	0.03	0.02	0.12	0.10	0.09	0.09	0.18
MgO	15.42	15.52	14.61	16.38	16.11	15.06	14.87	15.10	16.18	15.13
CaO	21.50	21.29	22.88	22.50	21.87	21.04	21.10	21.96	22.83	21.27
Na_2O	0.10	0.04	0.08	0.04	0.05	0.14	0.19	0.09	0.13	0.09
Total	100.39	99.22	99.44	99.40	98.97	99.44	99.69	100.18	100.54	100.32
Si	1.861	1.867	1.903	1.886	1.888	1.841	1.850	1.791	1.860	1.868
Ti	.016	.012	.006	.008	.008	.016	.015	.019	.009	.014
AlIV	.139	.133	.097	.114	.112	.159	.150	.209	.140	.132
AlVI	.039	.024	.010	.031	.054	.045	.032	.046	.046	.015
Cr	.001	.001	.001	.010	.016	.001	.004	.001	.006	.005
Fe_3	.072	.087	.078	.059	.030	.090	.096	.131	.078	.089
Fe_2	.174	.158	.166	.101	.132	.164	.174	.103	.082	.189
Mn	.004	.006	.007	.001	.001	.004	.003	.003	.003	.006
Mg	.837	.860	.811	.899	.888	.833	.822	.827	.877	.833
Ca	.849	.848	.914	.887	.867	.837	.839	.865	.890	.842
Na	.007	.003	.006	.003	.004	.010	.014	.006	.009	.006

Note: M.P. = Mud Pond terrane sector of Crescent section
B.H. = Boot Harbour terrane sector of Crescent section

C. Phenocryst core zones

Section	Mansfield								Crescent		Pilley's
Terrane	Mud Pond		Boot Harbour						M.P.	B.H.	N.Pil
Sample No.	14	25	29	36	69	972	103	120	83	116	56
SiO_2	50.15	50.81	50.46	51.15	50.62	50.58	51.07	48.87	50.62	50.61	51.74
TiO_2	0.63	0.37	0.38	0.34	0.33	0.40	0.24	0.61	0.41	0.30	0.27
Al_2O_3	4.19	3.25	3.81	3.24	3.44	4.09	3.58	5.54	4.60	3.11	3.36
Cr_2O_3	0.18	0.07	0.04	0.48	0.31	0.20	0.44	0.01	0.19	0.14	0.35
FeO_t	7.14	6.80	6.50	5.49	6.08	5.99	5.06	6.69	6.06	7.01	5.30
MnO	0.11	0.18	0.14	0.10	0.08	0.07	0.12	0.06	0.07	0.25	0.08
MgO	15.94	15.71	15.55	16.31	15.82	15.86	16.67	15.63	15.94	15.65	16.48
CaO	21.12	22.16	22.29	22.31	22.52	22.06	22.42	22.24	22.72	21.88	22.52
Na_2O	0.07	0.06	0.11	0.06	0.07	0.01	0.00	0.04	0.06	0.13	0.05
Total	99.53	99.41	99.28	99.48	99.27	99.26	99.60	99.69	100.67	99.08	100.15
Si	1.852	1.880	1.867	1.884	1.872	1.869	1.874	1.798	1.843	1.879	1.890
Ti	.018	.010	.011	.009	.009	.011	.007	.017	.011	.009	.007
AlIV	.148	.120	.133	.116	.128	.131	.126	.202	.157	.121	.110
AlVI	.034	.022	.033	.025	.022	.047	.029	.038	.040	.015	.035
Cr	.005	.002	.001	.014	.009	.006	.013	.000	.005	.004	.010
Fe_3	.078	.079	.085	.063	.084	.056	.072	.133	.092	.095	.053
Fe_2	.143	.131	.116	.106	.104	.129	.083	.073	.092	.123	.109
Mn	.003	.006	.004	.003	.003	.002	.004	.002	.002	.008	.002
Mg	.878	.867	.858	.895	.872	.874	.912	.857	.865	.866	.898
Ca	.836	.879	.884	.880	.893	.874	.881	.877	.886	.870	.882
Na	.005	.004	.008	.004	.005	.001	.000	.003	.004	.010	.004

Note: M.P. = Mud Pond terrane sector of Crescent section
B.H. = Boot Harbour terrane sector of Crescent section
N.PIL = Pilley's section (north)

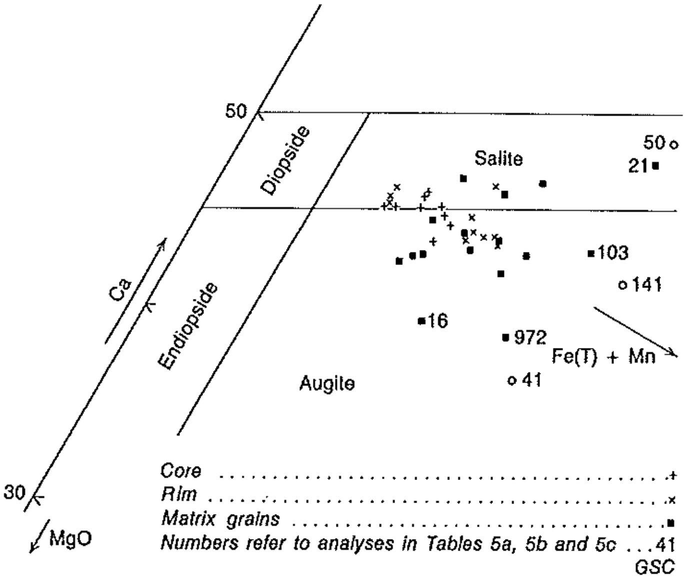

Figure 25. Clinopyroxene Ca-Mg-(Fe_t + Mn) diagram showing core (+), rim (x), and matrix grains (•).Numbers refer to analyses in Tables 5a, 5b, and 5c.

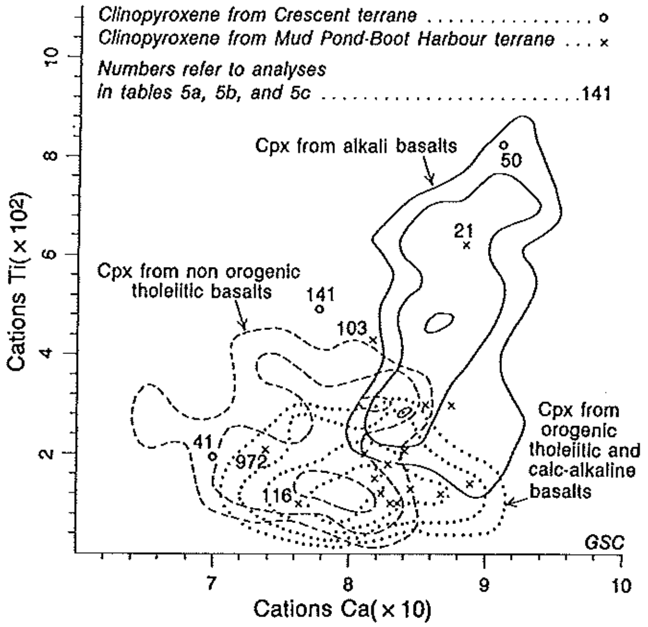

Figure 26. Clinopyroxene, Ca vs. Ti plot for matrix grains only showing compositional fields (Leterrier et al., 1982) for clinopyroxene from alkali basalts solid contours), nonorogenic tholeiitic basalts (dashed contours), and orogenic tholeiitic to calc-alkaline basalts (dotted contours).Numbers refer to analyses in Tables 5a, 5b, and 5c.

tendency of matrix grains to be similar to, or distinctly higher in Al(IV) than are the rims on phenocrysts from the same sample may reflect cramming of Al into tetrahedral pyroxene sites during eruption. It is consistent with the results of Mevel and Velde, (1976) who found that total Al could be correlated with increased rate of cooling of pyroxene in basalts.

Comparison of pyroxenes from the various terranes shows that FeOt, MnO and Na_2O contents of the three samples from Crescent terrane are equal to or higher than all those from both Mud Pond and Boot Harbour terranes. The Crescent terrane pyroxene may also tend to be higher in TiO_2 and lower in MgO than that from the other two terranes. Comparison of Mud Pond with Boot Harbour terrane, on the other hand, shows very similar ranges for all elements suggesting that the major contrast is between Crescent terrane and combined Mud Pond — Boot Harbour terrane.

Interpretation of tectonic environment can be made by comparing the Robert's Arm pyroxene data with contoured variation diagrams given by Leterrier et al. (1982). Although the data are few, matrix pyroxenes from the Cresent terrane extend from the field of alkali basalts into the central part of the field for anorogenic tholeiites (Fig. 26). This is consistent with the abundance of plagioclase phenocrysts in the rocks and common high Ti of the pyroxene. Matrix grains from the Mud Pond and Boot Harbour terranes plot mostly in the field for orogenic tholeiitic and calc-alkaline basalts. In the corresponding plots for phenocrysts (not shown) the Mud Pond-Boot Harbour data fall entirely within the field for orogenic tholeiites. The pyroxene data therefore support the view that the Robert's Arm Group encompasses two tectonic settings. The Crescent terrane, of anorogenic tholeiitic pyroxene type may be interpreted as an ocean floor or back arc possibly transitional to alkaline setting, whereas the combined Mud Pond-Boot Harbour terrane, of orogenic tholeiitic pyroxene type may be seen as an island arc tholeiitic, possibly transitional to calc-alkaline setting.

Plagioclase

Analyses of plagioclase from 23 samples from the three fault belts of the Robert's Arm Group were made. All but two are albites. Crystals analyzed include cores and rims of phenocrysts, matrix grains and plagioclase in amygdules. No zoning is visible in thin section and in only one sample were consistent changes between rims and cores apparent. In this sample three phenocryst rims were slightly more calcic (0.3% An) than the corresponding cores, but this difference is of marginal significance. Matrix grains and amygdular plagioclase likewise show variation within the range of other grains within their respective host rocks. Potash contents are erratic varying up to 13.6% Or in one spot analysis but most grains have Or percentage 1 or less even in this sample. The mean Ab percentage is in the range 91.2 — 98.2 except for two samples from within the aureole of the Sunday Cove granite. In those samples the Ab percentage is erratic ranging from 68.7 to 84.2. Ab ranges for other individual spot analyses only fall below 90% where K_2O is high.

Small amounts of iron are present in all the plagioclase presumably as Fe^{+3} substituting for Al^{+3}. Two samples from the Crescent Lake terrane and the two within the aureole of the Sunday Cove granite have distinctly more iron than the rest. The latter two are presumably more iron-rich due to calcification during

Table 6. Prehnite from the Mansfield section

(Ions calculated on the basis of 14 metal ions per unit cell with Fe_2-Fe_3 distribution based on charge balance).

Sector	Crescent Hump	Mud Pond	Boot Harbour	
Samp. No.	50	14	69	120
SiO_2	44.05	43.46	43.35	42.66
Al_2O_3	23.71	20.23	18.43	18.78
FeO_t	1.27	6.20	7.76	7.45
CaO	26.88	26.15	26.40	26.45
Total	95.91	96.04	95.94	95.34
Si	6.054	6.054	6.078	6.010
Al	3.841	3.321	3.046	3.119
Fe_3	.050	.152	.798	.861
Fe_2	.096	.151	.112	.017
Ca	3.959	3.903	3.966	3.966
Z	6.054	6.054	6.078	6.010
Y	3.891	3.893	3.844	3.980
X	4.054	4.054	4.078	4.010

amphibolite facies metamorphism and the consequent requirement of additional trivalent ions necessary to balance Ca substitution for Na. Plagioclase from the Crescent terrane on the other hand might be more iron-rich because the magma from which it crystallized contained more available Fe^{+3}, a situation consistent with two of the three pyroxene analyses from this belt.

Prehnite

Prehnite is commonly present in the basalts in most parts of the Boot Harbour terrane where it occurs both as larger crystals (up to 2 mm) in amygdules and as fine grained alterations within the basalt matrix. It was not found in the inverted slices about Loon Pond, or in the aureole about Sunday Cove granite, and is rare in the Boot Harbour terrane basalts on Pilley's and northern Triton islands.

In the Mud Pond terrane prehnite is typically finer grained. It is commonly present except in an area about and south of Robert's Arm, none being found in the Robert's Arm section south of Robert's Arm village.

Only a few occurrences of prehnite are known in the Crescent Lake terrane. All are in the southwest part of the terrane, the most northerly being a prehnite vein near the southeast end of Mansfield section. Most of the prehnite occurences are associated with veins but some are alterations of basalt matrix like those in the two belts to the northwest.

Prehnite from 4 polished thin sections representing each of the belts was analysed by electron probe (Table 6). Cations for each analysis were calculated on the basis of 14 metal cations with Fe^{+2}-Fe^{+3} distribution inferred from charge balance. Regardless of which method of calculation is used the presence of significant iron in the ferrous state is indicated. Total iron increases in these samples from Crescent through Mud Pond to Boot Harbour terranes and is reflected mainly in increasing substitution of ferric iron for aluminium. Investigation of additional samples is required to determine whether this is a characteristic difference between the three terranes. Comparison of these prehnites with those reported by Deer et al. (1963) suggests that the Boot Harbour prehnites may be unusually iron-rich (up to 7.76 wt. % FeOt in Boot Harbour basalts compared with 1.26 wt. % FeOt, Deer et al., 1963). Little difference in d-spacing is evident between prehnites in this study.

Table 7. Garnet from the Robert's section

(Ion calculation based on 24 oxygens per unit cell.)

Sample No.	1110A	
SiO_2	35.95	
Al_2O_3	1.57	
Cr_2O_3	.02	
FeO_t	27.35	
MnO	.95	
MgO	.63	
CaO	32.26	
Total	98.73	
Si	5.929	6.000
Al	.071	
Al	.235	4.011
Cr	.003	
Fe+3	3.773	
Fe+2	0.000	5.990
Mn	.133	
Mg	.155	
Ca	5.702	

Garnet

Garnet, colourless in thin section, was observed at several places in the Robert's Arm basalts. The garnet analyzed (Table 7) occurs in the eastern part of the Robert's section just north of Crescent Lake where it is associated with chlorite, carbonate and quartz in irregular patches. Crystals are small and scattered but commonly euhedral. Incipient amphibole needles are present in adjacent chlorite patches and along the margins of clinopyroxene crystals. A single altered, anhedral garnet grain was observed in basalt from the Mansfield section in the central part of the Mud Pond terrane. The host basalt is fine grained, altered and aphyric. The garnet may be xenocrystic. Garnet also occurs in patches with carbonate in amphibolite poorly exposed along Sunday Cove fault lineament. Amphibole in this amphibolite is pleochroic brown with thin rims of pale green amphibole suggesting retrogression from higher metamorphic grades than are characteristic of the surrounding basalts.

Seven spot analyses were made by electron probe on cores and rims of three different grains from the Crescent Lake garnet. Differences between spot analyses are small and show no consistent pattern to suggest zoning, so the analyses have been averaged. Cation values were calculated on the basis of 24 oxygens. Charge balance indicates that the iron is in the ferric state and the analysis is very similar to andradites reported by Deer et al., (1963).

Granitic plutonic rocks

Granitic plutonic rocks of the Robert's Arm Group comprise the Loon Pond pluton (at Loon Pond in the southwest part of the area), the Sunday Cove pluton southwest of Sunday Cove, and a small body just north of Boot Harbour Pond. Hybrid and granitic to dioritic rocks occur along the lower fault contact of the Sunday Cove Pluton, and similar rocks occur in a fault wedge along the same fault south of the pluton. These plutons are distinct from the Mansfield Cove plagiogranite because of their higher potash contents.

The Sunday Cove pluton consists of massive pink to grey-white, medium- to fine-grained, chlorite-biotite granite to granodiorite. In places irregular to amoeboid inclusions of darker, fine grained plutonic rocks are present and one deformed inclusion of amygduloidal basalt was seen. Numerous, thin, northwesterly trending mafic dykes are evident within the pluton along the shore, and one of these examined in thin section proved to be amphibolite. Typically, the rock consists of fine grained subhedral plagioclase with highly altered cores and strongly zoned oscillatory normal rims intergrown with somewhat larger quartz grains. In some granite specimens zoned plagioclase is commonly enclosed in cloudy altered potassium feldspar. Up to 5% of mafic minerals, chiefly chlorite and epidote, are present. Remnants of biotite are common and locally chlorite appears to have been derived from alteration of hornblende. Sericite and fine grained muscovite are present in some specimens. Accessory minerals comprise sphene, apatite, magnetite and zircon.

The Loon Pond pluton consists of massive fine grained grey-green to pink stained granodiorite. Mafic minerals are altered to chlorite-epidote but amphibole is evident in roughly half the specimens examined. The granodiorite is intruded locally by mafic dykes but these are not as common as dykes within the Sunday Cove pluton. Slightly feldspar-phyric rocks with finer matrices are transitional to felsite locally along the north and east margins of the intrusion, but although patches of granodiorite reach about 2 mm grain size sporadically in the southern part of the intrusion, there does not appear to be much overall change in grain size from north to south in the main body.

In thin section the granodiorite is seen to consist of sodic plagioclase, quartz, chlorite and epidote with brown-green pleochroic hornblende forming a substantial part of some sections, and fine muscovite is present in others. Sphene, apatite, magnetite zircon and carbonate are accessory minerals. Myrmekitic intergrowth of quartz-plagioclase is pronounced in some specimens.

The Boot Harbour Pond body is poorly exposed at the crest of a low hill north of Boot Harbour Pond; and a few large blocks of similar rock are present, possibly representing underlying outcrop, along the south side of a small pond to the north. Outcrop at the top of the hill consists of massive grey-white weathering, buff-green, medium- to fine-grained, granodiorite cut by epidote veins. Large blocks at the north end of the hill comprise massive pink-stained, medium grained, chlorite-epidote granodiorite cut by fine grained siliceous veinlets. No thin sections were examined.

Granitic to mafic plutonic rocks along the Sunday Cove fault are very poorly exposed on the forested hillside northeast of Boot Harbour Pond. The best showing near the top of the steep part of the hill consists of a series of small rounded ledges which barely pierce overburden. They are composed of pink, medium- to fine-grained, massive, chlorite granite bearing epidote veins. The rock resembles the Sunday Cove granite more closely than the Boot Harbour Pond granodiorite.

Farther down the hill are scattered smaller showings of dark green medium-to fine-grained massive hornblende diorite cut by granite veins and later epidote veins. Loose blocks of similar lithology were found on the same hillside about two thirds of a kilometre farther south. In thin section the granite consists of quartz, untwinned potassium feldspar in excess of altered sodic plagioclase, chlorite, sericite and allanite. Quartz encloses plagioclase as it does in the Sunday Cove granite. Tiny breccia veins are evident in thin section. The hornblende diorite consists mostly of brown-green hornblende and saussuritized plagioclase with minor epidote, quartz and magnetite. Epidote veins have fine grained margins and coarse interior zones. Some rocks resemble amphibolite found along the same fault north of Sandy Pond.

Chemical analyses

Two samples of granitic rocks were collected from the Sunday Cove pluton for analysis representing pink and grey-white phases along the shore of Woodfords Arm. Four samples of Loon Pond granodiorite and one of immediately marginal felsite were collected about Loon Pond. The data are shown in Table 8. The analyses suggest a wide range of composition within both plutons extending from granite to granodiorite. This range is similar to that shown by the felsites within the Robert's Arm volcanics, although the felsites include a few compositions that are substantially less potassic than any of the rocks analyzed from the two plutons.

Examination and comparison of these limited data indicate that the two samples taken closest to the north (vent) end of the Loon Pond pluton are more potassic, less sodic and have higher Rb and Zr contents than two samples taken nearer the southern interior end. This suggests that further studies of possible chemical zoning within Loon Pond pluton might be of interest. Comparison of two samples from Sunday Cove pluton with those from Loon Pond pluton suggest a similarity between interior parts of Sunday Cove pluton and the vent proximal phase of Loon Pond pluton.

Age and correlation of the Robert's Arm Group

The oldest rocks clearly belonging to the Robert's Arm Group are those of the Crescent Lake Formation. This formation occurs at the base of one of the fault blocks within Crescent terrane and is probably involved in the Sops Head Complex immediately beneath the easternmost major fault block of the terrane. Minor limestone, which occurs within fault slivers along the southeast margin of the Sops Head Complex, contains late Llanvernian-Llandeilian conodonts (Nelson, 1981) in a section which also contains altered basalts like those of Crescent terrane. These basalts might therefore indicate a locally preserved late Llanvernian-Llandeilian base for the Robert's Arm Group. On the other hand Dean (1978) and Nelson (1981) have interpreted the limestone and at least some of the basalts in these slivers as allochthonous; and Nelson has suggested that the limestone was originally deposited on top of the Robert's Arm Group and was, during late Orodivican time, transported by slump and debris flow into the adjacent sedimentary basin. By this interpretation the rocks exposed in fault slivers on the southeast margin of the Sops Head Complex are Upper Ordovician sediments of potential Sansom equivalence and the fossiliferous limestone "blocks" which occur within them provide a minimum late Llanvernian-Llandeilian age for the Robert's Arm Group. Nelson's (1981) interpretation is favoured in this report.

Within the Robert's Arm Group itself no fossils have been found. The Crescent Lake Formation is overlain apparently conformably by the basalts of Crescent terrane which occur in two major units separated by an oblique fault. To the west and north Mud Pond and Boot Harbour terranes are also separated by faults which are nearly parallel to bedding. Although any of these faulted terrane boundaries could be the locus of regional strike or dip slip, this seems less likely because the Robert's Arm Group shows some features suggesting internal integrity. Evolutionary physical and mineralogical variations progressing from Crescent through Mud Pond to Boot Harbour terrane have been discussed and some similar chemical changes will be described in the section on basalt chemistry. Loon Pond pluton is thought to be intrusive into rocks of Crescent terrane but is a feeder to felsites interleaved with Boot Harbour terrane, indicating that apparent age relations between these terranes derived from facing directions are consistent with the true age relations so far as they are known. No extraneous units recognizably unrelated to the regional Robert's Arm setting have been inserted within the group along these boundary faults. The group is therefore regarded as comprising faulted remnants of an assemblage of rocks that were originally spatially related.

Radiometric dating of the Robert's Arm Group (Bostock et al., 1979) indicates an Rb-Sr isochron age of 447 ± 7 Ma*, and a statistically similar age of 464 ± 13 Ma* for the Sunday Cove granite. Inasmuch as field relations suggest that granite and felsite are coeval, there is every reason to believe that the true age of both the felsites in the upper part of Robert's Arm Group and the granitic plutons have an age of about 455 Ma. This corresponds approximately to a Llandeilian age on the Van Eysinga (1975) scale, essentially the same age as that indicated by the Sops Arm conodonts which Nelson (1981) suggested were deposited in limestone immediately overlying the Robert's Arm Group.

Correlation of the basalts of Crescent terrane with those of Hall Hill Complex is unlikely because there is a large proportion of fine- to medium-grained clastic sediments associated with the Crescent terrane basalts, that is typically absent in the Hall Hill Complex and in related rocks of the Hungry Mountain Complex to the south. Direct correlation with basalts of the Lushs Bight Group exposed immediately north of the Lobster Cove fault seems unlikely because the Crescent terrane basalts appear to lie conformably upon a chert-shale-greywacke sequence (Crescent Lake Formation), whereas the Lushs Bight basalts are thought to form part of an ophiolite succession of which sheeted dyke and gabbro layers are exposed just north of Pilley's Island.

No detailed correlation is possible between Mud Pond and Boot Harbour belts. An attempt to determine paleomagnetic pole positions for a series of sites through the Mud Pond and Boot Harbour belts along Mansfield section provided a scatter of points about an early Paleozoic primary pole position for both belts, but no further conclusions could be drawn (Schwarz and Bostock, 1978).

Correlation of the Robert's Arm Group with other volcanic units within the Central Mobile Belt of Newfoundland may be based on fossil or radiometric ages, or upon similarity of the stratigraphic package within which they occur. Thus the Lawrence Head volcanics and the basalts of the Summerford Group across Notre Dame Bay to the east have comparable fossil ages established for conformable sediments which immediately overlie them. Similarly the Wild Bight volcanics are overlain by Caradocian black shales. Other units, while less precisely dated, are part of a similar stratigraphic package comparable to the Robert's Arm Group-

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* Insert footnote referring to Na/Ca *[1]. [1] The Na/Ca* ratio is determined using the value for CaO recalculated by subtracting the wt. % CaO necessary to combine with CO_2 and resetting negative values to zero. CaO* refers to the value for CaO produced by this subtraction.

Table 8. Chemical analysis of Loon Pond and Sunday Cove granite plutons

Pluton Sample No.	Loon Pnd 1025	Loon Pnd 1024	Loon Pnd 1023	Loon Pnd 1022	Sun. Cv. 27	Sun. Cv. 28
SiO_2	63.50	69.50	63.30	62.50	73.00	64.30
TiO_2	0.96	0.47	1.00	1.05	0.19	0.66
Al_2O_3	16.40	14.50	15.90	15.90	14.30	16.40
Fe_2O_3	1.60	1.20	0.40	2.10	1.30	1.50
FeO	3.10	1.90	5.10	3.60	0.70	2.70
MnO	0.15	0.04	0.10	0.08	0.03	0.04
MgO	2.00	1.25	1.82	2.21	0.55	1.88
CaO	3.64	1.70	2.12	3.90	1.07	3.12
Na_2O	4.60	4.60	6.00	5.10	4.00	3.90
K_2O	3.30	3.28	1.39	1.18	4.51	3.39
P_2O_5	0.32	0.14	0.35	0.40	0.06	0.31
H_2O	1.20	0.90	1.50	1.50	0.70	1.10
CO_2	0.60	0.40	0.90	0.09	0.50	0.09
S	0.01	0.01	0.77	0.01	0.03	0.10
F	0.09	0.05	0.09	0.11	0.05	0.10
Cl	0.08	0.03	0.02	0.02	0.05	0.07
FeO_t	4.54	2.98	5.46	5.49	1.87	4.05
Total	101.55	99.97	100.76	99.75	101.04	99.66
Li	2	2	4	3	1	2
Rb	49	55	21	21	125	104
Cs	1.7	.6	1.7	4.8	.1	.1
Sr	256	193	121	248	105	265
Ba	1640	1860	1760	1080	1200	1245
V	50	19	28	76	19	64
Zr	152	171	93	117	154	161

Sops Head Complex. In this category the Cottrels Cove Group of Fortune Harbour Peninsula (Strong, 1977) and perhaps the Chanceport Group of New World Island (Strong and Payne, 1973) may be included. To the southwest the Buchans Group (Thurlow, 1981), which comprises a variable assemblage of basic and felsic rocks, has an identical Rb-Sr isochron age (447 ± 18 Ma, Bel and Blenkinsop, 1981). Nowlan and Thurlow (1984) have recently shown that the age of limestone blocks within the Buchans breccias, which they argue are of local penecontemporaneous origin, is Middle Ordovician (Arenig to early Llandeilian). This disposition of the correlative units discussed above suggests that the Robert's Arm Group is part of an extensive, but perhaps discontinuous belt of Middle Ordovician volcanics that extends from New World Island in the east to Buchans in the southwest.

Sedimentary rocks of central Notre Dame Bay

The southeastern contact of Robert's Arm Group comprises part of a tectonic zone which increases in width within the map area (about Sops Head Complex). It projects across Notre Dame Bay to the east and also continues, presumably as a zone of faulting, for some distance southwestward beyond the present area. Within the tectonic zone, rocks potentially derived from formations both to the southeast and northwest, but likely including a predominant component of Robert's Arm Group, have been faulted and commonly penetratively deformed. In this section the general character of the formations lying to the southeast of the tectonic zone is reviewed, though mapping for the present project has not covered all of the Sops Head Complex and has only locally reached its contact zone with these rocks.

The oldest rocks southeast of the fault zone are greywackes of the Wild Bight Group. These are conformably overlain along their northern boundary by Caradocian chert and shale of the Shoal Arm Formation which are commonly fossiliferous. This widespread marker horizon is overlain by a variety of lithologies within which no local indigenous fossils have been found, but which are considered by Dean (1978) to be correlative with the Upper Ordovician Sansom Formation of eastern Notre Dame Bay.

Wild Bight Group

The Wild Bight Group immediately south and east of Kippins Pond consists of buff to olive-brown weathering, grey-green greywacke and chert with local graded bedding, scour and fill, intraformational conglomerate and slump structure. Thin blue-grey plagioclase-phyric basalt sills are present locally within the sediments. Some beds contain phyllosilicate flakes. Attitudes of bedding taken at 14 outcrops within the Wild Bight Group indicate that the rocks adjacent to the Robert's Arm Group form part of a single large northeastward-plunging, southeastward-overturned anticline.

The age of the top of the Wild Bight Group is confined by fossils in the overlying Caradocian Shoal Arm Formation. According to Dean (1978) the Wild Bight Group extends in conformable sequence some 10 km thick down to the Omega Point Formation at the core of the Seal Bay anticline. East of this anticline the group is in fault contact with undated rocks of the South Lake igneous complex (Lorenz and Fountain, 1982) that are comparable in part to the late Precambrian Hall Hill Complex of this report. The age of the base of the Wild Bight Group is therefore uncertain.

Shoal Arm Formation

The Shoal Arm Formation, originally defined by Espenshade (1937), was redefined by Dean (1978) to apply to Caradocian argillites and cherts which he believed to conformably overly the Wild Bight Group everywhere in the Notre Dame Bay area. By his definition the formation consists of a lower unit of banded red and green to black chert or cherty shale overlain by black carbonaceous shale. According to Dean, fauna from the Badger Bay area indicate a **Nemagraptus gracilis** zone age (Caradoc) for the black shale member. Only one isolated outcrop of black slaty shale belonging to this formation was examined during the present project.

Sansom Formation

The Sansom Formation was originally defined by Heyl (1936) in the Bay of Exploits area of eastern Notre Dame Bay, and later workers have continued use of the name as mapping progressed. Dean (1978) extended use of the name into western Notre Dame Bay where he believed lithologically similar greywacke and pebble conglomerates occupy the same relative position in the stratigraphy. McKerrow and Cocks (1981), working in eastern Notre Dame Bay, recognized several olistostromes and mass flow deposits interbedded with turbidites within the Sansom Formation. Their olistostromes include basalt, conglomerate and limestone in addition to greywacke, an assemblage that resembles rocks in fault slivers along northwestern Sops Arm. Within the map area rocks typical of the Sansom Formation are found only on the southeast half of Kay Island.

The Sansom Formation on Kay Island consists almost entirely of quartz-bearing greywacke and conglomerate. Cobbles and pebbles of leucocratic quartz diorite, more mafic rocks, and some felsite occur scattered through the greywacke and in discrete beds within it. One conglomerate bed on the northwest coast is 15 m thick, consisting of quartz dioritic roundstones up to 46 cm diameter and some more mafic clasts in a dense green matrix. Beds strike generally west-northwest to west, dip steeply north to vertical, and face northward. Basaltic rocks of Sops Head Complex on the northwest half of the island, although their attitude is less well defined, appear to trend northeasterly with steep dips across the trend of the greywackes. The contact therefore appears to be a fault.

Sops Head Complex

The Sops Head Complex comprises part of a regional tectonic zone extending eastward beneath Notre Dame Bay to Fortune Harbour Peninsula, and possibly southwestward where it apparently merges with faults within and west of Robert's Arm Group. Within the map area this zone may be divided into two subzones neither of which have been completely mapped. The eastern of these is confined to the Sops Arm area and comprises a series of fault slivers within which both mafic volcanics and fine to coarse clastic sediments and minor limestone are present. To the west a long southwestward-tapering wedge of deformed shales with local greywacke beds, containing local volcanic centres, follows the southeast contact of Robert's Arm Group.

Fault sliver zone

Lithologies in the zone of fault slivers comprise two different assemblages. One consists primarily of clastic sediments of which the constituent conglomerates bear some similarity to those seen in the Sansom Formation on Kay Island. The other consists primarily of mafic volcanic rocks and breccias which bear some similarity to the Robert's Arm volcanics. Both assemblages locally appear to be in contact within the same fault sliver, but many of these contacts could also be faults.

Unit A: fine clastic sediments

Interbedded slaty shale, siltstone, greywacke, some conglomerate and basalt of unit A are exposed in two slivers along the northwest shore of Sops Arm where they can be seen for only a few metres above tide level; and are exposed in incompletely mapped slivers inland at the southwest limit of mapping near Fifields Pond. At Sops Arm the southwestern sliver starts near the southwest end of the arm with greywacke containing an interval of conglomerate in excess of 15 m wide. Cobbles, chiefly of leucocratic quartz diorite resembling the Mansfield Cove plagiogranite, but including some felsite and more mafic volcanic clasts, occur in the quartz-bearing greywacke matrix (Fig. 27). Farther northeast grey limestone up to 10 m thick lies within a section of siltstone, mudstone, greywacke and minor basalt. This limestone with accompanying thin mafic volcanics appears at two places along the coastline about 600 m apart. Within the central part of the bight formed by bedding and these two exposures, similar limestone with associated minor volcanics was found some tens of metres inland. Although the rocks are considerably fractured, and limestone in places occurs between pillow-like basalt blocks, it appears that there is a continuous limestone-bearing horizon with associated

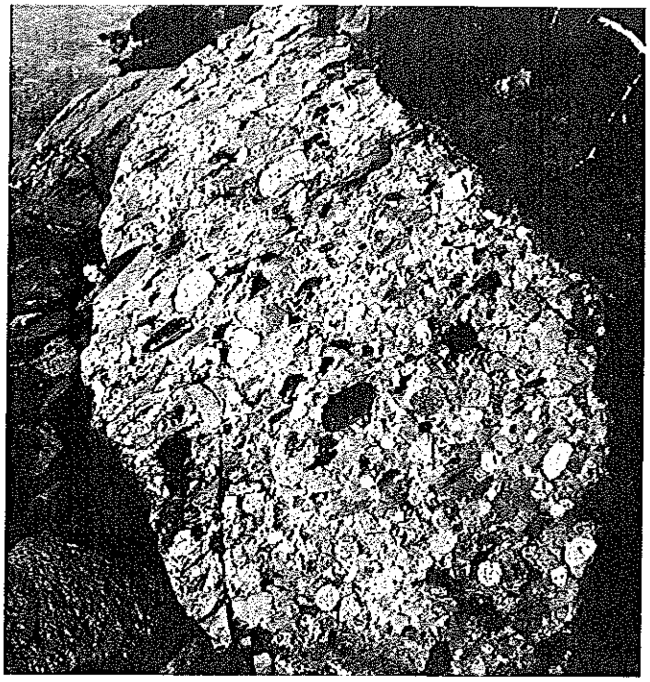

Figure 27. Plutonic cobble conglomerate with volcanic matrix in Sansom greywacke on the northwest shore of Sops Arm (GSC 167283).

minor basalt within the greywacke-siltstone section. A patch or block of similar limestone occurs within basalt on the west shore of Kay Island. Bedding in the southwest sliver dips 75-90° northwest and cleavage is commonly present dipping more steeply than bedding. At the southwest end of Sops Arm, scour and fill, and graded beds indicate that the strata are northward facing.

Samples of limestone from the shoreline were collected by Williams (1969) and by the writer in search of microfossils, but none were found. Nelson (1981), however, reported limestone blocks on the north shore of Sops Arm from which he obtained a fairly abundant conodont fauna. The precise age of this fauna (Stouge, 1980, *in* Nelson, 1981) he reported as Late Llanvernian-Llandeilian (zones of the Scandinavian conodont faunal succession; Bergstrom, 1971).

Uphill to the northwest of the southwestern sliver, sediments of unit A pass abruptly into schistose basalt of unit B, but the actual contact is not exposed. Southwest of Kay Island these basalts come down to the coast over an interval of some 500 m. Minor chert beds within greenschist at the northeast end of this interval strike 212° dipping 65° northwest. It is possible, therefore, that the two units may be stratigraphically conformable with unit B overlying unit A, but they may also be separated by a fault.

The northeastern sliver of unit A consists mostly of interbedded quartz-bearing greywacke and grey slate. Slate chip conglomerates occur locally. Thin buff carbonate beds are present at one place near the southwest end of the sliver and some basalt at the northeast end may belong within it. Beds within the northeastern sliver strike roughly parallel to the shore and dip from 65 to 90° northwest. Graded beds in the greywacke at one place suggest that they face northwest. Uphill to the northwest sediments of unit A pass abruptly into basalts of unit B. Unlike the southwestern sliver, however, the northeastern one has numerous minor folds which plunge north at about 40°.

Several possibilities for interpretation of the structure between the two belts of unit A exist. There is, however, a break in the ridgeline to the northwest of the inverval of basalt which separates them, and a lineament, visible on air photographs, suggests that an oblique fault passes through this gap. It seems most likely that the two slivers are part of two large overlapping fault lenses. Faulting oblique to these lenses is evident south of Sops Head where the Sops Head fault reaches the coast, and faulting is suggested at the west corner of Sops Arm where quartz veins and disturbed bedding are present on either side of the incoming creek.

Unit B: mafic volcanics

Within the zone of fault slivers, mafic volcanic rocks of unit B are present mainly on Kay Island, in the hills west and northwest of Sops Arm, and at the southwest end of Sops Arm. On Kay Island unit B consists chiefly of basalt, greenschist and breccia, with local interbeds of greywacke and slate up to 3 m thick. Near the southwest point of the island a contorted patch or block of limestone some 3 m in diameter occurs within the basalt. The small island north of Kay Island consists of pyroxene- and plagioclase-phyric basalt with lenses of greenschist and calcareous greenschist locally containing fragments of basalt. The west side of the island is largely breccia composed mostly of amygdaloidal to massive basalt fragments up to 15 cm diameter, but scattered pale grey feldspar-phyric felsite clasts are also present.

The ridgeline immediately northwest of unit A along Sops Arm is capped by altered medium to pale green variably schistose basalts commonly showing minor quartz veining. Although internally complicated by faulting, these basalts interdigitate southwestward with greywacke containing quartz and locally small felsic volcanic clasts. They also pass laterally southwestward into pale greenish-grey more highly altered argillaceous rocks that are partly basaltic breccias composed of amygdaloidal to massive basalt fragments commonly 5 cm in diameter, and partly more massive but altered rocks, possibly derived from basalt or argillite. Volcanic breccia containing fragments of basalt and locally felsite up to 25 cm in diameter, carbonate-bearing grenschist and some slaty siltstone are exposed at the head of Sops Arm.

Shale wedge zone

The shale wedge zone comprises a southwest-tapering block bordered on the north by Tommy's Arm, on the northwest by Robert's Arm volcanics, and on the east by the zone of fault slivers. Southwest of Fifields Pond mapping for this project did not reach the southeast boundary of the zone, but near Kippins Pond a single traverse crossed directly from deformed slaty shales into less deformed greywackes of the Wild Bight Group without an intervening zone of discrete fault slivers. All contacts are known or assumed to be faults.

The principal component of the complex comprises grey to greenish or black often silty or cherty, slaty shales with scattered commonly dismembered beds and lenses of quartz-bearing greywacke. Volcanic centres involving both felsic and mafic volcanics occur within these shales southwest from Sops Head, near Fifields Pond and west of Kippins Pond. A few small bodies of basalt and agglomerate, possibly representing isolated basalt flows, occur between the centres. In contrast to the greywacke beds, these larger volcanic bodies, although penetratively deformed in the northeastern part of the zone, do not appear to have been dismembered.

The Sops Head centre is comparable to other centres within the lower unit of the Robert's Arm Group in consisting of two or more quartz-phyric aphanitic green flows surrounded by an apron of apparently unbedded, whitish-weathering, fine grained, quartz-bearing detritus on all sides except the top (northwest). To the northeast this material is mostly intensely sheared and passes gradationally into, or interlenses with, greenschist and basalt near Sops Head. To the southwest it passes gradationally into grey slaty to cherty shales with a southwestward decreasing component of quartz-bearing greywacke. Near the apron along its western side, rock fragments up to 3 cm diameter were observed locally in the slaty shale. Mostly these are of quartz-phyric felsite, but at one place a clast of biotite granodiorite was observed. Rocks along the southeast margin of the complex are intensely sheared particularly near Sops Head. Scattered pyritiferous gossans occur within the felsite along its northwest margin where felsite passes rapidly into slaty shales. The spatial distribution of lithologies about the complex suggests that, although it has been deformed by shearing, it represents a coherent northwest-facing unit that has not been substantially dismembered.

The Fifields Pond centre has been only partly mapped. It consists primarily of fine grained, medium-green, massive spilitic basalt, but some outcrops at the northeast end of the centre are coarser grained, more bluish green, and contain distinctive laths of plagioclase. No contacts between these and the more normal basalts were found but they do not appear to form dykes. In thin sections of this latter basalt, altered intermediate plagioclase in laths commonly 1 to 2 mm in length are predominant with scattered remnants of colourless clinopyroxene. Mafic minerals have been largely altered to chlorite but late fibrous amphibole with distinctive blue and grey-brown pleochroism suggestive of soda amphibole is present locally in association with chlorite patches. Roughly 2% of altered magnetite-ilmenite, 1% of apatite and traces of sphene are also present. One or more bodies of massive, aphanitic, grey-green felsite occur along the northwest margin of the basalt, and a thin breccia, consisting of small clasts of fine grained felsite in a matrix of altered plagioclase and minor quartz grains, was found along the southeast margin of the basalt.

Fractured, altered massive basalt and greenschist about 152 m thick with some interbedded greywacke, siltstone and minor limestone occur along a small ridge west of Kippins Pond and immediately west of Tommy's Arm River. In thin section these basalts consist of plagioclase, clinopyroxene, epidote, chlorite, carbonate, magnetite-ilmenite, minor sericite, and quartz. Locally pumpellyite-bearing stringers are present. Plagioclase is mostly intensely altered but comprises albite microlites in ophitic quench textures with clinopyroxene in one section. These basalts are separated by only a thin band of shaly rocks from the main part of the Robert's Arm Group, which they resemble.

Structure within the Sops Head Complex is complicated because of the abundance of incompetent pelitic rocks. That deformation has been severe is indicated by the strength of foliation and the occurrence of polyphase minor folds and folded cleavage along the south shore of Tommy's Arm. Remnants of beds and foliation are typically parallel, striking northeasterly and dipping steeply. Thirty minor folds were measured within the complex and these are mostly steeply plunging with poorly defined maxima near vertical and near 60° southwest. A few minor folds, seen along Tommy's Arm, trend east-northeast with subhorizontal axes. Of the steeply plunging folds ten suggest right hand displacement, three suggest left hand displacement, and in the remainder no sense of displacement could be determined. These axes are not closely parallel to fold axes in the fault slivers to the southeast, but are more like those in the Crescent terrane. This suggests that rocks on either side of their contact have undergone a different strain history, or have been differentially rotatated, and therefore supports the view that their contact is a fault.

Chemical analyses of rocks within Sops Head Complex

Chemical analyses were made of one dense, pale green, quartz-phyric felsite flow from the Sops Head centre, and two basalts from the northeast end of the Fifields Pond centre. The results are shown in Table 9. Partial analyses were also made for five slates and greywackes from the Sops Head Complex in order to determine their TiO_2 and P_2O_5 contents for comparison with altered basalts in the lower part of the Robert's Arm Group (Table 10).

Most of the basalts from the Sops Head Complex appear closely comparable petrographically to altered (spilitic) basalts in the southeastern part of Crescent terrane. Two examples from the ridge southwest of Kippins Pond are given in Table 9. Two basalts from the northeast end of the Fifields Pond centre are petrographically atypical of spilites in the Robert's Arm Group in the coarse lathy texture of their plagioclase and their blue-green relatively less altered aspect. Analyses indicate that these atypical basalts have high FeOt/MgO, high Zr and P_2O_5, and low V with respect to those southwest of Kippins Pond. Values of these chemical characteristics lie more than one standard deviation beyond those for each of the Robert's Arm lithologies in all of the Robert's Arm terranes. For Zr and P_2O_5 they lie well beyond all individual analyzed values for Robert's Arm basalts. These latter two elements suggest comparison with the late, presumably Mesozoic, dykes which have lower values that are nevertheless greater than those of Robert's Arm basalts. Other elements, particularly Na_2O, MgO, TiO_2, V, and Cr, however, do not show comparable ranges. The distinctive texture of these rocks seems to indicate that they do not belong to the Robert's Arm Group and are therefore of post Robert's Arm age. The high contents of Na_2O and H_2O suggest that they have undergone metasomatic alteration which may have involved addition and subtraction of other elements.

The compositions of slates and greywackes from the Sops Head Complex are not unusual for such rocks derived from a predominantly volcanic terrane. Mean TiO_2 and P_2O_5 values (Table 10) are substantially below those of the basalts in Crescent Hump which overlies them along most of the western contact of Sops Head Complex. This suggests that these sediments did not provide a source from which the high values in basalts of Crescent Hump could have been derived.

Table 9. Chemical analysis of volcanics from Sops Head Complex

Lithology	Felsite	Alk Bslt	Alk Bslt	Spilite	Spilite
Sample No.	682	612a	612b	1076	1075
SiO_2	72.80	49.30	53.60	46.30	49.60
TiO_2	0.21	1.84	1.22	1.36	1.71
Al_2O_3	13.60	15.20	16.30	15.70	14.80
Fe_2O_3	1.20	4.80	4.70	1.90	7.10
FeO	0.70	9.80	7.70	8.80	5.00
MnO	0.05	0.29	0.25	0.21	0.20
MgO	0.24	2.58	1.62	7.50	7.50
CaO	2.53	5.35	3.98	9.70	5.90
Na_2O	3.90	4.90	5.30	3.20	4.30
K_2O	2.29	0.79	2.24	0.05	0.95
P_2O_5	0.06	1.59	1.05	0.17	0.26
H_2O	0.90	4.40	3.40	4.60	3.20
CO_2	0.20	0.09	0.10	1.10	0.40
S	0.02	0.01	0.01	0.01	0.01
F	0.02	0.07	0.02	0.03	0.04
Cl	0.01	0.03	0.06	0.01	0.03
FeO_t	1.78	14.12	11.93	10.51	11.39
Total	98.73	101.04	101.55	100.64	101.00
Li	2	23	14	23	26
Rb	28	8	20	3	32
Cs	.4	5.1	3.5	1.1	2.2
Sr	80	357	249	90	143
Ba	286	273	247	37	134
V	24	34	19	249	264
Zr	134	497	627	61	67
Cu	-	14	45	92	51
Zn	10	90	100	90	110
Co	-	35	20	53	45
Ni	-	34	18	110	70
Cr	-	12	6	58	93

Table 10. Chemical analysis of shales and greywackes from Sops Head Complex

Sample No.	709B	718B	724A	1303B	1317A	Mean	S.D.
SiO_2	64.40	54.60	58.50	54.60	57.75	57.97	4.01
TiO_2	0.71	0.59	0.77	1.15	0.74	0.79	0.21
Al_2O_3	14.50	17.10	16.30	17.80	17.30	16.60	1.29
Cr_2O_3	0.05	0.02	0.04	0.04	0.02	0.03	0.01
Fe_2O_3	1.20	2.30	1.60	2.10	1.20	1.68	0.51
FeO	4.00	6.70	5.80	7.10	7.30	6.18	1.35
MnO	0.10	0.22	0.08	0.13	0.11	0.13	0.05
MgO	3.72	3.46	3.99	4.22	3.98	3.87	0.29
CaO	0.43	3.08	1.02	2.21	0.39	1.43	1.18
Na_2O	2.60	5.80	4.90	3.80	5.15	4.45	1.26
K_2O	2.59	0.79	0.81	1.70	1.03	1.38	0.77
P_2O_5	0.13	0.16	0.10	0.19	0.13	0.14	0.03
H_2O	4.30	3.70	4.30	5.20	4.50	4.40	0.54
CO_2	1.40	0.80	1.90	0.30	0.40	0.96	0.68
S	0.01	0.01	0.02	0.01	0.05	0.02	0.02
FeO_t	5.08	8.77	7.24	8.99	8.38	7.69	1.61
Total	100.14	99.33	100.13	100.55	100.05	100.04	
Rb	80	40	60	50	80	62	18
Sr	50	330	190	150	85	161	109
Ba	400	320	180	310	215	285	88
Zr	240	50	140	140	100	134	70
Zn	110	110	60	130	135	109	30
Ni	90	20	130	80	70	78	40

Age and correlation of rocks within Sops Head Complex

Dean (1978) and Nelson (1981), on the basis of regional mapping in Notre Dame Bay east of Robert's Arm area, considered the Sops Head Complex, and the Boones Point Complex of Fortune Harbour Peninsula, to be western and eastern extensions of the same tectono-stratigraphic unit. Nelson (1981) described evidence, in part from rocks east of the Robert's Arm area, to suggest that this unit may be regarded as a high strain zone within an elongated belt of subaqueous debris flow deposits. He suggested that it marks the west to north boundary of a sedimentary basin into which Sansom Formation equivalent sediments were shed from an emergent Robert's Arm terrane during late Ordovician. The Sops Arm limestone, of late Llanvernian-Llandeilian age, was considered to have been deposited initially on top of Robert's Arm Group, from whence it was eroded during late Ordovician thrusting of the Robert's Arm Group southeastward over the basin margin. Independent evidence for thrusting of this type was found in parallel strike and north- to westward-facing directions in Sansom Formation and Robert's Arm Group on either side of the proposed thrust, and the apparent superposition of older Robert's Arm Group on younger Sansom Formation. Deposition was by coarse debris flow at the foot of an advancing thrust sheet. This hypothesis places a minimum late Llanvernian-Llandeilian age on the Robert's Arm Group.

The above hypothesis is tempered in the writer's view by insufficient clarity of evidence of allochthonous origin of the fossiliferous Sops Arm limestone. These occurrences could be interpreted as occurring along a single stratigraphic horizon within which thin competent basalt and limestone have been disturbed but not drastically rearranged. Some limestone could have been deposited in cavities in the basalt. This interpretation would imply that the enclosing rocks are the same age as the limestone, and would negate their correlation with the Sansom Formation. On the other hand, deposition of limestone and basalt "blocks" along one or a few discrete horizons may account for the observed distribution. Nelson's interpretation is accepted here because it appears possible. Similar relations are reported by him within mélange deposits farther east along the tectonic zone, and the age constraints which it introduces permit correlation of conglomerates, which have no counterparts in Robert's Arm Group, with similar conglomerates in the Upper Ordovician Sansom Formation.

Following Nelson's (1981) interpretation, the Sops Head Complex can be viewed as a thickened section of the tectono-stratigraphic zone boundary between emergent Robert's Arm Group and an Upper Ordovician sedimentary basin to the southeast. Thickening may reflect local ploughing up, or squeezing into dilatent zones, of overridden shale along the boundary thrust active in the Upper Ordovician. The zone of fault slivers, mapped as part of the Sops Head Complex, represents the faulted margin of the southeastern sedimentary basin receiving coarse clastics, perhaps including major elongate wedges of basalt, from the northwest. Sediments overridden by the thrust are likely to have included both the older Crescent Lake Formation and recently deposited sediments of the Sansom basin itself, but may have included isolated volcanic centres erupted in the Crescent Lake shale basin.

Springdale Group

The term, Springdale Formation, was first used by Espenshade (1937) for red beds in the Springdale and Pilley's Island areas. MacLean (1947) elevated the formation to group status in the Little Bay area where it was found to include volcanic units. Kalliokoski (1953, 1955), mapping to the southwest of the present area, found the group to be predominantly volcanic.

The Springdale Group is exposed within the present map area on Sunday Cove, Pilley's Island and Triton Island. At these localities only 185 m or less of section are preserved between the Robert's Arm-Springdale unconformity on the south and the Lobster Cove Fault on the north. On eastern Triton Island the Lobster Cove Fault cuts down into the Robert's Arm Group and only one small isolated fault remnant of Springdale Group is known. Similar rocks together with felsic and mafic flows are more extensively exposed in the Springdale area to the west of Halls Bay.

On Sunday Cove Island and Pilley's Island the group comprises up to 185 m of red siltstone and sandstone with conglomerate (Fig. 28) and locally reworked talus-like breccia (Fig. 29) along its contact with the Robert's Arm Group. Siltstone and sandstone occur in beds from laminae to 1.6 m thick. Crossbedding indicates current flow both from the east and west. Intraformational conglomerate (mud chip breccia) was observed at one locality. Clasts in conglomerates, which reach about 1 m in diameter on the east coast of Pilley's Island, comprise felsite, basalt, chert, siltstone, sandstone, quartz diorite and minor fine grained granitic rock.

On Triton Island conglomerate is absent and up to roughly 15 m of breccia (Fig. 29), comprising mostly basalt fragments but including up to 10% of gabbroic rock and red chert-argillite, are present at the base of the Springdale. Fragments locally reach 10 cm but are mostly 3 to 5 cm in diameter. Local crossbedded red

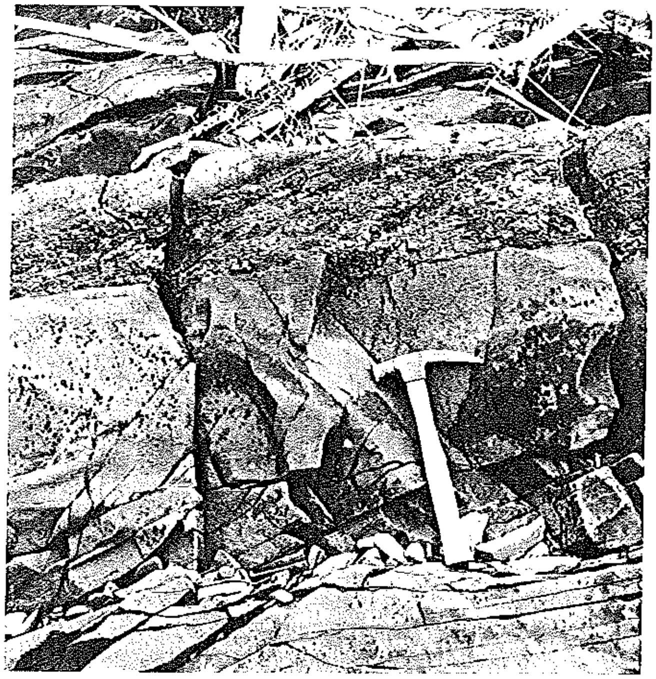

Figure 28. Overturned steeply dipping redbeds in the Springdale Group on the west coast of Pilley's Island (167104).

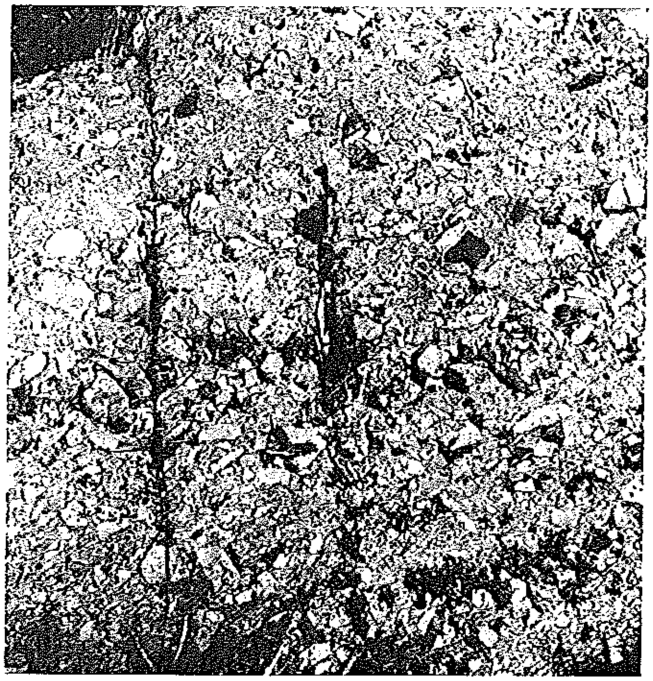

Figure 29. Breccia in the Springdale Group on Triton Island (GSC 179728).

sandstones suggest current flow from the east. The basal beds are overlain by up to 15 m of sandstone and siltstone including isolated finer breccia beds. Graded sandstone beds 15 cm thick are evident locally in the lower part of this sequence and crossbeds suggesting current flow from the west were observed in overlying beds. Mudcracks occur at one locality.

Five cobbles from the conglomerates on Pilley's Island were examined in thin section. Two felsite cobbles consist of pink plagioclase-phyric felsite with quartz amygdules (like those in the upper Robert's Arm Group) in a fine siliceous matrix. Epidote, sericite, chlorite, and carbonate are minor constituents, and hematite, magnetite and sphene are accessory. One abundantly amygdaloidal basalt cobble consists of a felted mass of plagioclase microlites with interstitial opaques. Amygdules are filled predominantly by carbonate, but patches of fine polycrystalline quartz are also present. One fragment of greywacke consisted of small felsic rock fragments the boundaries of which are commonly indistinct in a matrix of angular to subrounded grains of quartz and plagioclase. One quartz diorite cobble consists mostly of albitic saussuritized plagioclase with roughly 20% quartz and 5% mafic minerals altered to chlorite-epidote. Subhedral plagioclase appears to penetrate and be included within quartz.

The contact between Springdale and Robert's Arm Groups (Fig. 30) is exposed at several places on Pilley's and Triton islands where it is clearly unconformable. Recent road construction northeast of the old Pilley's Island mine has exposed about 55 m of section with up to 10 m of basal breccia containing intercalated sandstone near the top and overlain by red siltstones. The basalt below the unconformity has limonitic colour banding outwards from fractures, and breccia fragments are banded subparallel to fragment edges. Matrix of the breccia is sandy with a sideritic carbonate cement. On Bumble Bee Cove conglomerate containing boulders up to 0.3 m in diameter in places directly overlies the basalt whereas in other places siltstone forms the first beds above the Robert's Arm Group. Minor local faults in the volcanics do not penetrate the conglomerate and siltstone. On Pilley's Tickle conglomerate with boulders up to 1 m in diameter directly overlies altered basalt of the Robert's Arm Group.

On the south shore of Long Arm at the west end of Triton Island the unconformity projects southwards above low tide level for about 100 m along the coast. At this locality breccia with local crossbedded sands directly overlies relatively little altered basalt. At the east end of Triton Island on the south point of Grand Dismal Cove a faulted outlier of Springdale sediments about 60 m long and 30 m wide grades from breccia through altered basalt into fresher basalt beneath, over a distance of several metres.

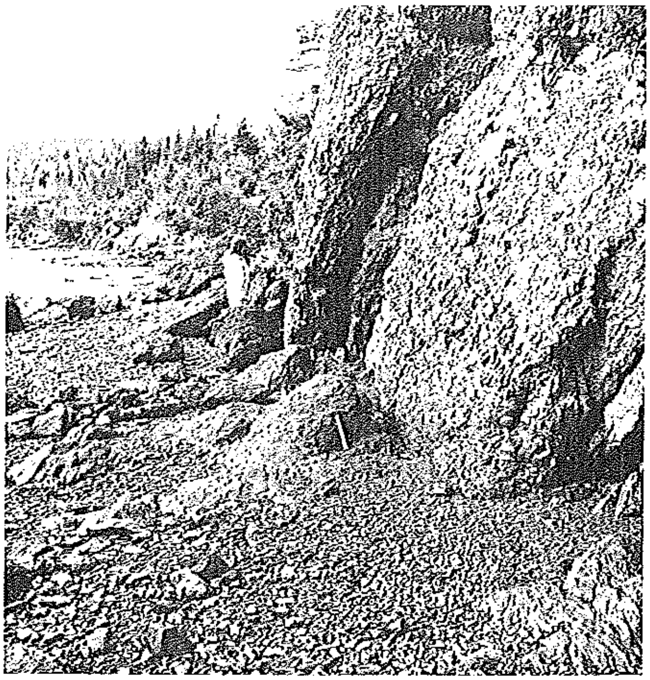

Figure 30. View westward along the steeply dipping unconformity between Springdale Group (bluff on the right) and felsite of the Robert's Arm Group (tide level on the left; GSC 167290).

All of the Springdale outliers within the map area lie along the Lobster Cove Fault. All face north and are steeply dipping to northward overturned; but minimum dips of about 60° north are prevalent on Sunday Cove Island and these increase to vertical and northward overturned on Pilley's Island. Minor folding and faulting are most prevalent on Triton Island. This suggests that Springdale tilting and deformation increased eastward. Spectacular south-southeast-trending slickensides that postdate folding in Robert's Arm Group appear within that group mostly on Triton Island, but extend as far west as the north shore of Tommy's Arm. Their spatial distribution and time constraints therefore associate them with Springdale deformation and suggest that tilting expressed in Springdale Group may have affected the Robert's Arm Group beyond the immediate vicinity of Lobster Cove Fault.

Structural relations at the Springdale unconformity also suggest an increasing eastward divergence between Robert's Arm and Springdale beds. On Sunday Cove Island trends are parallel but dips diverge by about 80°. On Pilley's Island the Springdale dips increase to about 60° overturned to the north and trends of unconformity and Robert's Arm Group are divergent (see map, Fig. 2, in pocket). Tops in the Robert's Arm Group nearest to the unconformity dip about 75° southward and face south. On eastern Triton Island adjacent Springdale and Robert's Arm groups are both northward overturned, but the unconformity appears to have cut much more deeply into Robert's Arm Group. These relations suggest that Robert's Arm basalts were steeply dipping in the west, southward overturned on Pilley's Island, and may have been recumbently folded on eastern Triton Island. There is a suggestion therefore that pre-Springdale deformation of Robert's Arm Group may also have increased eastwards.

The Springdale Group has recently been interpreted as a mixed assemblage of subaerial bimodal volcanics and fluviatile redbeds deposited as part of a caldera-fill sequence mainly west and southwest of Robert's Arm area (Coyle et al., 1985). Within the map area minor structures indicate changing current directions and periodic exposure to the atmosphere without evidence of evaporites. Basal beds show wide variation in clasts size and roundness but pass upwards into finer bedded clastics. These features suggest a period of instability followed by one of quiescence or subsidence. Concentration of conglomerate in the Pilley's Island area with largest clasts at Bumble Bee Cove suggests that this area was proximal to the mouth of a stream draining terrain of moderate to high relief. Lateral talus breccias indicate that this relief extended beyond the stream valley perhaps along a fault scarp. Some of the clasts examined within the Springdale have closely similar counterparts in the Robert's Arm Group; in particular the plagioclase-phyric felsites with quartz amygdules (but no quartz phenocrysts) are particularly abundant in the Robert's Arm Group. This suggests that drainage was from the south during Springdale time.

No fossils have been found in the Springdale Group within the Pilley's Island area. Previous workers have generally considered the group to be Silurian based on lithological similarity to Llandovery-Wenlock rocks in the Botwood area far to the east. More recently Chandler et al. (in press) have dated zircons from the Springdale felsic volcanics and from correlative units elsewhere in the Dunnage Zone, establishing a Llandovery age for these rocks. They further suggest that, together with similar rocks which overlie Avalonian terranes and the Meguma Zone, this assemblage defines an overlap sequence that fixes the minimum age of accretion of these terranes to North America.

Mesozoic dykes

Thin grey, fine grained basaltic dykes were found at two localities within the Robert's Arm area. The most readily accessible is an approximately vertical dyke about 3 m thick trending 070°, exposed in a low rock cut on the east side of the highway to Robert's Arm, about 0.8 km from South Brook. In hand specimen the rock is dark grey, distinct from the surrounding grey-green basalt, and contains scattered black very fine grained ovoid serpentine-like patches up to about 2 mm. In thin section the texture is ophitic with zoned intermediate plagioclase laths partly included within anhedral clinopyroxene. A very fine grained olive-green secondary mineral occurs in scattered amygdule-like patches surrounded by fine grained opaques, and in smaller areas is interstitial to plagioclase. Rare scattered euhedral plagioclase phenocrysts 3 mm in diameter are present. Opaques comprise about 1% of anhedral magnetite-ilmenite and traces of pyrrhotite.

At the second locality on Harbour Round Island along the south shore of Triton Island, two very fine grained, dark blue-grey dykes up to 1.3 m wide trend 305 and 140° dipping 70 and 50° northeast and southwest respectively. In thin section the dykes comprise fine grained, granular to prismatic, pale brownish, locally visibly zoned, clinopyroxene with interstitial plagioclase. Numerous patches of carbonate up to 1 mm in diameter are present as are patches of chlorite-serpentine some of which may be pseudomorphous after olivine. Fine grained magnetite euhedra are common.

Chemical analyses

A sample from each of the two localities was chemically analyzed. The results are shown in Table 11. The composition of the dykes falls within the range reported by Strong and Harris (1974) for alkaline intrusives in the Budgells Harbour and Twillingate areas farther east on Notre Dame Bay. The age of these rocks is given by Strong and Harris (1974) as 135-155 Ma based on K-Ar biotite age determinations, corresponding to the Jurassic-Cretaceous boundary. It seems likely that these minor intrusions in the Robert's Arm area are of related origin and similar age.

METAMORPHISM

The volcanics of the Robert's Arm Group have everywhere been subject to spilitization. Superimposed upon this early low grade metamorphism there is a regional increase in shearing, and in intensity of alteration that is most evident in passing from Southwest Crescent Block into Crescent Hump. Thus the rocks of the Crescent Hump tend to be somewhat paler shades of green and slightly more hydrous than those of the Boot Harbour belt which tend to be darker grey-green to grey. These trends are supported both by tabulation of the colour of rocks sampled for chemical analyses and by chemical determinations of H_2O. Higher grade epidote-amphibolite facies metamorphism is associated with emplacement of the granitic plutons within the Robert's Arm Group and regional metamorphic grade rises to epidote-amphibolite facies across the southwest end of the group. Rocks of this facies are typically dark green where they are true amphibolites, but may be lighter shades of green where crystallization of amphibole is incipient.

Rocks of Roberts Arm Group, particularly those within Mud Pond and Boot Harbour belts, are widely characterized by assemblages that include albite-chlorite with or without epidote, pumpellyite and prehnite. Such assemblages are characteristic of spilitic rocks of subgreenschist facies metamorphic grade. Garnets found within the group are either allochthonous, being present in fault slivers, or are xenocrysts, or are of andraditic composition. The latter, according to Deer et al. (1963), are most commonly found in higher grade scarns and

Table 11. Chemical analysis of Mesozoic dykes

Location Sample No.	S. Brook 1089B	Triton Is 245A
SiO_2	46.70	40.30
TiO_2	3.35	2.65
Al_2O_3	15.10	11.50
Fe_2O_3	6.30	3.70
FeO	7.80	7.80
MnO	0.27	0.19
MgO	5.60	8.08
CaO	9.60	13.10
Na_2O	2.10	2.20
K_2O	0.39	1.44
P_2O_5	0.83	0.58
H_2O	2.80	1.90
CO_2	0.10	7.00
S	0.06	0.10
F	0.05	0.07
Cl	0.01	0.03
FeO_t	13.47	11.13
Total	101.06	100.64
Li	7	22
Rb	9	36
Cs	1.4	2.6
Sr	301	595
Ba	198	541
V	300	299
Zr	124	214
Cu	72	71
Zn	120	90
Co	53	65
Ni	116	260
Cr	140	271

mafic rocks. Although the minimum temperature of crystallization is not known, it is likely that the restricted occurrence of this garnet in Robert's Arm rocks reflects local "hot spots" where the chemical composition of the host was favourable.

Rocks of the Crescent terrane contain similar mineral assemblages to those found in the two western terranes except that clinopyroxene and pumpellyite are less common and prehnite was found only southeast of Sandy Pond. The scarcity of clinopyroxene is an original feature of the basalts which have significantly fewer mafic phenocrysts than do those from the other two terranes. The prehnite which is present in the Crescent terrane, is commonly associated with veins and is at least in part distinctly more aluminous (*see* Table 6) than that found in the other terranes. It is possible that under the conditions of temperature and pressure attained in the northern part of this terrane prehnite became unstable without breakdown of pumpellyite but before the appearance of regional amphibole. The evident increase in schistosity and hydration of the basalts in this part of the terrane may have taken place during this metamorphic culmination. Fracturing and local veining with reintroduction of prehnite may then have occurred later under lower grade conditions.

Epidote-amphibolite facies metamorphism has been superimposed upon each of the terranes in differing degree. In all three terranes incipient crystallization of amphibole in chloritic patches and at the ends of clinopyroxene crystals can be found locally. In Boot Harbour terrane zones of such incipient higher grade metamorphism are in places found to follow one side of a fault and to pass laterally into the dark green amphibolite facies aureoles recognizeable in the field, which occur about the granite plutons. The distribution of these zones suggested by thin section study, is shown in Figure 31, and is interpreted in the section on structural geology.

STRUCTURAL GEOLOGY

Structural elements

Bedding and foliation

Bedding, described in the petrographic section of this report, provides the best approximation to a horizontal datum at the time of Robert's Arm deposition. Pillow lavas, which provide a more common structural element within the Robert's Arm Group, display a planar fabric which is both less closely associated with the horizontal at the time of deposition (see Fig. 13), and more difficult to measure in most outcrops. Pillow attitudes must therefore be regarded as potentially substantially less reliable indicators of original horizontality. They nevertheless tend to follow bedding in many instances where both are present.

Foliation in the Robert's Arm map area is extensively developed only in the Crescent Lake Formation of Crescent fault belt, and to a lesser extent in the spilites of the northern part of this belt. Foliation is thus concentrated where oroclinal bending of the group as a whole from north-south to east-west trends is sharpest. In Mud Pond and Boot Harbour belts bending appears to have been absorbed by adjustments along cross faults, and sediments are mostly unfoliated.

Joints

Joints at outcrop scale within the Robert's Arm Group appear to be mostly irregular. Nevertheless measurements were made wherever through-going joints were observed. The total population of 161 joints measured were divided into three groups based on the structural

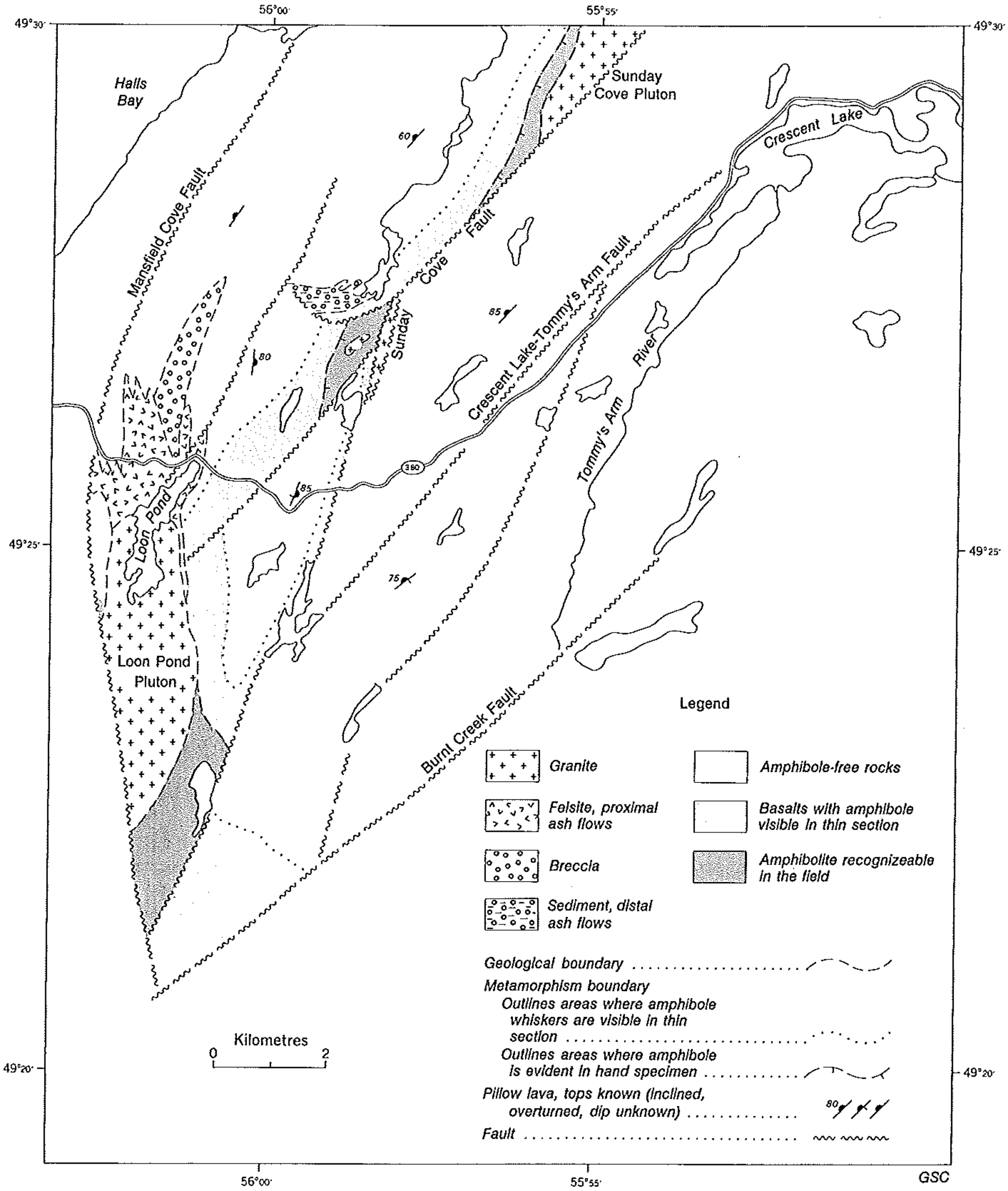

Figure 31. Map showing faulting and metamorphism in the southwestern Robert's Arm Group.

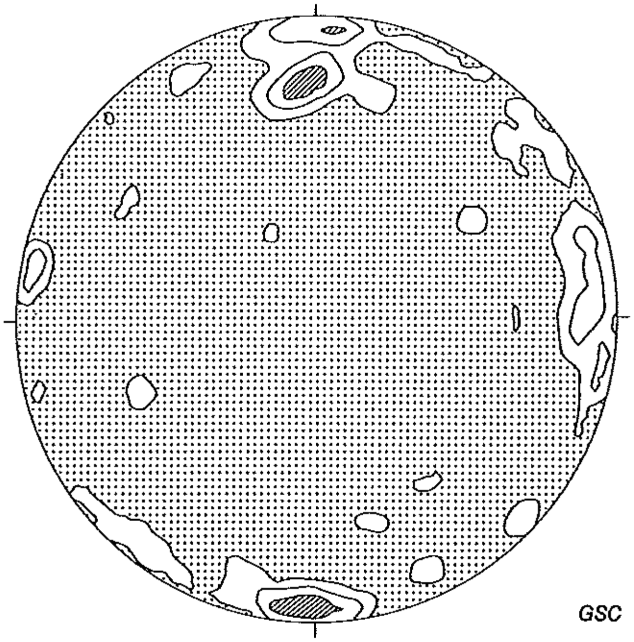

Figure 32. Stereoplot (Starkey, 1979) showing contours for lower hemisphere pole intersections for joints in Robert's Arm region. Contoured at 2, 4 and 6 points per 0.6% area.

trend of the zone within which they occurred. These zones comprise:

1. A zone of northerly structural trends south of the north end of Crescent Lake;
2. A zone of easterly trending rocks about Robert's Arm and east of Woodfords Arm;
3. A zone of northeasterly trending rocks on Triton and adjacent islands.

Although these three structural zones differ in regional trend, the joint patterns in all three are similar. The data have therefore been combined in Fig. 32.

The data suggest that the joints are mostly steeply dipping with maxima for joints trending roughly east-west and north-south. The north-south maxima are distinctly strongest in the northern zones (2 and 3) whereas the east-west maxima are present approximately equally in all three zones. Thus there appears to be a tendency for joints to develop roughly perpendicular to structural trends combined with one for east-west joints in the northern part of the map area. The predominant east-west joint pattern is roughly parallel to a marked gravity gradient which approximately follows the trace of the Lobster Cove Fault (Miller and Deutsch, 1976).

Minor folds

Minor folds are sparsely distributed in most parts of the Robert's Arm area except in Crescent fault belt where they are concentrated in the thicker northern parts of the Crescent Lake Formation. The folds are typically steeply plunging and are commonly asymmetrical or irregular in form in the western part of the formation where bedding is typically involved (Fig. 33). Farther east and particularly in the northern part of the belt folded cleavage and a few refolded small scale folds are evident. In amplitude they vary mostly from a few centimetres to a few metres. Possibly related major folds truncated by faults are indicated by pillow trends south of the north end of Crescent Lake and on the north shore of Tommy's Arm. Although in most cases only a single fold nose is evident, one quarter of the folds observed have the form of drag folds. Both left- and right-handed forms are evident among these.

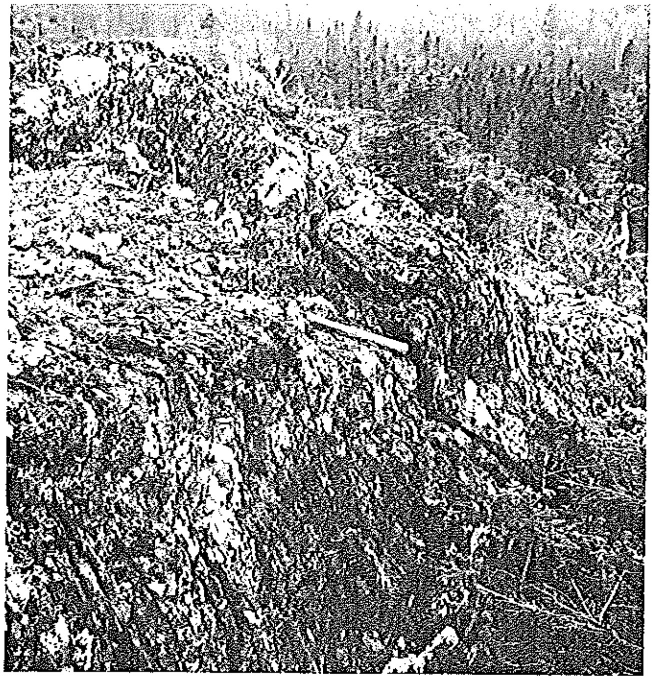

Figure 33. Steeply plunging minor fold in the Crescent Lake Formation north of Tommy's Arm River (GSC 167257).

Trend and plunge data have been measured for minor fold axes in the Crescent terrane (31 axes) and in the deformed shale wedge of Sops Head Complex (26 axes). Although the data are few, both terranes have a prominent vertical maximum with dispersion northeast-southwest parallel to foliation. A second maximum of more southerly plunging folds is possible in the Sops Head Complex. Trends of these folds and that of the major fold visible on air photographs south of Crescent Lake may be similar, but they appear distinct from the trends of minor folds (7. axes) measured in the fault slivers along Sops Arm. This change occurs across the fault through Sops Head which separates rocks included in the deformed shale wedge and those comprising the zone of fault slivers along the north shore of Sops Arm.

Slickensides

Slickensided surfaces were observed at scattered localities throughout the Robert's Arm area, but as mapping progressed eastward along Tommy's Arm and onto Triton Island it became evident that slickensiding is atypically well developed in this part of the area. Slickensides occur characteristically on gently dipping surfaces of variable dip azimuth, but plunge mostly gently at shallow angles to

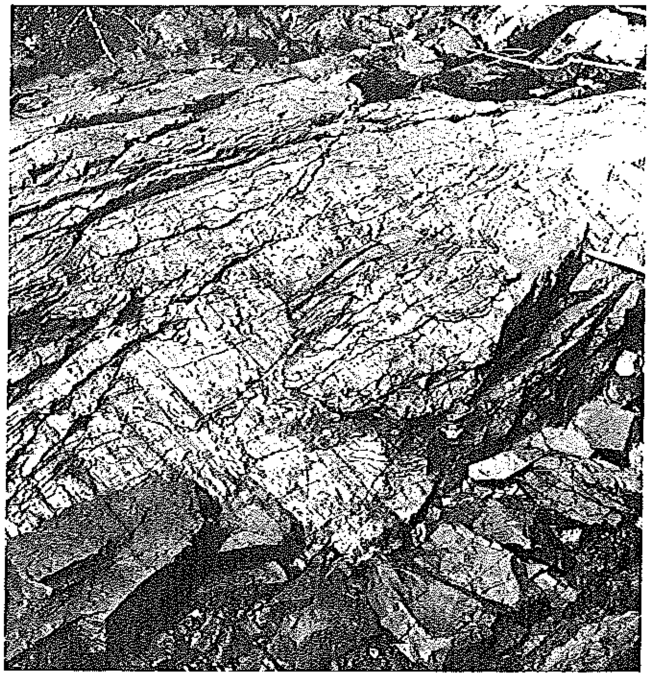

Figure 34. Slickensides plunging 15° south-southeast cutting northward- overturned basalt in the Robert's Arm Group on Triton Island (GSC 179713).

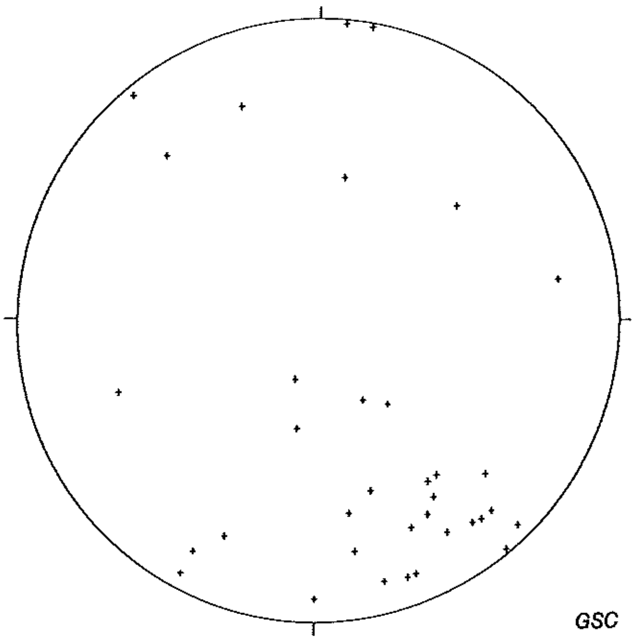

Figure 35. Stereoplot (Starkey, 1979) showing lower hemisphere intersections for 35 slickensides from Triton Island and adjacent localities.

the south-southwest. The general trend of slickensiding is maintained across the main axis of pillow top reversal on Triton Island, and thus slickensiding has developed after this reversal. It therefore reflects late compression and overthrusting of the Robert's Arm Group from the south-southeast. One example of a slickensided surface at Long Arm, Triton Island, is shown in Figure 34, and the consistency of orientation of the slickenside lineation is illustrated in a stereoplot (Fig. 35).

Structural-stratigraphic interpretation

Structure within the Robert's Arm Group is dominated by faulting which is largely subparallel to bedding. One regional and five major faults have been recognized, and several lessor faults are evident. Evidence of faulting is provided by truncation of granitic plutons and their associated metamorphic aureoles, by truncation of folds, by deflection of bedding trends, and locally by development of schistosity. The amount and sense of movement are largely unknown.

The major faults define the Robert's Arm fault belts and are called from east to west: the Burnt Creek fault zone, Tommy's Arm, Sunday Cove and Mansfield Cove faults. In the southwest half of the map area these faults are well established, but in the northeastern part, where the Robert's Arm Group is bent eastward and crumpled, the structure becomes more complicated and much of it is covered by the sea. Projection of the major faults into this area is more speculative. The three fault-bounded belts defined by these faults are called from east to west: the Crescent Lake, Mud Pond, and Boot Harbour belts (*see* Fig. 12). The Crescent terrane, which includes all of the Crescent Lake fault belt and the southern end of the Boot Harbour fault belt, is characterized by basalts that are mostly plagioclase-phyric accompanied by small quartz-plagioclase-phyric felsite bodies (except in Crescent Hump), and by local intertonguing fine clastics of the Crescent Lake Formation. The Mud Pond terrane, equivalent to the Mud Pond fault belt, comprises predominantly plagioclase-pyroxene-phyric basalts and is to a greater extent free of felsite bodies, except perhaps in the northeast where division of the terranes is uncertain. Boot Harbour fault belt is characterized by similar basalts with small plagioclase-phyric felsites locally throughout, and with large felsite centres in its upper part. It extends at least as far to the northeast as the fault through Loadabats Pond and may include part or all of the undivided rocks farther east. The basalts that form the greater part of each of the fault belts are not generally recognizably different from one belt to the next in the field.

Within each fault belt the rocks are steeply dipping with facing directions predominantly to the west and north. Three areas, all within the Mud Pond and Boot Harbour belts, which depart from this pattern are known. The first comprises an extensive area of basic volcanics east and northeast of Loon Pond pluton within which numerous but isolated pillow lava exposures clearly face eastward. The second comprises southward facing pillow lavas at Haywards Head and is believed to extend across Sunday Cove to the central part of Pilley's Island immediately south of the Lobster Cove Fault where southward facing pillow tops are less well established. The third area comprises a zone of folding within the pillow lavas along the north shore of Tommy's Arm extending from the vicinity of Sops Head in the west to the east end of Triton Island.

At either end the Robert's Arm Group (sensu stricto) is terminated by the convergence of the major faults. In the southwest it is possible that the volcanic belt, which continues farther south, is for some distance made up largely of older rocks of the Hall Hill Complex, but volcanics equivalent to the Robert's Arm Group reappear either as fault slivers or possibly as outliers unconformably upon the Hall Hill Complex. In the northeast the same convergence is evident but it appears that pre-Springdale erosion has also been responsible for removal of a large part of the upper Robert's Arm Group along the Springdale unconformity.

Crescent Lake fault belt

The Crescent Lake fault belt, the most easterly of the three major Robert's Arm fault belts, is obliquely transected by two lineaments which are likely faults. Both splay from the Crescent Lake-Tommy's Arm Fault at their northern ends where they are expressed by truncation of structural trends and lithological units. Both lineaments appear to weaken before merging with the Burnt Creek Fault zone in the south. The eastern fault, which separates Crescent Hump from the Southwest Crescent Block, truncates a large eastward plunging fold structure in the sediment-basalt sequence along its western side near Crescent Lake narrows. Upstream on Tommy's Arm River opposite the creek from Third Pond it separates the Crescent Lake Formation and overlying, westward facing basalts to the west, from a small lens of apparently eastward facing greywacke. This is the only suggestion of southward facing stratigraphic sequence known to the writer within the Crescent Lake Fault belt. It seems most likely that it represents a small fault wedge tectonically isolated from the rest of the sequence.

The more westerly fault lineament splays from the Crescent Lake-Tommy's Arm Fault just south of Crescent Lake, and passes along the valleys of Fox Pond and Spot Pond. It appears to truncate a large sedimentary lens within the basalts west of Ski Pond, and farther north isolated wedges of basalt appear displaced within the slate-chert outlier along its trace.

The fault blocks defined by these faults are in some aspects distinctive. The easternmost block, Crescent Hump, comprises an extensive accumulation of pillowed to massive basalts that chemical analysis suggests are distinctively titanium-rich. These basalts are flanked at either end by large breccia masses, they include very few minor felsites, and they overlie slates of the Crescent Lake Formation-Sops Head Complex. It appears that the breccia bodies may be remnants of a breccia apron now seen in section, and that the basalts were built up as a distinct promontory resembling a small sea mount.

The central block, like that to the east, comprises west facing basalts overlying slates and cherts of the Crescent Lake Formation. In contrast to the eastern block, however, the basalts are somewhat less rich in TiO_2 and are interlensed with scattered small quartz-phyric felsic volcanic centres. A large lenticular outlier of the Crescent Lake Formation lies along the upper fault margin of the block northeast of Ski Pond. The contacts of this remnant with the surrounding basalts appear to have been involved in mezoscopic folds, bedding within the lens is commonly distorted showing numerous minor folds, and minor interflow sediments within the adjacent basalts depart locally from regional trends. It is evident therefore that this part of the block is structurally complex and the rocks not necessarily entirely in west facing sequence. The southwest end of the block comprises a great northeastward-facing greywacke-shale wedge, possibly the distal facies of a river delta.

The western block is composed of lithologies like those of the central block, but the main bodies of sediment occur as lenses within it and not at the base as they do in the other blocks. Of the two major sedimentary lenses the eastern appears to be truncated by the eastern fault boundary. The western lens is distinctive in progressing from siltstone-shale at its northeastern toe through a large greywacke mass to coarse volcanic greywacke and felsite at its southwestern head. The structure is suggestive of a peripheral section through the sedimentary apron about a small felsic volcanic centre modified perhaps by coastal currents or bottom slope. The upper margin of this structure appears to be truncated by the Crescent Lake-Tommy's Arm Fault which marks the west boundary of the Crescent Lake fault belt. Lithologically similar basalts which occur within the Boot Harbour belt west of the southern part of Crescent belt have fewer large interleaved lenses of sediment and those present have a more tuffaceous aspect. Because these central and southwestern blocks together appear distinct from Crescent Hump both in their environment of origin and in their chemistry, they have been collectively called the Southwest Crescent Block. They have been included in Crescent terrane together because they are characterized by mineralogy and rock composition distinct from basalts in the Mud Pond — Boot Harbour terrane.

The Crescent Fault belt as a whole thus comprises three fault blocks which represent from northeast to southwest.

1. A mid-basin basalt accumulation of distinctive chemical composition, with apron of basalt breccia (Crescent Hump).
2. A northeastward shelving block adjacent to a stream delta to the southwest.
3. A similar block perhaps marginal to the same delta.

This interpretation implies that the Crescent Lake Formation both underlies and intertongues with the basalts.

Mud Pond fault belt

Structures within the southwestern part of Mud Pond belt are probably mostly simpler than those in the Crescent Lake belt because the rocks face uniformly west and few through-going fault lineaments are evident. Southward pinching out of the belt and a slight angular discordance between the Sunday Cove Fault and bedding, indicated by large pillow breccia lenses within the belt, suggest that the original basalt section thickened northward toward the central part of the map area. This, the abundance of basalt breccias, the more than normal local concentrations of pyrite in the basalts west of Robert's Arm, and the presence of a prominent gabbro body low in the section near the bend in Crescent Lake, suggest that Mud Pond belt represents a shield-like basalt accumulation with its centre near Robert's Arm. East of Boot Harbour Pond on the upper part of the southern flank of this centre a local basin formed. Within this basin distal fine grained volcaniclastic sediments coarsen but thin northward toward the centre. North and east of Mud Pond, trends of pillow lava and interflow breccias bend eastward and the rocks are broken by numerous irregular curving valleys. Marked discontinuities of bedding trend occur across some of these valleys and it appears that the belt has broken up with disruption and rotation of internal fault blocks at the locus of maximum bending. An isolated hill immediately south of Sunday Cove pluton near Woodfords Arm, called the rotated block, is characterized by discordant structure, chemical composition and metamorphic grade when compared with adjacent rocks south of Sunday Cove Fault. Farther north, beyond the valley extending west-northwest from Robert's Arm toward central Woodfords Arm, topographic trends change from northward to southeastward and interleaved felsite bodies appear within the basalts as they do in the Boot Harbour terrane. The Robert's Arm Fault, which follows this valley, has therefore displaced or faulted off the northeastward continuation of Mud Pond belt. Robert's Arm Fault continues southeastward into the depression west of Robert's Arm where it in turn appears to be truncated by the northward splay from Crescent Lake-Tommy's Arm Fault.

East of Robert's Arm and south of the fault through Loadabats Pond (on Pilley's Island), the basalts north of Crescent Lake-Tommy's Arm Fault are accompanied by quartz-amygdule felsite bodies as far as Butlers Bight on central Triton Island. Most of the felsite bodies are small but it is not known whether this entire region is correlative to the Boot Harbour belt to the southeast, or whether part or all of it is equivalent to the Mud Pond belt. Petrographic and chemical data indicate that the basalts differ from those in the Crescent terrane but do not differentiate clearly between those of the Mud Pond and Boot Harbour terranes. This region is therefore shown as undivided on Figure 12.

Boot Harbour fault belt and undivided rocks

Rocks of the Boot Harbour belt have been complexly faulted. Pillow tops show that much of the southwestern part of the belt has been inverted and now faces east. Chemical analyses suggest that these inverted rocks resemble those of the Crescent belt and they have been included in the Crescent terrane. Rocks near the northeastern end of the Robert's Arm Group include numerous felsite bodies like those in the Boot Harbour belt farther southwest, but many of these bodies lie south of what appear to be the most likely projections of the belt-boundary faults. Minimal northeastward extension of Boot Harbour belt is defined by the fault through Loadabats Pond on Pilley's Island (*see* Fig. 12) and distribution of phenocrysts seems to provide some evidence in favour of this boundary. Chemical analyses are inconclusive and the distribution of felsites appears to favour a boundary along or near the Crescent Lake-Tommy's Arm Fault suggesting that the entire northeastern part of Mud Pond belt has been removed by faulting. As a result of this uncertainty the region east of Robert's Arm has been defined as undivided Mud Pond — Boot Harbour belt.

In the southwestern corner of the map area, emplacement of Loon Pond pluton above apparently older inverted basalts of Crescent terrane provides some interesting implications for the interpretation of local geology, and important confirmation of age relations between the basalt terranes. Extrusion of the Loon Pond felsites as a shallow level dome complex apparently interleaved between westward facing pillow lavas at the north end of Loon Pond pluton, suggests that the pluton itself faces west and was either emplaced between two allochthonous slabs of older basalt, or was intruded into the core of an evolving recumbent fold immediately before deposition of the felsites. Patterns of epidote-amphibolite facies metamorphism within the inverted basalts suggest that they comprise two separate fault blocks (*see* Fig. 31). The northwesternmost of these blocks contains at least four small diatreme breccias which are thought to have been emplaced when the block formed a plug in front of the advancing Loon pond magma. Emplacement of the pluton on a rather gently southwestward sloping surface may have resulted in extrusion of this block upon the northward facing slope now seen in section. Distribution of diatremes in the western (upper) part of the block and of granodioritic magma of the small Boot Harbour Pond body with an aureole of amphibolites in the northern lower part may indicate that the block was rotated during extrusion oblique to the present surface. It is potentially significant that felsite at the northeast end of Loon Pond, occurring near the base of Loon Pond pluton, passes northward into proximal ash flow deposits, whereas felsite on the northwest and upper side of the pluton interfingers with basalts to the north without a similar change. Expulsion of the plug may therefore have allowed degassing of the magma with the result that subsequent felsites were emplaced as massive felsite domes rather than as ash flows. Seismic disturbances accompanying the early emplacement of the pluton probably broke up pillowed flows formed higher up the slope over the orifice. Debris from these disrupted pillow lavas migrated down slope forming the largest single pillow breccia lens within the Robert's Arm Group. Scarcity of felsite fragments in the debris is consistent with the view that the felsites were shallow intrusives.

The critical area for interpretation of the Loon Pond structure, that at the northeast end of the inverted block, is very poorly exposed. Local abrupt changes in bedding trends indicate that the structure is disturbed consistent with observation that pillowed basalts roughly along strike to the north and south of the assumed terrane boundary, face in opposite directions (*see* geological map, Fig. 2, in pocket). Pillow tops both east and west of this area face westward. Interpretation of the terrane boundaries in this region as the contacts of a huge inverted slumped block appear possible, but more detailed information will be required to confirm it.

West of Loon Pond pluton there is a narrow belt of pillow lava and basalt which lies between the pluton and the southward projection of the Mansfield Cove Fault. These basalts occupy the ridge top and are separated from the first outcrops of the Hall Hill Complex by a covered interval some 320 m wide through which the fault is assumed to pass. Six samples from the hill top have a mean water content of 3.15 wt. percent with a standard deviation of 0.94, whereas the 15 Hall Hill amphibolites (*see* Table 1) have a mean H_2O content of 1.58 and standard deviation of 0.63. This and the absence of gabbro dykes or plagioclase glomerocrysts common in the Hall Hill Complex support the view that the rocks along the ridge top belong to the Robert's Arm Group. These ridge top basalts are also accompanied by small felsite dykes which are at least locally quartz-phyric like most felsites in the Crescent terrane. Furthermore examination of the TiO_2-P_2O_5 data for the 6 ridge top samples indicates that they all plot in the field of Crescent terrane tholeiites. Pillow structures are not well exposed in this area but the shape of single pillows locally suggests the possibility that these rocks face west like the Boot Harbour belt to the north, but unlike the Crescent terrane to the east. Although it must be emphasized that the pillow tops in this area are open to question, the available data suggest these basalts along the west margin of Loon Pond Pluton represent a remnant of its roof.

The Sunday Cove pluton directly underlies the felsites at Burnt Head and felsite dykes are concentrated within the basalts between them suggesting that the pluton formed a subvolcanic magma chamber from which the felsites were derived. A huge breccia lens (up to 400 m thick) beneath the felsites on the flank of the subjacent pluton (*see* geological map, Fig. 2, in pocket) likely formed in response to uplift of the basalts during inflation of the pluton. Thickness of basalts between the breccia and the granite is roughly constant at about 500 m suggesting that the pluton was within this distance of the surface at the time of its emplacement. Basaltic debris, which collected at the flanks of uplift as the chamber inflated, was buried by basalt flows filling the basin to the west. Felsite debris is rare in the breccias, so it appears that they were derived either as pillow breccias on the steepening slopes of the dome, or through disruption of earlier basalt flows along faults such as the one evident near the north end of the breccia lens. The scarcity of felsite breccias at the base of, and within, the overlying felsite pile may reflect volatile low composition of the magma. The flat base of the felsite relative to the outline of the magma chamber below suggests that basalts were accumulating rapidly in the depression to the southwest as the granitic pluton was emplaced.

The Burnt Head felsites appear to be overlain by a more extensive accumulation of felsites extending southwestward from Boot Harbour to Mansfield Cove (the Mansfield Cove centre). These felsites may well represent later magmas derived from a southwestern extension of the Sunday Cove pluton extending beneath the present surface of exposure.

The Nippers Harbour and Haywards Head centres both occupy similar positions within the Boot Harbour fault belt. They intertongue laterally with the basalts and have notably flat floors. Unlike the lower part of Boot Harbour belt to the southwest no evidence of any extensive high grade metamorphism has been detected beneath the Haywards Head centre or any other centre farther east, either in the field or in thin section. This is consistant with the view that the lower part of the Boot Harbour belt together with possible shallow granitic magma chambers, like the Loon Pond and Sunday Cove granites, were removed by movement along Robert's Arm Fault.

East of Robert's Arm and southeast of the fault through Loadabats Pond on Pilley's Island undivided basalts of Mud Pond — Boot Harbour belt appear to form an assemblage of imbricated fault slices (*see* map, Fig. 2, in pocket). Mud Pond belt to the southwest overlaps a felsite-bearing sequence to the east along the splay from Crescent Lake-Tommy's Arm Fault. Farther east these rocks are transected by a lineament (fault?) through Tilley Cove and the deep bay to the southeast which may have accommodated foreshortening expressed in the east-west folding still farther east.

Basalts on the north shore of Tommy's Arm show a well developed foliation. From the deep bay north of Sops Head east to Raft Tickle this foliation penetrates no more than a few tens of metres inland. Strikes parallel the coast and dips vary from 65 to 90° southward. On Pretty Island discrete steeply dipping shear zones parallel to the coast are present, and farther east the foliation, though present, is mostly less intense as far as Cards Harbour.

Pillow lavas along the east coast of the deep bay opposite Sops Head (and north of the foliation zone) are mostly northward facing and steeply dipping like those typical of the belt farther west. Toward the mouth of the bay, however, they swing south and are sharply truncated by the zone of strong foliation. Similar truncation can be demonstrated on the coast about 1 km farther east but pillow orientations are mostly obscured elsewhere by the foliated zone. The structure is like that in the truncated folded basalts above the Crescent Lake Formation south of Crescent Lake. Both appear to suggest truncation of large north- to east-plunging right-lateral drag folds, or of tilted recumbent folds.

On Raft Tickle two more shallowly plunging major folds are indicated by reversals in pillow tops. The northern of these is an isoclinal anticline overturned to the north but the southern fold is synclinal, more open and upright. On Pretty Island pillow top determinations are less numerous but there is a suggestion that the two fold axes spread, with the upright syncline dying out near the coast and the overturned anticlinal axis continuing through the northern tip of the island.

On eastern Triton Island excellent south facing pillow tops are exposed all along the coast between Pretty Tickle and Sevier Point whereas north-facing northward-overturned pillows are present at the north head of Butlers Bight and south of the Pretty Tickle causeway. The same northward-overturned anticlinal axis therefore passes approximately through the western extremity of Triton Island and reaches the coast again just north of Butler's Bight. Southward facing pillows are again present along about 1 km of coastline east of Jims Head and again at Sisters Point near the eastern extremity of the Island. The western patch of south facing pillow lavas are much cut up by white quartz veins and both occurrences may constitute isolated fault wedges rather than southward facing limbs of continuous folds. Pillows in the central and northern parts of Triton Island are mostly steeply southward dipping and northward overturned. On Big Island in Pilley's Tickle, however, dips shallow to horizontal and the basalts are upside down. Spectacular slickensides trending south-southeastward are developed on gently dipping surfaces across Triton Island and are found as far west as the mainland north of Tommy's Arm.

Pilley's Island south of the Lobster Cove Fault is disected by a prominent fault lineament through Loadabats Pond. This lineament marks a possible eastern continuation of the boundary between Mud Pond and Boot Harbour belts. South of this fault the basalts are commonly pillowed, north-facing, and steeply dipping to northward overturned. North of the fault, however, very few tops were found and pillow lava is scarce. This is partly because of the high proportion of felsite but also reflects emergent conditions suggested by flow banded felsite, felsite breccias and the abundance of spatter-like basalt breccia. One good occurrence of pillow tops indicated by both spikes and vesicle concentration is visible half way up the cliff along the highway in Pilley's Island village (Fig. 36). Although overturned, these pillows clearly face north and indicate that the mine felsite centre overlies them. Less well exposed pillows on the hillside west of Mine Pond suggest that the basalts there dip and face southward. Although this determination is not as reliable as that on the opposite side of the felsite, diamond drilling within the mine felsite between these two pillow sites shows that the felsite bottoms in altered basalt (Tuach, 1984). Thus the mine felsite is believed to lie at the core of a northward overturned, eastward plunging syncline. Although potentially complicated by faulting this structure probably projects along strike westward through Spencer's Dock area to line up with the synclinal axis through Charley's Cove on the west side of Sunday Cove.

Summary of structural interpretation

Early deformation of Robert's Arm Group began in the southern part of the map area during volcanism, however, in the northeastern part it followed volcanism (involved the Boot Harbour felsic volcanics) but was pre-Springdale. It furthermore appears to have increased in severity from west to east across the northern part of the area. Between these folded zones the Boot Harbour belt has been faulted over Mud Pond belt and Mud Pond belt over Crescent belt. It is possible that evolution of this structure began with folding and continued with listric thrusting from the northwest so that fold noses and southeast facing limbs have been removed by faulting and erosion leaving the present succession of west facing thrust sheets. The assumption that these thrust sheets are directly related to the folding at their extremities is invalid, however, because of the difference in timing and in character of folding. It must be assumed that the original terminal fold zones occurred beyond the limits of the map area and have been faulted off at the its extremities.

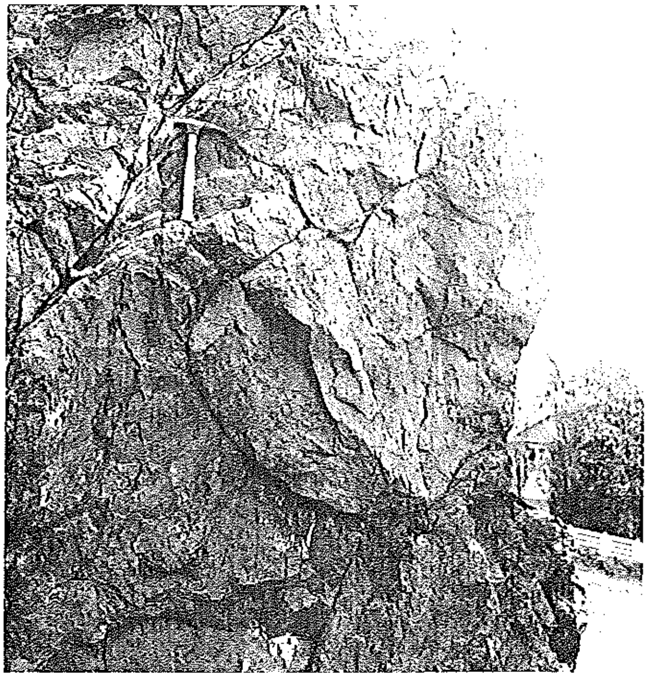

Figure 36. Pillow lava in the Robert's Arm Group in Pilley's Island village seen from the west. Bun tops and amygdule concentrations clearly face northward indicating that the basalts underlie the mine felsite.This is the only well documented pillow top determination in the group on Pilley's Island north of Loadabats Fault (GSC 179730).

The Crescent belt, in contrast to the other two belts, shows penetrative foliation particularly in northeastern Crescent Hump, and has no indications of major shallow plunging folds. Rather, minor folds in the Crescent Lake Formation and one major truncated fold involving the basalts, have moderate to steep plunge. There is a suggestion therefore that the major fault slices of Crescent belt were assembled in a different fashion than were those of Mud Pond and Boot Harbour belts.

Synthesis of these local structures to form a coherent picture of structural evolution within the Robert's Arm Group will be speculative until more detailed knowledge of these deformations and of the sequence in which they occurred is obtained. If events along the east margin of Robert's Arm Group can be interpreted as suggested by Nelson (1981), then there is a gap between early synvolcanic deformation which is of pre-Llanvernian-Llandeilian age and the culmination of southeastward thrusting of Robert's Arm Group which occurred in late Ordovician time before Springdale deposition. This latter event was presumably responsible for folding, perhaps now partly preserved in the northeastern part of the area, and for stacking of thrust sheets from the west or northwest wich may haave eliminated opposing fold limbs from the central part of Robert's Arm Group.

Major tilting of Springdale beds occurred along Lobster Cove Fault in post-Lower Silurian time and there is some evidence that this tilting increased in severity eastward. Spectacular slickensides developed in basalts at the northeastern extremity of Robert's Arm Group after folding, suggesting subhorizontal transport, most likely from the southeast. Time restraints and spatial association of these phenomena imply that they were related. Tilting of Springdale beds was therefore not confined to the immediate vicinity of the Lobster Cove Fault but was a more widely spread event, perhaps related to back rotation and steepening of the southeastward verging Robert's Arm thrust sheet terrane. In this interpretation tilting of Springdale beds accompanied back rotation and steepening of the previously southward verging Robert's Arm Group with slickensides developed late in the process where back thrusting was strongest. This deformation presumably occurred during the Devonian Acadian Orogeny when deformation of sediments farther east in Notre Dame Bay is also thought to have occurred (Nelson, 1981).

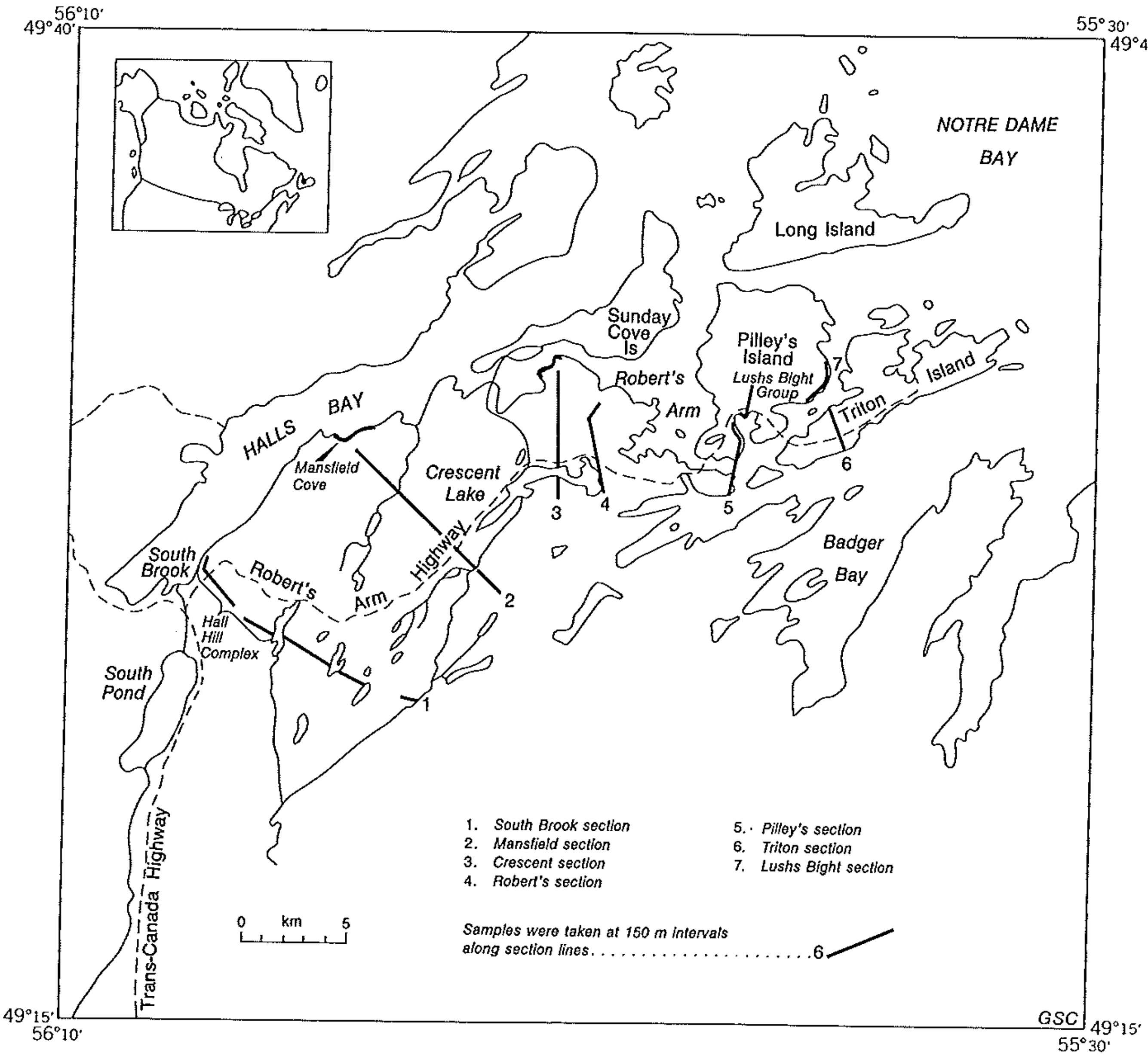

Figure 37. Map showing chemical sections of the Robert's Arm Group.

Steepening of Robert's Arm Group was followed by eastward oroclinal bending of the Group about an axis near Robert's Arm because the steep plunge of this regional axis suggests that the strata were already steeply tilted. Bending is thought to have been related to late right lateral movement along the Lobster Cove Fault which produced apparent regional dextral drag, and locally juxtaposed presumed Devonian structures in Robert's Arm Group against less deformed Lushs Bight strata. Cross-faulting, buckling and overlapping of fault blocks in the northeastern part of Robert's Arm Group may reflect late westward wedging out of these rocks between Lobster Cove and Crescent Lake-Tommy's Arm Fault near their acute convergence.

ROCK CHEMISTRY OF ROBERT'S ARM GROUP

Sampling procedure

Sampling of the Robert's Arm Group for chemical analysis was carried out at 150 m intervals along seven sections within Robert's Arm Group. From southwest to northeast these are called the South Brook, Mansfield, Crescent, Roberts, Pilleys, and Triton sections (*see* Fig. 37). Collections of felsite were made from the major felsite centres at similar intervals (Fig. 38).

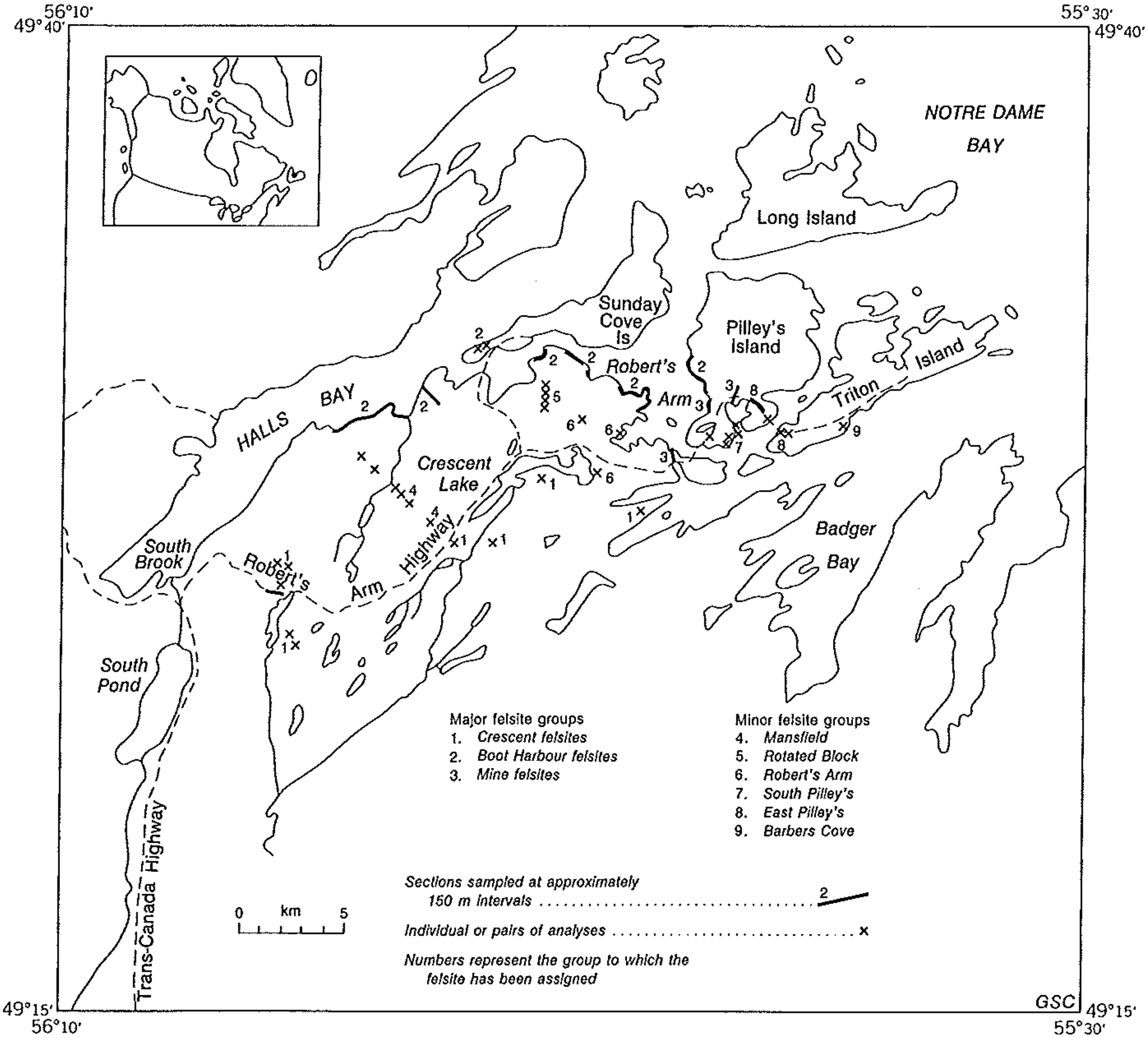

Figure 38. Map showing location of felsite localites sampled.

At each station one or more samples weighing about 2 kg were taken representing all variations in lithology present. In general pillow lavas were sampled from the intermediate zone between core and chilled margin. In some cases where outcrop was particularly scarce sample stations were offset parallel to strike to the nearest bedrock exposures. Veined areas were avoided where possible, but in some cases where outcrop was very scarce, samples for analysis were crushed in the field and vein material excluded by hand picking. Concentrations of carbonate amygdules were also avoided, where possible, but because of the very wide and abundant distribution of these structures it was not practical to obtain both carbonate free samples and a representative sampling of the group. Therefore no attempt was made to hand concentrate material free of carbonate amygdules in the basalts or of common silica amygdules in the felsites. Thus many of the basalts contain up to 5%, or more, of amygdaloidal carbonate and some of the felsites contain similar amounts of amygdaloidal silica. For breccias carbonate content locally approaches 20%.

Methods of analysis

Petrochemical samples were analyzed by XRF methods for the major and minor elements, and by spectrographic methods for trace elements. F and Cl were analyzed by the selective ion method, and Li, Rb and Cs by the screw rod method. The screw rod method for Cs and Rb analyses was subsequently found to be less reliable than originally thought. The results for these elements therefore provide only a semiquantitative estimate for the group as a whole and cannot be used for subunit comparisons. For lithium the precision was found to be substantially better, but because of the importance of Li distribution within the volcanics 20 samples representing the range of Li variation present were reanalyzed by atomic absorption. The maximum deviation between sets of analyses proved to be just under 56% of the lower value near the top of the higher range (up to 153 ppm) with most duplicates within 20%. For the lower range (below 20 ppm) all analyses fell at or within ± 3 ppm. Comparison of the two sets of analyses indicates that the means are very similar (40.3 ppm by screw rod and 39.1 by atomic absorbtion). The confidence levels of discriminations between basalt subunits using one or other of the two sets of analyses were essentially the same. The contrasts and patterns suggested by the original lithium screw rod analyses are therefore believed to be real. These methods and estimates of the accuracy attained for the various elements are reviewed in Appendix 1. Investigation was limited to those elements which could be handled on a large scale in the laboratories of the Geological Survey of Canada in order to permit statistical comparisons of all parts of the Robert's Arm Group.

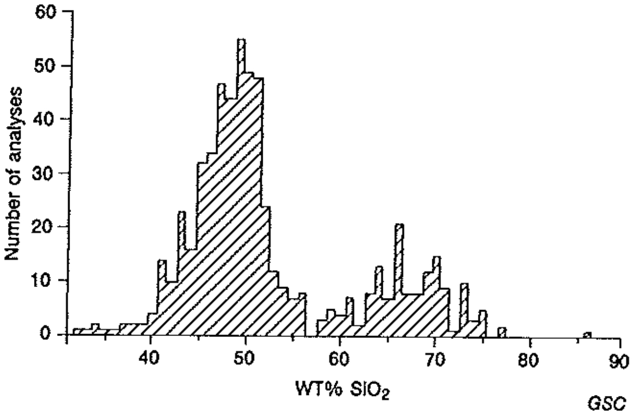

Figure 39. Silica histogram for Robert's Arm volcanics illustrating their bimodel character.

General petrochemistry

The Robert's Arm volcanics constitute a bimodal assemblage. Basalts and felsites are in most instances readily separable in the field, and the paucity of the intermediate compositions is well illustrated in the silica histogram for all analyses (Fig. 39). The chemistry of these two volcanic lithologies is discussed separately.

Mafic volcanics

Introduction

There can be no doubt that all of the Robert's Arm mafic volcanics have undergone substantial alteration. It is demonstrated by the ubiquitous presence of albite, and high contents of H_2O in most of the rocks. Albitization of plagioclase involves substitution of Na-Si for Ca-Al so that there is likely to be a secondary bias towards high Na-(Si) and low Ca (assuming that Al is redeposited locally in secondary minerals). More or less calcium, however, has been introduced into most of these rocks as part of amygdular calcite. Because none, some, or most of the calcium derived from breakdown of intermediate to basic plagioclase may have been redeposited in calcite, the original composition of the rocks is not easily recast. These aspects are characteristic of spilitic alteration.

Comparisons with Hall Hill and Lushs Bight volcanics show that these types of chemical alteration increase from Hall Hill though Lushs Bight to Robert's Arm rocks, and suggests an increasing likelihood not only of Na-Ca exchange, but also of mobility of other elements as well. In this study the affects of these aspects of alteration are minimized by re-examining statistically significant contrasts for the mathematical affects of dilution, and through the use of element ratios. The volcanics have been divided into structural-stratigraphic units on the basis of field mapping and compared on an element by element basis; and advantage has been taken of the representative character of the sample to search for patterns of element variation that cross unit boundaries or that might indicate chemical units not recognized in the field.

Chemical contrasts between basalt litholigies

Rocks in each of the subunits have been classified as miscellaneous basalts, pillow lavas or breccias, and mean and standard deviation for each lithology in each subunit has been calculated (Table 12). The table shows that the basalts generally contain least carbonate, the pillow lavas slightly more, and the breccias substantially more. This variable carbonate dilution has tended to progressively raise the standard deviations of all elements in the sequence basalt, pillow lava, breccia. Hydration on the other hand does not follow this sequence of enrichment but rather is greatest in Crescent Hump, intermediate in southwest Crescent block and Mud Pond terrane, and is least in Boot Harbour terrane.

Statistical comparison of basalts, pillow lavas and breccias of the various subunits using Student's "t" statistic indicate that some of the elements show consistent changes in addition to carbonate contrasts between lithologies. Best established are increases in Ni and Cr and decrease in Ni/Cr ratio that occur between basalts and pillow lava because this change occurs despite a sympathetic addition of carbonate. For the same reason the equivalent changes between basalt and breccia, although not established at the 99% confidence level, are also likely significant. Comparisons for SiO_2, Al_2O_3, FeOt and MnO suggest that these elements are enriched in the basalts, but the statistical validity of these comparisons is reduced by carbonate dilution. Nevertheless, ratios suggest that Si/Fe and likely Fe/Mg are higher in the basalts than in pillow lava. Although these corresponding differences are less clearly significant between basalt and breccia, the direction of change suggested in each case is the same. Hence, the data are consistent with field observations that the breccias have originated mostly from broken up pillow lava which has perhaps been more altered than the other lithologies.

The tendency of pillow lavas to be more mafic than massive basalts might reflect higher temperature and lower viscosity of the more mafic lavas, but this distinction is not typical of pillow lavas, and is not fully satisfactory here because pillow lavas and massive basalts with high Ni/Cr, Fe/Mg ratios and low absolute Ni and Cr contents, which are thought to have undergone differentiation by pryoxene settling, do not show this contrast. It is perhaps possible that the site of eruption, whether from a main conduit or from a flank fissure, may have exerted a significant influence. Such contrasts in eruption site might be associated with tapping of magma from different levels in subjacent chambers which may account for the increased tendency for pillow lavas to be pyroxene-phyric, whereas differing eruption rates from the different orifice types may have affected the internal structure of the flows.

Chemical contrasts between basalt terranes

The Robert's Arm Group has been divided along faults into three terranes, and the basalts from these terranes have been shown to differ in frequency, type and composition of phenocryst which they contain, and in the relative abundance of felsite. These are called the Crescent, Mud Pond and Boot Harbour terranes in succession from

Table 12. Composition of the Robert's Arm mafic volcanics

Sector	Crescent Hump				SW Crescent Block				Mud Pond-Boot Harbour terrane.						Pilley's Island mine area					
Lithology	Basalt		Pillow lava		Basalt		Pillow lava		Basalt		Pillow lava		Breccia		Basalt		Pillow lava		Breccia	
No. of samples	20		09		38		13		167		72		25		09		04		01	
Statistic	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
SiO	44.47	2.54	43.71	2.39	48.36	2.23	47.58	1.85	48.04	3.33	45.89	4.65	44.34	6.93	44.56	3.75	43.55	3.49	45.20	-
TiO_2	1.93	0.35	1.74	0.18	1.28	0.38	1.40	0.61	1.01	0.29	0.81	0.26	0.74	0.23	0.85	0.34	0.77	0.49	0.65	-
Al_2O_3	16.40	1.73	16.28	1.25	15.52	1.08	15.22	1.07	15.18	1.14	14.14	1.61	14.18	2.54	16.12	0.77	15.28	0.35	16.70	-
Fe_2O_3	2.84	2.19	2.11	1.27	2.42	0.76	2.54	1.36	2.60	1.32	2.52	1.19	2.29	1.02	1.37	0.47	2.68	0.90	1.50	-
FeO	6.39	2.21	6.54	1.31	8.09	1.27	7.23	1.36	6.97	1.69	5.61	1.77	5.81	2.10	6.77	1.62	4.43	1.65	5.80	-
MnO	0.21	0.04	0.19	0.03	0.22	0.07	0.18	0.03	0.19	0.04	0.18	0.04	0.19	0.05	0.27	0.14	0.18	0.04	0.21	-
MgO	8.04	2.60	8.30	1.53	8.10	1.92	8.33	2.65	7.02	2.59	6.70	2.18	5.93	1.98	7.47	1.90	4.98	1.37	7.60	-
CaO	8.38	3.56	9.84	2.55	7.77	1.79	8.66	1.97	8.64	7.80	11.72	4.31	12.66	5.28	8.53	2.59	11.33	2.86	6.80	-
Na_2O	3.09	1.04	2.16	0.77	3.62	1.17	3.43	1.41	3.26	1.35	3.34	1.42	3.12	1.46	3.67	1.18	4.38	1.05	4.20	-
K_2O	0.74	0.63	1.63	0.72	0.64	0.71	0.67	0.69	1.15	0.91	0.88	0.66	0.96	0.60	1.17	0.64	1.37	0.69	1.34	-
P_2O_5	0.37	0.13	0.35	0.05	0.18	0.11	0.18	0.08	0.29	0.11	0.26	0.11	0.28	0.08	0.24	0.08	0.35	0.28	0.16	-
H_2O	4.50	1.32	4.36	0.49	3.26	1.03	3.15	1.14	3.43	1.02	3.10	0.98	3.22	1.03	3.30	1.33	3.10	0.76	4.40	-
CO_2	3.10	3.53	3.17	3.16	1.07	1.34	1.61	1.40	2.42	2.74	5.28	3.84	6.40	5.80	5.38	3.07	8.18	2.26	5.90	-
S	0.04	0.04	0.06	0.04	0.04	0.05	0.04	0.04	0.08	0.11	0.07	0.08	0.13	0.09	0.52	0.53	0.17	0.07	0.08	-
F	0.05	0.01	0.05	0.01	0.04	0.01	0.03	0.01	0.05	0.02	0.05	0.02	0.06	0.02	0.07	0.04	0.06	0.01	0.04	-
Cl	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.00	0.01	0.00	0.01	-
Total	100.57		100.50		100.53		100.27		100.35		100.57		100.33		100.30		100.82		100.59	
FeO_t	8.94	1.65	8.44	0.80	10.27	1.54	9.52	1.92	9.31	1.67	7.87	1.44	7.87	1.94	8.00	1.44	6.83	1.02	7.15	-
CaO*	4.48	1.99	5.80	2.86	6.42	2.48	6.61	3.11	5.64	2.88	5.05	2.57	4.71	2.94	1.91	2.11	1.15	1.32	0.00	-
Li	74	41	50	11	19	13	29	25	17	14	18	17	14	13	25	9	14	5	25	-
Rb	20	17	44	22	11	14	15	19	29	28	20	17	29	26	18	12	29	16	22	-
Cs	1.9	1.4	1.6	1.4	1.3	0.8	1.5	0.9	0.9	0.8	0.8	0.8	0.6	0.7	0.5	0.3	0.3	0.2	0.5	-
Sr	300	210	202	52	147	85	146	85	195	101	185	92	215	78	181	62	183	69	227	-
Ba	191	276	271	98	118	102	130	128	345	276	325	439	380	594	396	242	319	96	352	-
V	258	51	256	36	282	83	256	106	277	71	246	71	236	75	242	47	205	26	200	-
Zr	107	32	104	10	69	27	74	38	69	28	53	28	61	32	88	27	74	19	76	-
Cu	61	22	58	14	75	55	88	32	116	116	106	83	108	83	97	44	78	39	59	-
Zn	78	15	68	10	101	124	79	26	97	120	75	23	82	22	97	30	93	25	110	-
Co	38	7	44	7	33	12	36	15	37	11	37	10	35	9	35	7	25	5	34	-
Ni	116	39	161	42	68	38	135	114	68	67	97	86	80	63	71	37	55	25	58	-
Cr	184	109	318	130	151	113	297	275	141	201	281	335	256	352	186	151	173	130	91	-

* CaO recalculated on a carbonate free basis with rare negative values reset to zero.

southeast to northwest (*see* Fig. 12). Each terrane faces predominantly westward, so there is an apparent stratigraphic relationship from Crescent at the bottom to Boot Harbour at the top, which is partly supported by inferred intrusive relations of granite and felsites about Loon Pond pluton. The Crescent terrane has been further divided into Crescent Hump and the Southwest Crescent Block which are separated by a fault that cuts obliquely southward across Crescent terrane so that Southwest Crescent Block appears faulted over Crescent Hump. The basalts from each of these subunits are not generally distinguishable in the field. Nevertheless the subunits form the best presently known basis for grouping and comparing the basalt analyses.

Table 13. Contrasts in basalt petrochemistry

Comparison	(Confidence level for difference of means)				
Subunits	1-2	2-3	3-5	4-5	1-5
SiO_2	-.000	+.037	+.005	+.001	-.990
TiO_2	+.000	+.000	+.138	+.297	+.000
Al_2O_3	+.004	+.005	-.000	-.000	+.174
Fe_2O_3	+.682	-.470	+.028	+.069	+.060
FeO	-.001	+.000	+.305	+.076	+.553
MnO	-.582	+.078	-.156	-.258	-.255
MgO	-.938	+.001	+.704	+.804	+.064
CaO	+.217	-.000	+.851	+.644	-.600
Na_2O	-.006	+.139	-.108	-.069	-.004
K_2O	+.034	-.001	-.522	-.977	-.380
P_2O_5	+.000	-.000	+.892	+.606	+.046
H_2O	+.000	-.472	+.720	-.174	+.003
CO_2	+.006	-.000	-.002	-.000	-.007
S	+.641	-.000	-.024	-.031	-.015
F	+.000	-.000	-.003	-.073	-.042
Cl	-.002	+.610	+.000	+.000	+.082
FeOt	-.001	+.000	+.011	+.005	+.021
CaO*	-.009	+.023	+.000	+.000	+.000
Li	+.000	+.117	-.319	-.000	+.000
Sr	+.000	-.003	+.710	+.034	+.024
Ba	+.049	-.000	-.736	+.253	-.046
V	-.218	+.508	+.074	+.017	+.093
Zr	+.000	+.139	-.015	-.004	+.016
Cu	-.022	-.001	+.125	+.165	-.024
Zn	-.176	+.737	-.611	-.396	-.022
Co	+.013	-.064	+.081	+.001	+.004
Ni	+.001	+.464	+.296	+.228	+.000
Cr	+.325	+.912	+.942	+.872	+.328
Ti/P	-.000	+.000	+.117	-.693	+.000
Ni/Cr	+.655	-.006	+.083	+.063	+.650
Fe/Al	-.000	+.001	+.000	+.000	+.071
F/CL	+.000	-.000	-.000	-.000	-.024
F/P	+.000	+.011	-.034	-.007	-.002
Li/Al	+.000	+.355	-.612	-.000	+.000
Na/Ca*	+.759	-.279	-.000	-.000	-.000

Subunit Designation:

1. Crescent Hump
2. Southwest Crescent block
3. Mud Pond – Boot Harbour terranes combined
4. Mud Pond terrane (excluding northeastern undivided terrane)
5. Rocks of Pilley's section about Pilley's Island mine.

* CaO recalculated by subtracting the wt. percent of CaO necessary to combine with CO_2 and resetting negative values to zero.

Note: Comparisons are made on a wt. percent basis. The difference in means is significant at the 95 percent confidence level if the value given is .050 or less, significant at the 99 percent level if the value given is .010 or less and significant at the 99.9 percent level if the value given is .001 or less. The value given is positive if the mean of the first subunit is greater than that of the second, and negative if the reverse is true.

Problems with this classification arise from uncertainty of projection of the Sunday Cove Fault (separating Mud Pond and Boot Harbour terranes) into the northeast part of the map area, and from severe alteration of samples from the Pilley's Island section in the neighbourhood of Pilley's Island Mine. Comparison of basalts from Mud Pond-Boot Harbour terrane on the basis of various assumed northeastern terrane boundaries using discriminant analysis and on an element by element basis indicates that the basalts in these two terranes are more similar to one another than to the Crescent terrane basalts, and does not provide a strong basis for differentiating between them. Patterns of variation for certain elements, particularly TiO_2 and FeOt, suggest that processes which may have been predominant in Crescent terrane, reoccurred at scattered localities within Mud Pond and Boot Harbour terranes thus obscuring potential chemical contrasts between the latter two. The same conclusion is suggested by comparison of pyroxene compositions. The data from Mud Pond and Boot Harbour terranes have therefore been combined for general illustrative purposes (Mud Pond — Boot Harbour terrane). Basalts from Pilley's section, from the fault through Loadabats Pond to the ridge-top north of the Mine felsite, have been removed from Mud Pond — Boot Harbour terrane to form a separate subunit representing alteration in the mine area.

Comparisons between mafic volcanics from Crescent Hump, Southwest Crescent Block, and Mud Pond — Boot Harbour terrane have been made using Student's "t" statistic on an element by element basis, each subunit being compared with the one above it in the apparent stratigraphy (*see* Table 13). Mud Pond — Boot Harbour and Boot Harbour terranes have been compared with potentially altered rocks in the Pilley's Island Mine area to which they are otherwise correlative, and the latter have been compared with rocks from Crescent Hump which are also apparently severely altered. Comparisons were made using basalts and pillow lavas separately, and then with the two lithologies combined. It was found that the pattern of significant contrasts between subunits was similar for both lithologies, and that the significance level of contrasts was enhanced by combining basalts and pillow lavas of each subunit into one population. Analogous to the basalt-pillow lava comparison, differences are regarded as clearly established where the CO_2-rich unit has a statistically significant and higher mean. If the CO_2-rich unit has the lower mean the respective element has been considered as a ratio (wt. %) with some other element for which the comparison of means has the same sign. If the difference of ratio means remains statistically significant without change of sign, then the difference is considered established.

Comparison of Southwest Crescent Block with Mud Pond — Boot Harbour terrane indicates that TiO_2 and FeOt are significantly depleted and K_2, P_2O_5, S, F, Ba and Cu are significantly enriched in the rocks of Mud Pond — Boot Harbour terrane. This conclusion is consistent with the change in FeOt and possibly in TiO_2 indicated by clinopyroxenes from the two terranes. Difference in P_2O_5 and K_2O may also reflect primary difference between the terranes because of relative immobility of P_2O_5 and very even low values of K_2O over extensive regions of Southwest Crescent Block consistent with interpretation of these rocks as low potash tholeiites. Higher and more erratic values of K_2O in Mud Pond — Boot Harbour terrane on the other hand may reflect local alteration of these rocks.

Comparison of Southwest Crescent Block with Crescent Hump indicates that Al_2O_3, TiO_2, P_2O_5, H_2O, F, Li, Sr, Ni, and Zr are enriched in Crescent Hump. The means for SiO_2 differ substantially and may indicate that Crescent Hump is significantly depleted in SiO_2, but the criterion employed here (ratio with FeOt) does not establish this conclusion. Cobalt and K_2O show differences at the 95% confidence level which are probably significant because they parallel changes in both CO_2 and H_2O. Most of the elements enriched in Crescent Hump with respect to the Southwest Crescent Block are commonly enriched in alkaline rocks suggesting that these rocks may have been part of an alkaline centre. On the other hand, obvious alteration of rocks in Crescent Hump and the immobility of most of the elements concerned suggests that they could have been concentrated by residual accumulation. Comparison of Al_2O_3, TiO_2, P_2O_5 and Zr between Crescent Hump and Southwest Crescent Block, however, indicates strongly increasing proportional concentrations in the order Al_2O_3, TiO_2-Zr, and P_2O_5 in Crescent Hump. Thus simple residual accumulation of these elements during alteration of a starting material like the basalt in Southwest Crescent Block is not indicated. Derivation of these elements from surrounding source rocks also seems unlikely because in no other Paleozoic rocks in the area (including the Sops Head Complex; *see* Table 10) do TiO_2 or P_2O_5 reach such high concentrations. The most likely conclusion therefore is that the rocks of Crescent Hump represent a distinct, more alkaline complex within Crescent terrane that has also undergone substantial alteration.

Comparison of basalts in the Pilley's Island Mine area with those of Mud Pond — Boot Harbour terrane suggests only a few differences at high confidence levels; however, if the comparison is confined to rocks of the Boot Harbour terrane in the restricted sense (northwest of the fault through Loadabats Pond) then several further contrasts are suggested. The rocks about Pilley's Island Mine are severely altered as is indicated by high Na/Ca* ratio and corresponding high normative corundum (mean 5.75, S.D. 3.17). Addition of carbonate is accompanied by increased Al_2O_3, Zr and Li; and fluorine may also be high as suggested by comparison with the full Mud Pond — Boot Harbour terrane. A large difference in means for SiO_2 from the two units suggests the possibility that some of the basalts of the mine area have been depleted in SiO_2 and similar statistics for the felsites suggest a similar conclusion.

Regional patterns of chemical variation

The above comparisons have suggested differences in composition between basalt units defined on the basis of available knowledge of the stratigraphy within the Robert's Arm Group. Patterns of chemical variation reflecting processes which postdate volcanism, or which arise from features not recognized in the field, require a different approach. For this purpose the chemical data were plotted in a series of sets of stratigraphic sections, each set representing data for one element or ratio (expressed in wt. % percent for major elements and ppm for minor ones) for the entire group. The ratios employed are: $Na_2O/(Na_2O+CaO^*)$, $Li/(Al_2O_3)$, $TiO_2/(TiO_2+P_2O_5)$, $Ni/(Ni+Cr)$ and $FeOt/(FeO+MgO)$. In the following text they are abreviated Na/Ca*, Li/Al, Ti/P, Ni/Cr and Fe/Mg. These sections were examined for patterns that transgressed subunit boundaries or indicated distinctive chemical units within the terranes. Of these sections four have been chosen to illustrate complex patterns, namely: Na/Ca*, Li/Al, Ti/P and Ni/Cr.

*Na/Ca**

The Na/Ca* ratio reflects the substitution of Na-Si for Ca-Al in plagioclase during spilitization. Because this alteration appears petrographically to be nearly complete, Na_2O values will also in part reflect the amount of plagioclase in the rocks. Estimates of CaO contents will be subject to uncertainities already mentioned, but two extremes are evident, use of analyses on a calcite-bearing or calcite-free (CaO*) basis. The latter has the advantage that it will not likely produce CaO values much higher than those in the original rock because this would probably involve introduction of alumina. It will also register maximum loss of CaO. Both extremes were examined but only the latter showed significant patterns. Recalculation of analyses on a carbonate-free basis produced some slightly negative values which were arbitrarily raised to zero for ratio use. The patterns obtained resemble those produced by calculation of normative corundum, but they have the advantage that a complete range of Na-Ca substitution is represented. Examination of CO_2 distribution patterns suggests that anomalously high CO_2 contents occur in the same general zones as high NaCa* ratios but the two are not simply related.

Patterns shown by the Na/Ca* ratio (Fig. 40) suggest that the peripheral parts of the Robert's Arm Group, comprising the South Brook, Mansfield, and Triton sections, have ratio values that oscillate close to the overall mean for the group. Extreme high values are concentrated in the area about Pilley's Island Mine and across a zone within southern Pilley's Island. Comparison of Pilley's Island Mine area with other basalt subunits indicates these values to be distinct at the highest level of confidence. Lesser anomalies occur in Crescent and Robert's sections on either side of the Old Crescent Lake

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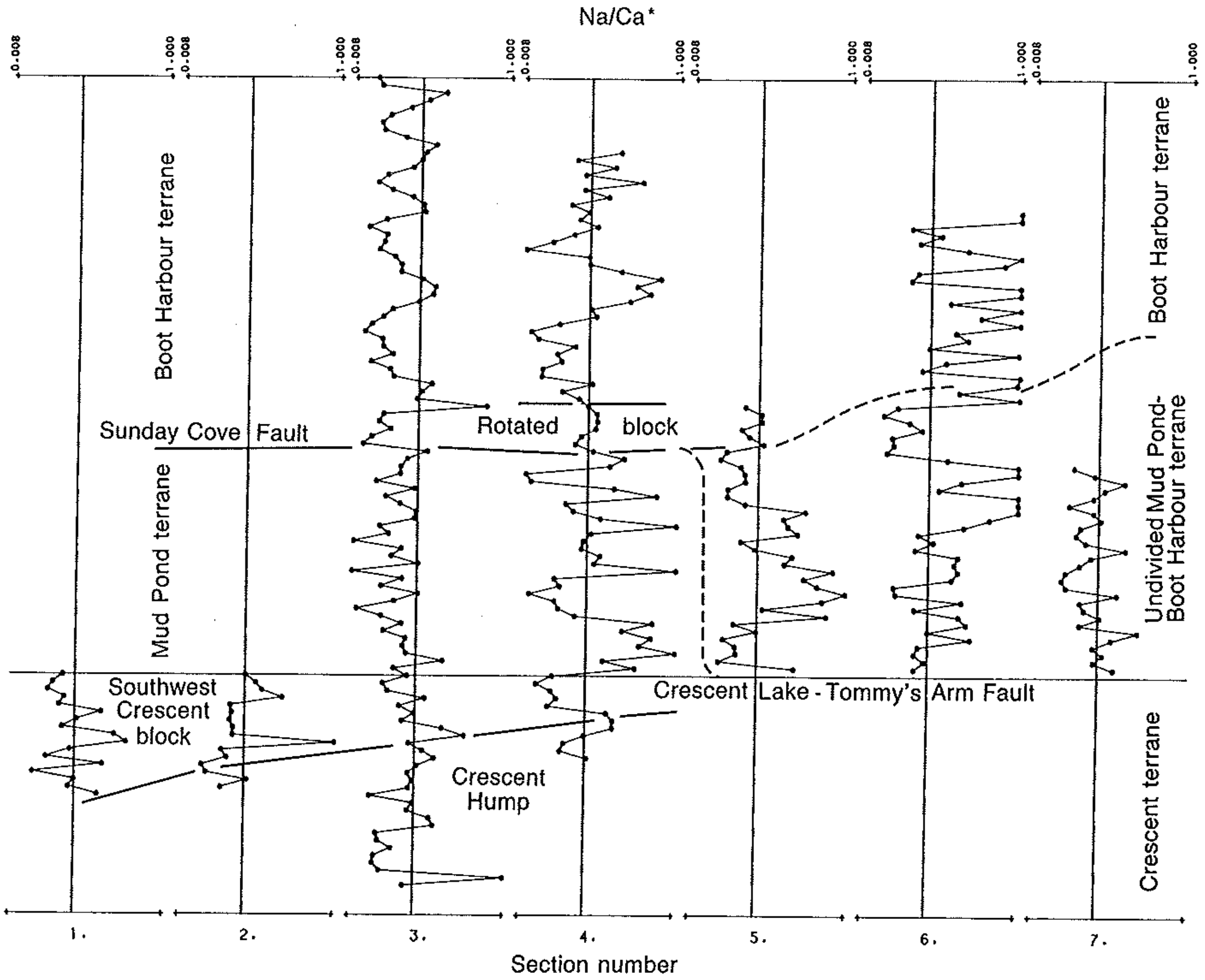
* The Na/Ca* ratio is determined using the value for CaO recalculated by subtracting the wt. % CaO necessary to combine with CO_2 and resetting negative values to zero. CaO* refers to the value for CaO produced by this subtraction.



1. North sector of South Brook section reversed to accommodate inversion of basalts
2. South sector of South Brook section in normal E-W sequence
3. Mansfield section
4. Crescent section
5. Robert's section
6. Pilley's section
7. Triton section

Note: Vertical lines represent mean ratio values with maximum and minimum shown by numbers at opposite ends of the upper horizontal bars

Ca* indicates calculation of the ratio (Na_2O/Na_2O+CaO) on a calcite-free basis with the few negative values of CaO reset to zero

Upper and lower dashed lines delineate minimum and maximum Boot Harbour terrane where projection of terrane boundary faults is uncertain. The diagram as a whole presents the succession of chemical sections from southwest (left) to northeast (right) through the Robert's Arm Group. Each section is composite in the sense that each terrane is thought to have been stacked upon the one beneath along the terrane boundary faults

GSC

Figure 40. Na/Ca* Stratigraphic Sections.

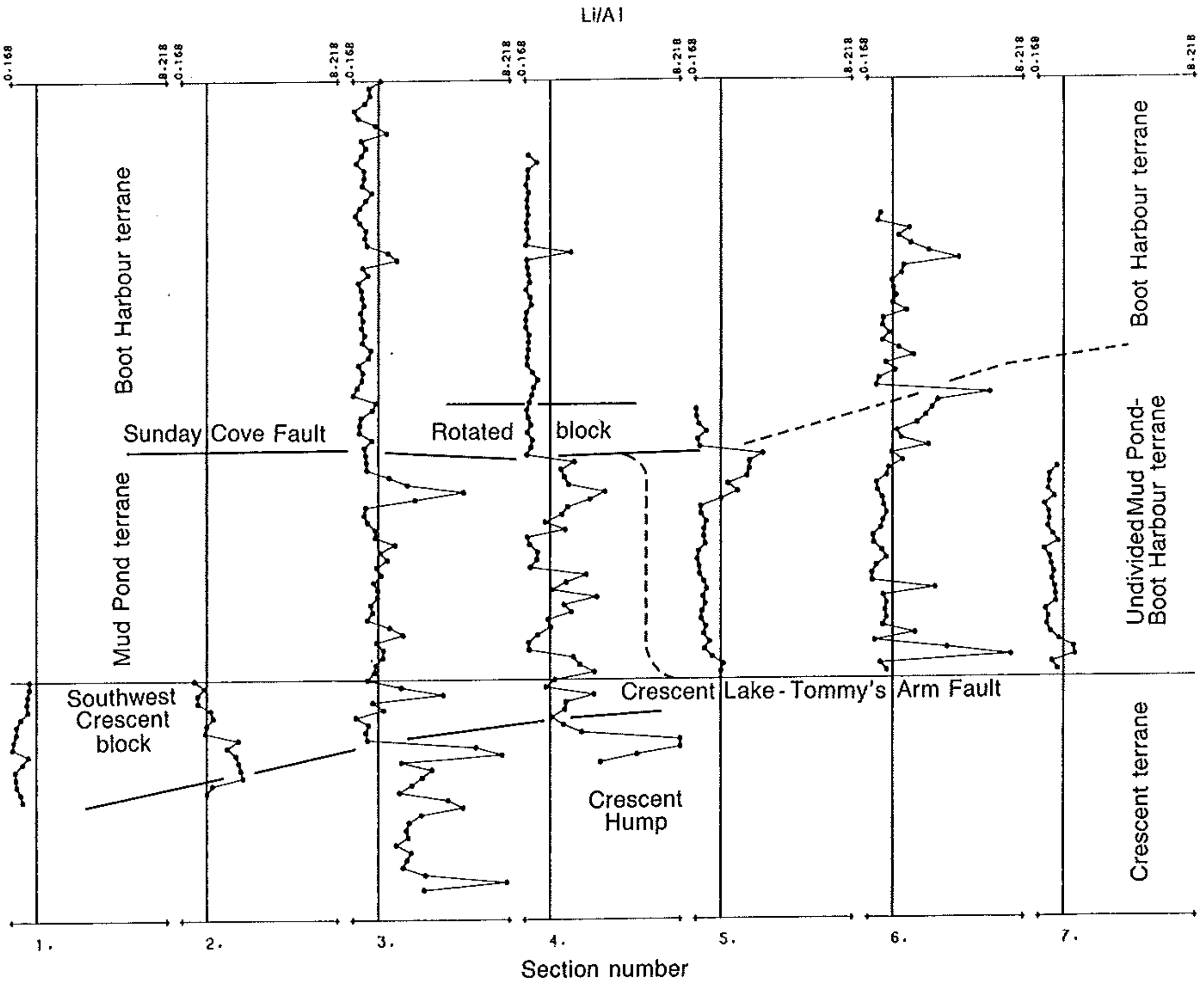


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Figure 41. Li/Al Stratigraphic Sections.

Mine. Other anomalous zones are of more restricted extent and probably result in part from sampling of altered breccia zones. Crescent Hump, which by other criteria appears the most altered and deformed, does not show particularly anomalous zones with this ratio. Depleted CaO* and hence increased mobility of Ca ion may reflect increased flux of CO_2-bearing solutions either from hydrothermal sources or as a result of barely emergent litoral environments.

Li/Al

The Li/Al ratio is of interest because some circulating brines are known to have Na/Li ratios suitable for Li deposition (Shaw et al., 1977). Lithium in the Robert's Arm Group has a greater relative range than Al_2O_3 and therefore the Li/Al ratio will be primarily controlled by Li.

Lithium contrasts between subunits (Fig. 41) suggest that Li is significantly enriched in Crescent Hump and possibly in the Pilley's Island mine area. Examination of regional patterns, however, suggests that the enrichment pattern is more extensive and complex than this. Within the northward trending part of Robert's Arm Group south of Robert's Arm Fault erratic high Li/Al ratios spread across both the southwest Crescent block and Mud Pond terrane, but in the southern part of the map area the anomalous area contracts towards the basal part of the group. To the northeast of Robert's Arm Fault where the basalts are apparently broken into several more easterly trending fault blocks, high Li/Al anomalies are less extensive but occur near the basal fault boundary of Mud Pond terrane, at its upper margin beneath a possible extension of the Sunday Cove Fault, and within a breccia zone near Lobster Cove Fault. The Pilley's mine area, although significantly richer in Li than most of the rest of Boot Harbour terrane, has substantially lower Li/Al ratios than Crescent Hump.

The regional pattern of high Li/Al anomalies cuts across three subunit boundaries and therefore probably reflects addition of lithium some time after volcanism. The change in pattern where Robert's Arm Group is oroclinally bent near Robert's Arm, from one focused in Crescent Hump and along the basal contact of Crescent terrane to a more irregular pattern perhaps related to faulting, may reflect Li deposition during deformation. Concentration of high Li/Al ratios within Crescent Hump suggests that the source of Li-bearing brines was proximal to Crescent Hump. Coincidence of the tectonically thickened Sops Head Complex at this locality suggests that the area was one of dilation during tectonism and therefore a potential site of fluid accumulation. Lithium-related alteration of Crescent Hump and surrounding rocks may therefore have occurred during post-volcanic faulting, perhaps during thrusting of Robert's Arm Group over the Sops Head Complex suggested by Nelson (1981). Northeast of Robert's Arm this pattern may have been complicated by continued faulting so that the fault blocks now juxtaposed were at greater distance from the Li source or were Li-enriched only along their margins.

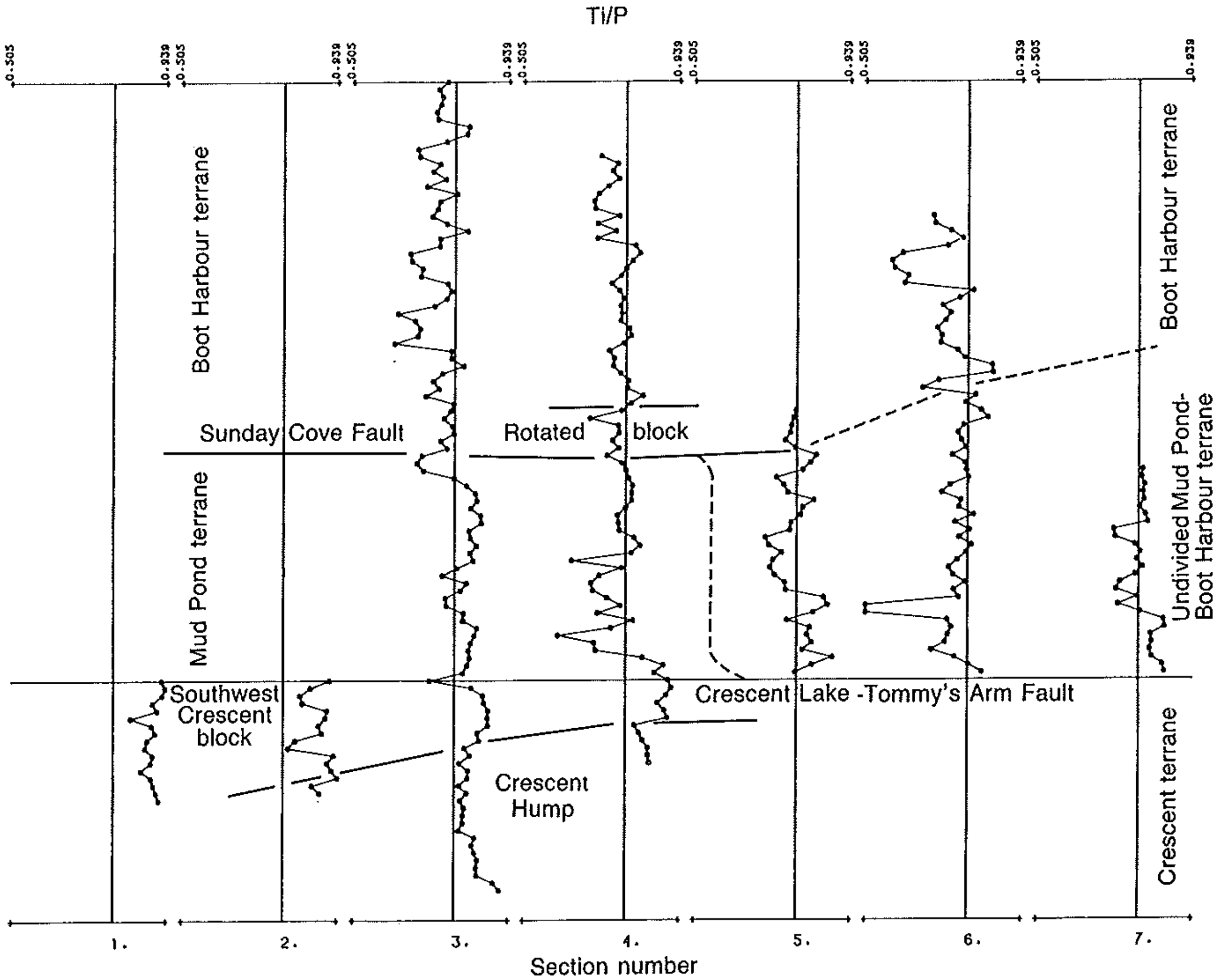
Ti/P

Titanium and phosphorous are incompatible elements whose concentrations in basaltic magmas are affected differently by changing conditions of partial melting at depth (Chazen and Vogel, 1974). The Ti/P ratio is therefore a potential indicator of magma type. Titanium is considered inert in most secondary environments and phosphorous is likely to be mobile only under conditions of low pH. Normal conditions allowing deposition of calcite should therefore favour a stable Ti/P ratio.

Ti/P ratio patterns (Fig. 42) conform more closely to the proposed primary subdivision of Robert's Arm volcanics than do the previously discussed ratios. High values due to high Ti content in the basalts are present in Crescent Hump, but through the rest of Crescent terrane low P_2O_5 values become a significant factor in raising the ratio. Similar high ratio values locally cross into Mud Pond terrane and may reflect approximate stratigraphic continuity across the bedding plane fault at the terrane boundary. The TiO_2 vs. P_2O_5 plot (Fig. 43a) shows that both Crescent Hump and southwest Crescent block tend to have lower P_2O_5 for equivalent TiO_2 than does the rest of the Robert's Arm Group.

Comparison of basalts from Robert's Arm Group with data from Bass et al. (1973) in Figure 43a suggests that rocks from Southwest Crescent block have TiO_2:P_2O_5 distribution like those of ocean ridge basalts, but basalts of Crescent Hump depart from this field toward that of alkali basalt. The data are consistent with interpretation of the southwest Crescent block (rocks at the apparent base of Robert's Arm Group) as ocean ridge tholeiite like the basalts of Hall Hill Complex and Lush Bight Group. Despite increased alteration the distribution of breccias about the margin of Crescent Hump and the composition of the basalts suggest that it may represent a distinct, possibly more alkaline, centre within Crescent terrane. Local persistence of high Ti/P ratios across the fault boundary into Mud Pond terrane suggest that the same magmatic processes responsible for high values of this ratio in Crescent Hump have persisted locally in Mud Pond terrane.

Mud Pond — Boot Harbour terrane, in contrast to Crescent terrane, is broadly characterized by both lower TiO_2 and Ti/P ratio. This is illustrated in the TiO_2-P_2O_5-MnO diagram (Fig. 43b) of Mullen (1983), which also shows field boundaries for basalts from various oceanic and ocean margin settings. In this diagram Mud Pond — Boot Harbour basalts cluster astride the calc-alkaline-island arc tholeiite boundary whereas those from Crescent terrane tend to straddle the island arc tholeiite-oceanic basalt boundary with rocks from Crescent Hump extending into the alkaline basalt field. This separation of Robert's Arm Group into two major terranes, marking a potential change from oceanic anorogenic volcanism to plate margin orogenesis, is consistent with interpretation of change in pyroxene composition at the terrane boundary.



1. North sector of South Brook section reversed to accommodate inversion of basalts
2. South sector of South Brook section in normal E-W sequence
3. Mansfield section
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Note: Vertical lines represent mean ratio values with maximum and minimum shown by numbers at opposite ends of the upper horizontal bars

Upper and lower dashed lines delineate minimum and maximum Boot Harbour terrane where projection of terrane boundary faults is uncertain. The diagram as a whole presents the succession of chemical sections from southwest (left) to northeast (right) through the Robert's Arm Group. Each section is composite in the sense that each terrane is thought to have been stacked upon the one beneath along the terrane boundary faults

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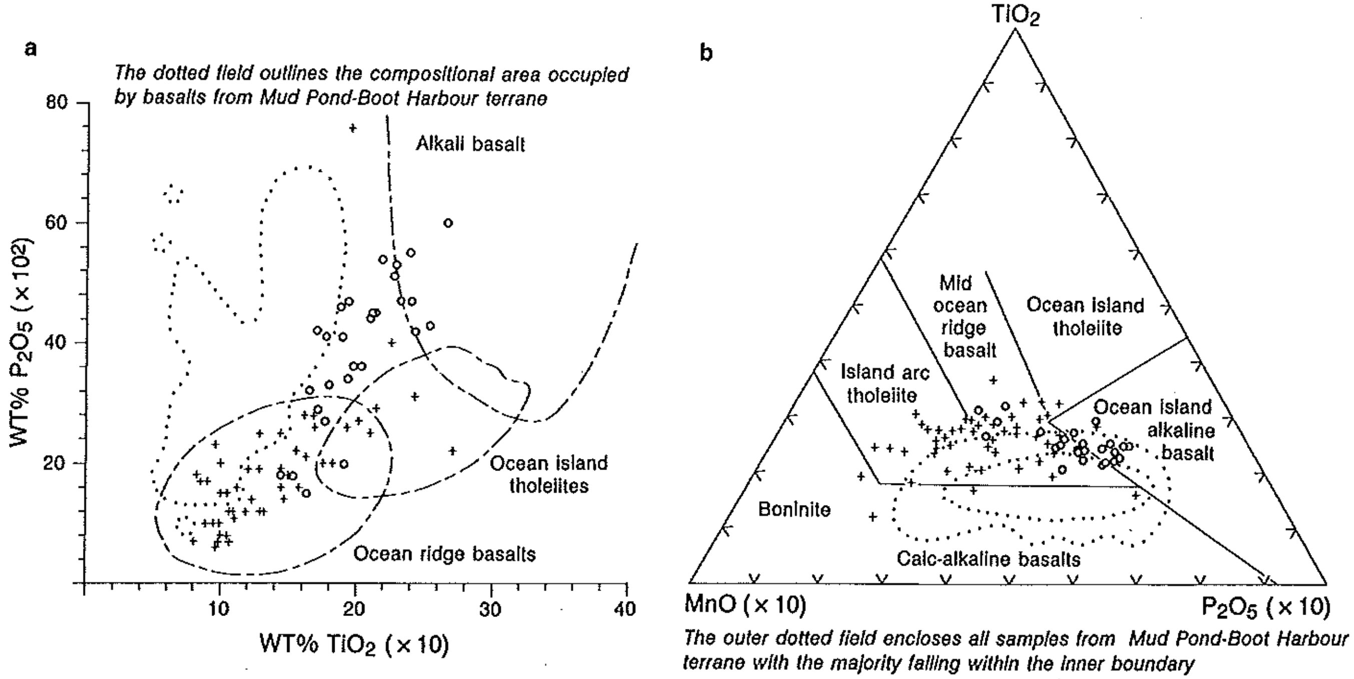
Figure 42. Ti/P Stratigraphic Sections.



The dotted field outlines the compositional area occupied by basalts from Mud Pond-Boot Harbour terrane

The outer dotted field encloses all samples from Mud Pond-Boot Harbour terrane with the majority falling within the inner boundary

Individual plotted points represent samples from Crescent terrane with those from Crescent Hump represented by circles and those from the Southwest Crescent Block represented by crosses

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Figure 43a. TiO_2 vs. P_2O_5 plot for Robert's Arm basalts showing dashed field boundaries of Bass et al. (1973) **b.** The MnO-P_2O_5-TiO_2 diagram with field boundaries of Mullen (1983).

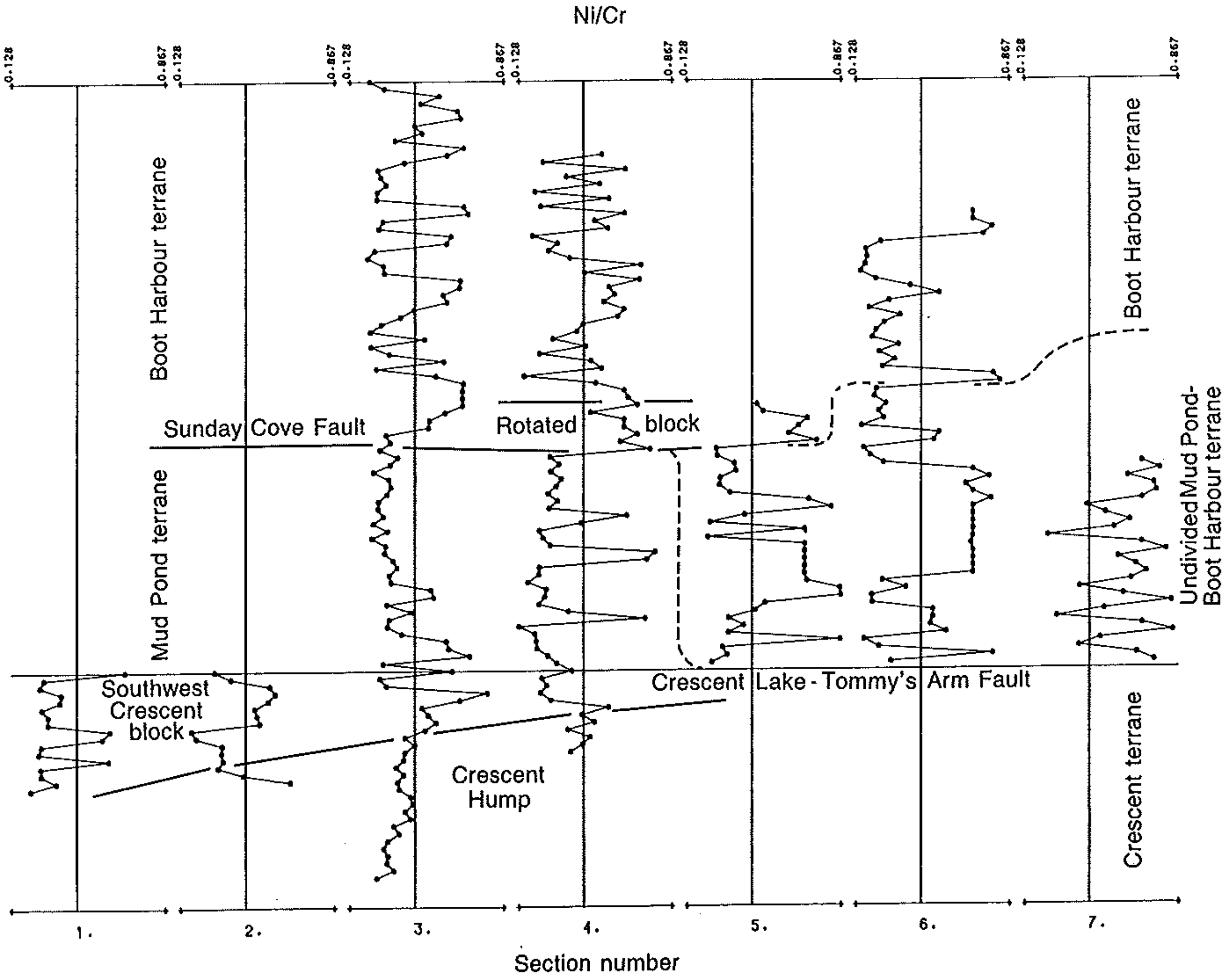
Ni/Cr and Fe/Mg

In studies of unaltered basalts the Fe/Mg ratio provides an index to degree of crystallization differentiation which the rocks have undergone, whereas Ni/Cr and Ni/Co ratios may be more sensitive to involvement of different minerals in differentiation. Fe/Mg may be expected to show positive correlation with Ni/Cr and negative correlation with Ni/Co in most basalts reflecting early removal of Cr and accumulation of Co in differentiating basalt magmas. In secondary environments both MgO and FeO are likely to be mobile but Cr and Ni are less so.

Correlation coefficients (Table 14) were calculated for FeOt, MgO, Ni, Cr, and Co for the four basalt subunits omitting 22 samples (all from Mud Pond — Boot Harbour terrane) which contained Ni and Cr below their respective detection limits of 10 and 5 ppm where these elements were involved. Correlation for most pairs is weakest in Crescent Hump and in the area about Pilley's Island mine where the rocks are likely most altered. Ni/Cr correlation coefficients, however, show very little change in significance of correlation suggesting that they have been little affected by alteration, or (less likely) that they have been affected in similar ways by it.

Regional patterns for the Ni/Cr ratio are less likely to be affected by alteration than Fe/Mg and show less apparently random variation, but they tend to show the same anomally patterns in chemical section. Ni/Cr has therefore been chosen to illustrate these patterns (Fig. 44) despite the presence of 22 samples from Mud Pond — Boot Harbour terrane below the detection limits for Ni and Cr. Because other samples with measureable but low Ni and Cr values also tend to have high Ni/Cr ratios these samples can be included in the diagram at Ni and Cr contents of 9 and 4 respectively, one ppm below their detection limits, without causing much distortion of the regional patterns. All of these 22 samples are from Robert's, Pilley's, and Triton sections.

Low Ni-Cr samples (below detection limits) are concentrated in two continuous intervals reaching up to 1070 m width in Pilley's and Robert's sections where they are accompanied by distinct high Fe/Mg anomalies and a scarcity of pyroxene phenocrysts. These intervals therefore suggest the presence of a distinct chemical unit within the basalts that was not recognized in the field. Elsewhere within the group less extensive high Ni/Cr ratio anomalies with accompanying high Fe/Mg occur in Boot Harbour terrane, but are less common, and still less extensive in Crescent and Mud Pond terranes. These anomalies all have measureable Ni and Cr values although the absolute Ni and Cr contents are small. This pattern of Ni/Cr anomalies suggests a contrast between Boot Harbour terrane and Mud Pond-Crescent terranes in which the former shows a tendency to be differentiated into pyroxene-aphyric, low Ni-Cr, high Ni/Cr ratio rocks, and pyroxene-phyric rocks of the reverse chemical characteristics; whereas the latter shows only limited differentiation on this type.



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Upper and lower dashed lines delineate minimum and maximum Boot Harbour terrane where projection of terrane boundary faults is uncertain. The diagram as a whole presents the succession of chemical sections from southwest (left) to northeast (right) through the Robert's Arm Group. Each section is composite in the sense that each terrane is thought to have been stacked upon the one beneath along the terrane boundary faults

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Figure 44. Ni/Cr Stratigraphic Sections.

Evolution of high Ni/Cr and Fe/Mg ratios in association with low absolute Ni-Cr implies that pyroxene rather than olivine settling has been a controlling factor in differentiation of basalts in Mud Pond — Boot Harbour terrane because liquid-crystal partition coefficients (Duke, 1976) suggest that olivine differentiation will concentrate Cr whereas pyroxene differentiation will concentrate Ni in the residual melts (assuming chromite fractionation is negligible). The common occurrence of pyroxene phenocrysts in these rocks supports this conclusion. Comparison of the compositions of basalts with and without pyroxene phenocrysts indicates that the pyroxene-phyric rocks are richer in MgO, Ni, and Cr, have lower Ni/Cr ratios and lower FeOt all at the 99% confidence level or better. These data suggest that the high Ni/Cr ratio, pyroxene aphyric-basalts have undergone a phase of pyroxene settling which has progressed to completion, whereas the pyroxene-phyric rocks represent either more primitive basalts tapped during their settling phase, or cumulate-enriched basalts tapped from the lower regions of differentiating magma chambers. Contrasts in composition between pillow lava and massive basalts seem to favour the latter alternative. The increased proportion of differentiated basalts evident in Boot Harbour terrane (Fig. 44) is consistent with build up of the Robert's Arm volcanic pile and consequent longer periods of magma retention in subjacent chambers. Given the tendency of pillow lavas to form from more mafic lavas throughout the Robert's Arm Group, this buildup may also be responsible for the marked increase in coarsely pyroxene-phyric pillow lava in Boot Harbour terrane. Presence of the most strongly differentiated units in Triton, lower Pilley's and lower Robert's sections provides some further evidence that the undivided northeastern part of Robert's Arm Group may belong in Boot Harbour terrane.

Miscellaneous patterns

Many elements show patterns of possible importance that are more local in distribution or are characterized by contrasts of lower confidence level. In most cases the reason for these constrasts is unknown and they are not further discussed. Some, however, are of special interest.

Chlorine and fluorine show antipathetic behaviour in Crescent Hump, chlorine being depleted and fluorine concentrated at very low levels. Chlorine shows high concentration in the amphibolites about Sunday Cove pluton and is similarly concentrated in the amphibolites of Hall Hill Complex suggesting that Cl has entered preferentially into amphibole. Basalts of Boot Harbour terrane that overlie the aureole, however, also show local anomalous chlorine concentration at a lower level. There is therefore a suggestion that Cl may have been introduced into these rocks during emplacement of the pluton.

More than other elements Ba, S, and Zn tend to show isolated peak values. Ba anomalies are concentrated in the upper (Mud Pond and Boot Harbour) subunits so that these appear anomalous in the statistical comparisons, although the mine area does not. Only one Zn anomaly (1600 ppm) in the lower part of Mud Pond sector of Crescent Section was detected in the basalt. Sulphur shows anomalous concentration in basalts of Pilley's Island Mine area and also locally in the Mud Pond sector of Crescent section. Scattered peak anomalies of all three of these elements through the Mud Pond sector of Crescent section sets this sector apart from others and is consistent with numerous minor sulphide showings known along strike west of the village of Robert's Arm.

Table 14. Correlation coefficients for major and trace mafic elements

Basalt subunit	FeMg/NiCr	FeMg/NiCo	Fe/Mg	Ni/Cr	Ni/Co	Ti/P
Crescent Hump	+.47240 .00483	-.50688 .00251	+.53009 .00155	+.93380 .00001	+.50526 .00259	+.75788 .00001
Southwest Crescent	+.63327 .00001	-.82211 .00001	-.50359 .00008	+.94033 .00001	+.31230 .01284	+.62593 .00001
Mud Pond-Boot Harbour terrane	+.68586 .00001	-.78623 .00001	-.17603 .00329	+.90752 .00001	+.23597 .00001	+.66373 .00001
Pilley's Mine	+.55912 .02349	-.51425 .03610	+.46910 .05292	+.93222 .00001	+.63955 .00785	+.65223 .00785

Note: The upper figure represents the correlation coefficient, and the lower the respective significance level. Analyses for which Cr and Ni were below detection limits are excluded where these elements are involved.

Table 15. Chemical analysis of major and minor felsite groups

Unit	Crescent		Boot HBR		Pilley's Mine		Mansfield		Rotated Blk		Robert's Arm		S. Pilley's		E. Pilley's		Barbers Cve	
No. of samples	15		65		19		06		04		03		05		05		01	
Statistic	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
SiO_2	70.99	5.05	67.03	4.02	64.30	2.96	65.40	4.92	66.08	3.26	65.73	7.41	66.67	1.43	65.20	9.13	62.40	-
TiO_2	0.45	0.34	0.58	0.20	0.65	0.15	0.63	0.18	0.60	0.13	0.47	0.35	0.55	0.09	0.66	0.31	0.79	-
Al_2O_3	14.11	2.18	15.19	1.21	15.93	1.75	15.83	2.36	15.53	1.15	15.33	1.07	15.26	1.38	15.34	2.44	16.00	-
Fe_2O_3	0.99	0.76	1.20	0.77	0.57	0.46	0.92	0.45	0.83	0.38	1.60	0.20	1.08	0.43	1.30	0.27	0.90	-
FeO	2.17	1.69	2.52	1.17	3.55	0.89	3.12	0.50	3.93	0.89	2.43	2.23	2.96	1.05	2.70	1.66	4.50	-
MnO	0.07	0.04	0.12	0.05	0.15	0.07	0.14	0.03	0.14	0.04	0.10	0.07	0.11	0.02	0.12	0.03	0.13	-
MgO	1.41	0.85	1.31	0.64	2.26	1.42	1.56	0.35	1.33	0.36	2.27	0.98	1.54	0.38	2.64	1.84	3.62	-
CaO	1.88	1.25	1.71	1.00	0.84	0.61	2.14	1.13	1.63	0.39	2.68	1.96	1.56	0.97	1.61	1.23	1.24	-
Na_2O	3.96	1.50	4.76	1.42	3.01	1.85	4.02	2.26	3.40	1.38	3.37	1.85	4.74	2.02	4.06	0.98	6.10	-
K_2O	1.95	1.57	3.38	1.62	4.96	2.47	3.82	2.27	4.85	2.27	3.06	0.99	3.26	1.70	2.51	1.06	1.21	-
P_2O_5	0.13	0.10	0.18	0.09	0.16	0.03	0.18	0.05	0.19	0.05	0.19	0.17	0.13	0.02	0.16	0.05	0.18	-
H_2O	1.36	0.82	1.12	0.47	1.85	0.90	1.23	0.33	1.20	0.48	2.17	0.32	1.46	0.58	2.36	1.11	2.30	-
CO_2	0.57	0.56	0.88	0.89	0.72	0.90	0.48	0.71	0.30	0.40	1.17	0.68	1.56	1.02	0.74	1.01	0.40	-
S	0.16	0.32	0.06	0.09	0.90	0.89	0.03	0.03	0.09	0.01	0.03	0.02	0.04	0.05	0.05	0.03	0.04	-
F	0.05	0.03	0.07	0.03	0.08	0.05	0.05	0.03	0.07	0.03	0.05	0.01	0.06	0.04	0.05	0.02	0.08	-
Cl	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.00	0.02	-
Total	100.27		100.13		99.95		99.57		100.19		100.67		100.99		99.52		99.91	-
FeO_t	3.05	2.02	3.60	1.33	4.06	0.89	3.94	0.67	4.67	1.09	3.87	2.39	3.93	0.75	3.87	1.63	5.31	-
C*	3.94	2.68	2.68	1.55	6.36	3.24	3.06	1.08	3.16	1.28	5.97	3.04	4.98	2.21	5.01	2.48	4.13	-
Li	6	11	4	9	4	3	4	3	4	1	6	3	4	1	8	3	9	-
Rb	52	45	75	44	95	54	84	54	92	57	93	50	82	73	84	48	22	-
Cs	0.8	0.9	0.4	0.4	0.7	0.5	0.7	0.7	0.4	0.3	0.6	0.5	1.7	1.9	2.1	0.7	0.4	-
Sr	131	93	164	125	55	23	195	105	122	52	133	112	49	24	146	49	133	-
Ba	580	368	1051	623	1146	568	1287	921	1201	475	886	239	602	388	1182	606	245	-
V	38	26	35	27	26	8	33	15	25	5	68	69	23	7	68	74	34	-
Zr	137	31	167	40	206	52	150	24	175	23	209	64	160	18	207	30	188	-
Cu	24	17	31	16	92	158	29	14	22	11	31	34	23	20	36	12	20	-
Zn	40	25	55	31	489	1101	83	43	135	62	67	15	84	38	60	7	130	-

C* Normative corundum

Felsic volcanics

Patterns not only of composition but also of distribution differ between basalts and felsites of the Robert's Arm Group. Basalts are spread throughout the Group whereas felsites are concentrated in large centres in its western and northern parts. Elsewhere they occur as minor dykes, sills or flows and appear to be quite rare in some extensive regions (as in the Mud Pond terrane). This distribution has required both a different scheme of sampling for chemical investigation (Fig. 38), and a different approach in the search for patterns of chemical variation.

Preliminary examination of the felsite analyses suggested that chemical variation within the Robert's Arm felsic volcanic centres was approximately as great as variation between them. In order to test the data for significant regional differences various groupings where compared using the SPSS (Statistical Package for the Social Sciences) procedure, DISCRIMINANT, Klecka (1975). This procedure suggested division of felsites into three major groups, and a fourth miscellaneous group consisting mostly of minor felsite bodies situated within the Mud Pond and lower part of Boot Harbour terrane beneath the major felsite centres.

Felsite subunits

The most successful subdivision of the felsite analyses obtained through discriminant analysis was found to include three principal felsite groups:

1. Felsites of the Crescent terrane including those related to Loon Pond pluton. These will be called the Crescent felsites.
2. Felsites from all other major centres except three occurring in the general vicinity of Pilley's Island Mine. These will be called the Boot Harbour felsites.
3. Three felsite centres about and to the west of Pilley's Island Mine including felsites west of the Mine Fault, felsites at Spencer's Dock, and felsites at Tilley's Cove east of Robert's Arm. These will be called the Mine felsites.

Minor felsite bodies, each comprising one or a few isolated flows, sills or dykes, mostly below the major centres in Boot Harbour terrane, but including the extensive felsites immediately east of the Mine Fault on Pilley's Island, were found to diminish the significance of the discrimination if included with the major groupings to which they appear to be most closely associated. They are therefore deleted from the detailed comparison.

The means and standard deviations for analyses from the three principal felsite groups and six minor groups are given in Table 15. Comparisons between major groups were made on an element by element basis using Student's "t" statistic both with alumina normalization to minimize affects of silica dilution in amygdules, and on a raw data basis. Because alumina normalization did not materially change the significance and pattern of discrimination, only comparisons employing the raw data are illustrated (Table 15). The data suggest that all three major felsite groups may have distinct SiO_2, K_2O and Zr compositions at the 99% confidence level or better. Certain other elements will distinguish between only two of the three major subunits.

Calculation of normative corundum (Table 16) suggests that most of the felsites are corundum normative. Although unaltered felsic volcanics commonly produce values reaching 1% of normative corundum (LeMaitre, 1976), the much larger amounts present in many of the Robert's Arm felsites indicate that these rocks have everywhere been subject to alteration. The

Table 16. Contrasts in felsite petrochemistry

Comparison Subunits	(confidence level for difference of means) 1-2	2-3	1-3
SiO_2	+.002	+.008	+.000
TiO_2	-.166	-.142	-.041
Al_2O_3	-.082	-.100	-,011
Fe_2O_3	-.338	+.000	+.055
FeO	-.449	-.001	-.010
MnO	-.000	-.180	-.001
MgO	+.640	-.010	-.047
CaO	+.574	+.000	+.003
Na_2O	-.056	+.000	+.116
K_2O	-.003	-.015	-.000
P_2O_5	-.081	+.205	-.269
H_2O	+.295	-.003	-.109
CO_2	-.205	+.493	-.581
S	+.249	+.001	-.003
F	-.025	-.288	-.029
Cl	+.512	+.006	+.055
FeOt	-.332	-.162	-.090
C*	+.053	-.000	-.097
Li	+.478	-.757	+.605
Sr	-.338	+.000	+.008
Ba	-.000	-.550	-.002
V	+.705	+.016	+.091
Zr	-.007	-.001	-.000
Cu	-.125	-.110	-.077
Zn	-.091	-.103	-.093
KAl	-.008	-.044	-.001
MnAl	-.001	-.304	-.004
ZrAl	-.122	-.011	-.001
BaAl	-.001	-.684	-.010

Subunit designation:
1. Crescent Hump
2. Southwest Crescent block
3. Mud Pond – Crescent block

Note: The difference in means is significant at the 95% confidence level if the value given is .050 or less, significant at the 99% level if the value given is .001 or less. The value given is positive if the mean of the first subunit is greater than that of the second, and negative if the reverse is true.

C* Normative corundum

increasing mean normative corundum values in the sequence from Boot Harbour felsites through Crescent felsites to the Mine felsites is suggestive of increasing alteration. Statistical comparison of the Boot Harbour and potentially correlative Mine felsites indicates this difference is real at the 99% level, but the intermediate position of Crescent felsites overlaps sufficiently with both other groups that its distinctness is not statistically established.

Potential chemical contrasts between felsites of the three major felsite subunits are accompanied by substantial additions or depletions of SiO_2 unlike the basalts which have mostly undergone major carbonate addition. In the Mine felsites, silica has been depleted with respect to the Boot Harbour felsites, and other elements, Fe_2O_3, CaO, Na_2O, Cl, Sr, and possibly V, which also show significant depletion levels, are therefore depleted in the Mine felsites as well. The Zr/Al and K/Al ratio comparisons remain negative and are either significant or very nearly significant at the 99% level suggesting that the Mine felsites are enriched in these two elements. These contrasts mostly differ from those listed for the basalts presumably because the criterion for acceptance of significance of basalt contrasts is biased toward addition, whereas that for the Mine felsites is biased toward depletion. If all the possibly significant contrasts indicated by the two tables are considered valid, then similar trends are suggested in depletion of SiO_2, CaO^{I}, Cl, and possibly Sr, V, and Fe_2O_3; and in addition of Zr and S. The two elements which appear to have contrasting behaviour between basalts and felsites are the alkalis. Possible addition of Zr to both basalts and felsites in the mine area is of interest because Zr is known to be mobile in late fluids derived from differentiating alkaline magmas (Erlank et al., 1978).

Alteration of the felsites in the western part of the Pilley's Island Mine area was considered in detail using samples from drill core by Lemon (1982) who found that SiO_2 and Na_2O are removed and Fe, S, Cu, V, Cr, Ag and Pb are added in the immediate vicinity of the ore body. Mg, Ca, Li and Sr are depleted in the sericitic zone above it. The present study is consistent with these results, but the samples from the mine area used here are more dispersed, and they are compared with correlative felsites entirely beyond the Pilley's Island Mine. They therefore suggest that some aspects of this type of alteration extend well beyond the immediate vicinity of the west mine.

Chemical contrasts between felsites of Boot Harbour and Crescent terranes (where felsites occur only in the southwest Crescent block) are more likely to include some contrasts that reflect the primary character of the rocks. This comparison, however, shows no significant contrasts sympathetic to enhancement of SiO_2 in the Crescent felsites. Examination of the potentially depleted elements, K_2O, MnO, Ba and Zr, in ratio form with Al_2O_3 suggests that K_2O, Ba and MnO are significantly depleted in these felsites, but Zr may not be. High silica is consistent with the common appearance of quartz phenocrysts in the Crescent felsites and may also be related to their apparently more explosive character. The data are of interest because they suggest a subtle change in composition between felsites in different terranes that have been shown to be characterized by different basalt chemistry.

Summary of petrochemistry

Representative sampling has produced a regional estimate of compositional variations within the Robert's Arm volcanics. These variations indicate that Robert's Arm Group has been subject to two episodes of extensive alteration: early spilitization followed by alteration of the southeastern basalts thought to have occurred during deformation and faulting. These alterations have cast doubt on the interpretation of primary compositions particularly insofar as the more mobile elements are concerned, but some contrasts between basalt subunits involving less mobile elements, supported by mineralogical contrasts, indicate that two terranes of differing basalt composition erupted in different volcanic settings are present. Pillow lavas in Robert's Arm Group tend to be more mafic than the associated massive basalts, and in Boot Harbour terrane where pyroxene phenocrysts are most abundant, they are also more commonly pyroxene-phyric.

Spilitic alteration involving Na-Si-Ca mobility, hydration, and addition of CO_2, is an ubiquitous characteristic of Robert's Arm volcanics. Maximum contrasts in these elements are present on Pilley's Island particularly in the vicinity of Pilley's Island Mine where detailed studies (Lemon, 1982) indicate that Na-Si have undergone major depletion and other elements have been mobile in the felsites adjacent to the ore bodies during hydrothermal action. Enhancement of spilitic alteration on a broader scale about the mine may therefore be partly related to this local centre of hydrothermal activity. Additional depletions of Cl-Sr, and enhancement of Zr in both basalts and felsite in the broader mine area perhaps support this view. Chlorine is enriched in the rocks of the amphibolite facies aureole about Sunday Cove Pluton, and to a lesser extent in adjacent rocks, suggesting that Cl has been mobile during shallow granite plutonism. If enhancement of trace Zr in the mine area is of secondary origin, it may indicate a contribution to local hydrothermal fluids from a shallow felsic magma chamber.

Late alteration is suggested by the pattern of variable high Li anomalies, concentrated in Crescent Hump along the base of Robert's Arm Group, which spreads northwestward across fault boundaries into Mud Pond terrane. In Crescent Hump these anomalies are accompanied by common foliation, enhancement of H_2O, CO_2, F and more common normative corundum in contrast to rocks of Southwest Crescent block. The distribution of Li anomalies within Crescent Hump, focused in the northeast where the underlying Sops Head Complex appears to be tectonically thickened, may relate this alteration to movement of fluids from dilatant zones along the basal fault during the thrusting of Robert's Arm Group over Sops Head Complex suggested by Nelson (1981).

Potential primary contrasts between Southwest Crescent Block and Mud Pond — Boot Harbour terrane, the least altered parts of the Robert's Arm Group, involve high TiO_2-FeOt and low P_2O_5-(K_2O) in the forms. These correspond to high FeOt-TiO_2 in the respective unaltered pyroxenes of the two terranes and to a predominance of plagioclase phenocrysts in the former. Such contrasts commonly separate basalts of tholeiitic and calc-alkaline types. Comparisons of these data with general studies of basalts from different tectonic settings are consistent with the interpretation that the tholeiitic rocks of Crescent terrane represent an ocean floor or back arc tectonic setting whereas the basalts of Mud Pond — Boot Harbour terrane are more comparable to island arc tholeiitic or calc-alkaline arc settings.

The primary composition of basalts of Crescent Hump is less certain due to evident alteration. Scarcity of pyroxene phenocrysts, high FeOt-TiO_2 of the single analyzed pyroxene matrix sample, and high whole-rock TiO_2 suggest closer affinity to Southwest Crescent block than to Mud Pond — Boot Harbour terrane. Chemical contrasts between basalts of these terranes involve significant enhancement of Al_2O_3, TiO_2, P_2O_5 and Zr, elements which commonly concentrate in alkaline rocks. Crescent Hump may therefore comprise an isolated altered fault remnant of an alkaline basalt centre (small sea mount) that evolved within Crescent terrane. Despite the overall differences established between Crescent and Mud Pond — Boot Harbour terranes, it is evident that the chemical characteristics of Crescent terrane continue locally into Mud Pond terrane suggesting that although the terranes are separated by faults they may reflect volcanism in a single evolving tectonic setting rather than an assemblage of totally unrelated fault slices.

Felsic rocks in the Robert's Arm area are characterized by substantial local variation on a scale too fine for investigation in this study. Subtle regional variations exist in SiO_2, and possibly K_2O which may differentiate on a primary basis between felsites evolved within Crescent terrane (Southwest Crescent block), which are commonly quartz-phyric, and those of the major centres of Mud Pond — Boot Harbour terrane, which are mostly quartz-amygdaloidal.

VOLCANO-TECTONIC INTERPRETATION

The earliest basalts of the Robert's Arm Group are altered tholeiites of the Crescent Lake terrane deposited mostly on top of, but locally intertonguing with, a chert-shale-greywacke unit (the Crescent Lake Formation). Some, such as those of Crescent Hump, may have been slightly alkaline and built up individual basalt accumulations with associated breccia aprons on the basin floor. Similar remnants of oceanic island basalts of potentially similar age are suggested in the Summerford Group of eastern Notre Dame Bay (Jacobi and Wasowski, 1985). Other basalts, less titanium-rich and with smaller bodies of associated breccia, were deposited perhaps less rapidly within a section locally receiving fine- to medium-grained clastic sediments implying proximity to an emergent block. The upper Robert's Arm Group is thought to comprise two sections longitudinal to an asymmetric volcanic centre of comparatively more calc-alkalic affinity than the lower part. The western part of this centre was characterized by extensive bimodal volcanism which included large volumes of felsite texturally and possibly chemically distinct from the minor felsic bodies of the lower Robert's Arm Group. Shallow granite magma chambers fed these more extensive felsite accumulations. Similar volcanic associations, correlative to the Robert's Arm Group along strike in either direction (Buchans and Cottrels Cove groups), are also bimodal.

The foundation upon which the Robert's Arm Group is thought to have evolved comprises tholeiitic basalts, tonalitic plutonic rocks, and gabbro like those of Hall Hill and South Lake complexes. These rocks are not typical ocean floor crust because of the unusually large component of sialic rocks which they include. Likewise the

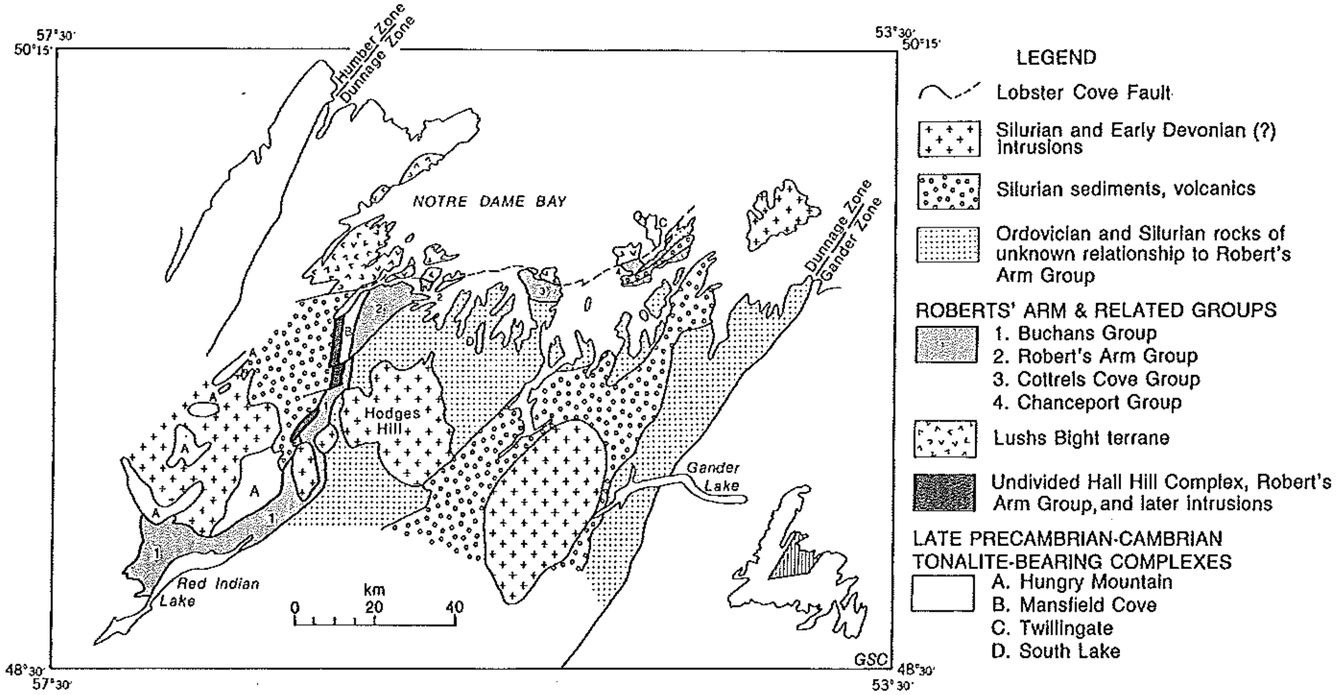

Figure 45. Geological Map of Notre Dame Bay Region.

Robert's Arm Group with its bimodal character, voluminous greywacke-bearing felsic volcanic debris, and upper basalts of more calc-alkaline ilk is unlike ocean floor crust. At the same time the bimodal nature of the group is typical of tensional rather than compressional environments in which most calc-alkaline suites are evolved (Martin and Pinwinskii, 1972), but is perhaps consistant with evolution in a back arc environment analogous to that described by Karig (1974).

The Robert's Arm segment of the back arc basin was floored after early rifting by distal volcanic sediment from neighbouring areas, but became more strictly volcanic as the upper (western) Robert's Arm volcanic pile thickened and rose above the submarine floor. Thus the lower Robert's Arm Group, which formed part of the ambient basin terrane, was overlain first by an extensive presumably enlongate shield composed of basalts comparable to island arc tholeiite, and this was intruded penecontemporaneously along its western margin by voluminous felsitic magmas.

The bimodal character of the upper Robert's Arm Group is in apparent conflict with the chemistry of the basalts (Strong, 1977, and this report) which suggest volcanism of a transitional to calc-alkaline character, and perhaps with that of the corresponding clinopyroxene phenocrysts in the basalts which show a chemistry most comparable to clinopyroxene from orogenic plate margins. It will be recalled, however, that the crust upon which the Robert's Arm Group was deposited likely contained a widespread sialic component abnormal to typical ocean floor crust, and that volcanism occurred just before or possibly during collapse of the basin. Conflicting aspects of Robert's Arm chemistry may therefore reflect a change from simple back arc spreading to an environment in which a more complex interplay of petrological factors became effective.

The geology of the Canadian Appalachian Orogen has been reviewed by Williams (1979) who divided Newfoundland into four tectono-stratigraphic zones. From west to east these comprise: 1) the Humber Zone representing the late Precambrian-Early Paleozoic margin of eastern North America; 2) the Dunnage Zone thought to contain the vestiges of Iapetus Ocean; 3) the Gander Zone forming the eastern margin of Iapetus Ocean; and 4) the Avalon Zone, a more stable belt that may have evolved upon a cratonal basement common to the Gander Zone since late Precambrian time. The northern part of the Dunnage Zone with adjacent zone boundaries is shown in Figure 45. Later, Williams and St. Julien (1982), emphasized the Baie Verte-Brompton Line, which forms the western boundary of the Dunnage Zone, as the major suture along which the Humber and Gander zones are mostly juxtaposed outside Newfoundland. The Dunnage Zone is thus seen as a locally preserved tectonic remnant between two convergent continental cratons. The oldest rocks of Dunnage Zone, which comprise the late Precambrian-early Paleozoic basalt-tonalite-gabbro-ultramafic complexes,

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* New U-Pb zircon data, 479 + or-3 Ma for Mansfield Cove plagiogranite (Dunning et al., 1987) suggest that this pluton is early Ordovician, only slightly older than Robert's Arm Group, rather than Hadrynian. The likelihood of this correlation is therefore reduced.

though extensive only along the west margin of the zone, also appear in uplifted blocks well within Dunnage Zone such as the South Lake Complex (Lorenz and Fountain, 1982), and possibly in the Twillingate granite (Williams and Payne, 1975; Williams et al., 1976). At face value they suggest that at least parts of the Dunnage Zone lie upon rocks that are not typical ocean crust, however, whether these rocks can be considered "basement", or whether they, and the rocks which overlie them, are part of a zone-wide allochthonous succession, or indeed whether only the Middle Ordovician-Silurian rocks are allochthonous, has become an open question in the light of work by Colman-Sadd and Swinden (1984) in central Newfoundland.

On the basis of their mapping in the Topsails terrane along the west margin of the Dunnage Zone, Whalen and Currie (1983) suggested as one possibility, that this terrane may have overlain an east-dipping subduction zone which became active some time after the opening of Iapetus Ocean. The trench associated with this zone was considered to lie near the Bay Verte-Brompton line, and the Central Mobile Belt of Newfoundland was seen as having formed in a back-arc tensional environment. Rifting in this environment decoupled sialic basement from the eastern craton (Gander Zone) which then provided a source for later Topsails magmas formed by partial melting. The Hungry Mountain Complex of Topsails terrane, which may be continuous (beneath covered intervals) with the Hall Hill Complex of Robert's Arm area, presumably formed at least in part during the early stages of this rifting. Zircon U-Pb ages for syn- and pre-tectonic granitic and volcanic rocks from Avalon Zone are similar to that for Mansfield Cove pluton* suggesting that the eastern margin of the back-arc basin may be preserved in eastern Newfoundland. The hypothesis of zone-wide allochthony of Dunnage Zone (Colman-Sadd and Swinden, 1984), which admits that the intervening Gander Zone may also be allochthonous, allows that Dunnage and Avalon zones may once have been contiguous. In this case collapse of the back-arc basin during continental collision may have immediately preceded allochthonous stacking of the basin crust expressed in Dunnage Zone on top of the associated arc from the east. Clearly, further evidence is needed to test these relations.

Interpretation of the evolution of the Robert's Arm Group within this framework suffers from a number of uncertainties. The group is bounded and dissected by faults for which the timing and displacement are largely unknown. The search for fossils of any sort within the group has been unsuccessful and differences between fault belts suggest that two mafic volcanic units of significantly different age could be present. Even the absolute age of the upper part of the group, determined by a Rb-Sr isochron (455 Ma), leaves substantial uncertainity when attempts are made to fit the group into the rapidly evolving Ordovician framework of the Central Volcanic Belt. Indirect but suggestive evidence bearing on the solutions to these uncertainties has already been discussed, and in the following interpretation the preferred solutions are assumed as follows:

1. That faults internal to the Robert's Arm Group have not been the locus of more than a few kilometres or possibly tens of kilometres of lateral offset.
2. That the Crescent Lake belt basalts, whose distinctive tholeiitic chemistry and petrography resembles that of an ocean floor (back arc) terrane, are part of a platform upon which local volcanics of the Robert's Arm were laid down essentially conformably, but possibly to some extent contemporaneously.
3. That the isochron age of the upper part of the group is the most likely age for comparison with the regional stratigraphic time scale, that is to say, the age of the Robert's Arm volcanism is approximately Llandeilian.*

Negation of any of these assumptions will clearly alter the picture.

Following the model of Whalen and Currie, (1983), the tectonic belt to the west of the Robert's Arm Group may be interpreted as part of the telescoped, uplifted outer edge of the foundation against which a Lower or Middle Ordovician fore arc-volcanic arc complex now concealed by younger deposits, intruded by late plutonic rocks, or eroded away, was built. This foundation extended along the Central Mobile Belt from south of Buchans northeastward to Robert's Arm and perhaps farther to the northeast where it has subsequently been truncated by the Lobster Cove Fault (Fig. 45). Southeast of this arc the Robert's Arm Group lies on the west margin of the adjacent back arc basin overlying rifted remnants of sialic crust described above. The group evolved during or immediately before obduction of the allochthons of western Newfoundland and hence during the terminal phase of basin activity, possibly when collapse had already begun.

Deformation of the Robert's Arm Group began in Middle Ordovician, before the end of volcanism, with inversion of Crescent terrane basalts about Loon Pond pluton. It was followed in Late Ordovician time by folding and thrusting from the northwest responsible for stacking of the thrust sheets from which the basalt terranes were eventually formed. A culmination of folding and thrusting in the northeastern part of the group may have occurred at this time. Thrusting of Robert's Arm Group over the upper Ordovician Sansom basin to the southeast was accompanied by the shedding of coarse detritus including limestone blocks of Robert's Arm (Llanvernian-Llandeilian) age into the basin (Nelson, 1981). Shales, primarily from the Crescent Lake Formation, but perhaps including similar rocks from the southeastern basin as well, lubricated the basal fault plane and were

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* New U-Pb zircon data, 473 + or-2 Ma for rhyolites from Robert's Arm Group (Dunning et al., 1987) suggest that the Group is somewhat older Ordovician than the earlier Rb/Sr isochrons had indicated.

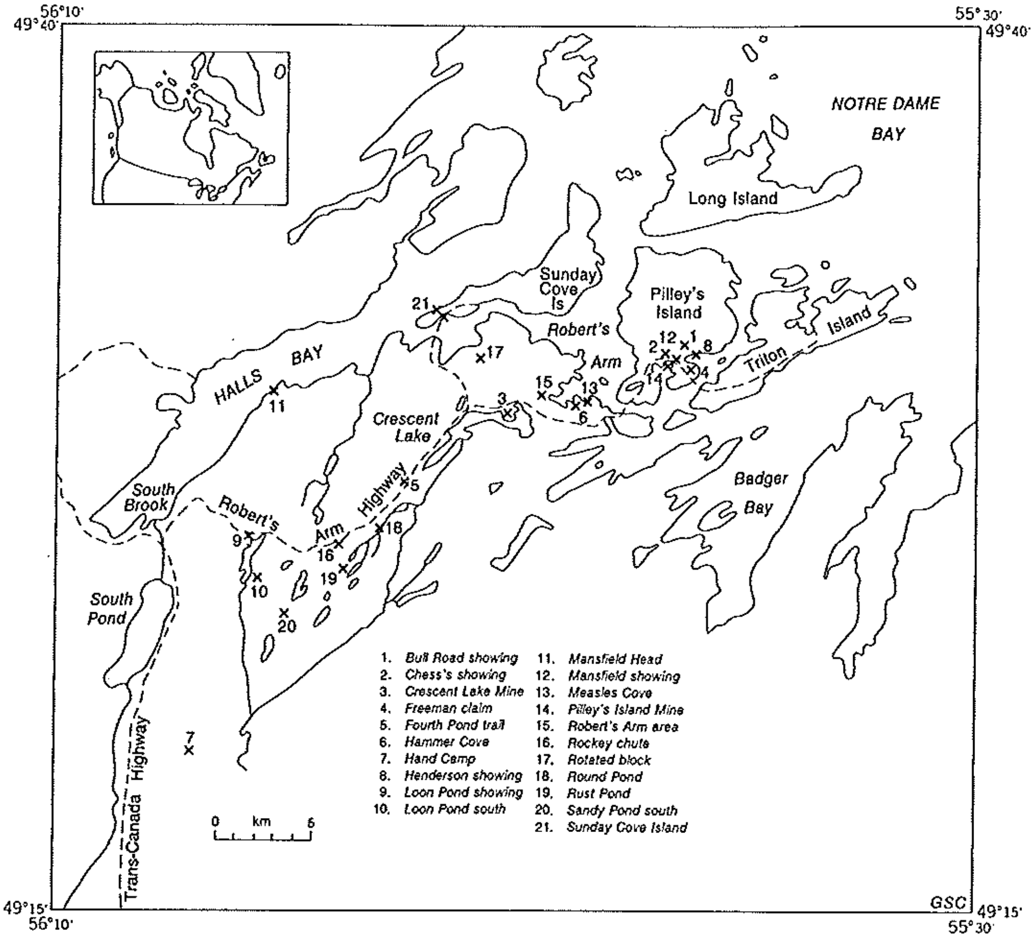

Figure 46. Map showing the location of economic mineral occurrences within the Robert's Arm area.

tectonically thickened in dilatent zones one of which now forms the Sops Head Complex. Such zones may also have concentrated lithium-bearing fluids responsible for late alteration of the overlying basalts. Age constraints for this deformation permit that it could be coeval with post-Middle Ordovician zone-wide allochthony suggested by Colman-Sadd and Swinden (1984).

Evidence for succeeding events in Robert's Arm area is fragmentary. Pre-Silurian deformation involving thrusting from the northwest had presumably left the Robert's Arm basalts with gentle dips and southeast vergence beneath the Springdale unconformity. Deposition of the Springdale Group upon these strata as an onlap sequence in Llandoverian time has been interpreted as fixing the minimum age of accretion of Avalonian and Meguma zones to north America (Chandler et al., 1987). It was followed by the Devonian Orogeny perhaps responsible for steepening and back rotation of the Robert's Arm Group, and for northward tilting of the Springdale. Subsequent right lateral displacements along the Lobster Cove Fault were likely responsible for final eastward oroclinal bending and buckling of the basalts. The latest tectonic event, marked in the Robert's Arm area by minor alkaline dykes, is presumably Mesozoic and occurred during opening of the present Atlantic Ocean.

ECONOMIC GEOLOGY

Introduction

Since the discovery of the Crescent Lake and Pilley's Island mines, and particularly in the past three decades, a substantial amount of exploration has been carried out in the Robert's Arm area by various mining companies. This work has located numerous indications of base metal mineralization within the Robert's Arm Group, the more promising of which have been mapped in detail, studied by geophysical methods and investigated by drilling to shallow depths. Because of the reconnaissance nature of the current work, and the forested and overburden-covered nature of the country, it has been difficult to satisfy both the need to examine these occurrences in some comprehensive way, and as far as possible to expand examination of the regional setting in which they occur. In this project emphasis has been placed upon the latter objective. The locations of known occurrences of mineralization have been obtained from available reports and marked on the map, but no systematic effort has been made to visit all of these. Rather, available information has been summarized. The writer is indebted to the Newfoundland Department of Mines and Energy, and to Brinco Mining Limited for providing copies of unpublished reports which bear on the regional geological aspects of these occurrences. Only showings at which some base metal sulphide has been found during this work, or for which some descriptive account has been found, will be described (Fig. 46). The thrust of this section is to relate base metal mineral occurrences to the broader aspects of the volcanic setting in which they occur.

Hall Hill terrane

Very little evidence of sulphide mineralization except for trace pyrite was observed within any of the components of Hall Hill Complex during mapping for the current project, and none is indicated in the same area on the current compilation map issued by the Province of Newfoundland (Map No. 7632). A light malachite stain was seen on a fracture in basalt about 1/3 km south of Mansfield Head but no other occurrence is known. Immediately south of the map area in rocks that appear to lie within the same fault belt as "the Southern Wedge" of Hall Hill terrane, the existence of the Hand Camp gold prospect has been known since 1928. A brief description of this property summarized from a report by de Ferriere (1978) is given here because of its potential significance for the interpretation of relations between Hall Hill Complex and the Robert's Arm Group.

The Hand Camp property (Fig. 46) is located in an area of exceptionally poor outcrop so that most of the geological information available has been derived through stripping, trenching and shallow drilling. The property straddles a zone of mixed felsic and mafic volcanics, cherts and argillite that is limited on the east and west by mafic volcanics. The best mineralization occurs within a pyritized argillized unit within this zone. Felsic pyroclastic units, which occur throughout the zone, are coarsest in the west where clasts reaching "agglomerate" size are reported. Mafic flows are locally feldspar-phyric and pillow lavas, present on the west margin of the zone, face west like those in the Rowsell Hill basalts of Hall Hill Complex farther north. Bedding within the zone strikes mostly just east of north and dips steeply. Minor folds of S, M and Z section, are abundant with axes trending mostly 5 to 10° and plunging either north or south (presumably at low angles?). If the latter assumption is correct they contrast with near vertical plunges observed in Crescent terrane to the northeast. Much of the folding is interpreted as due to slump, and Fryer (1980) believed the mineralized zone itself is transported. Quartz-epidote veining and chloritization are common. The rocks are considered to have reached maximum lower greenschist metamorphic grade unlike the amphibolites in the Hall Hill terrane to the north, or the southern part of the Robert's Arm Group to the northeast.

Periodic examinations of the property since 1928 have delineated a zone of possibly discontinuous low grade Pb-Zn-Cu-Au-Ag mineralization with quartz and barite gangue. The zone is 1200 m in strike length open at both ends, and though the width is apparently variable it is said to average 20 ft in the early work. Highest gold assays reported by de Ferriere (1978) reach 4.70 oz/ton but 0.15 oz/ton are common in the mineralized zone.

The presence of Buchans type mineralization, the abundance of felsic volcanic and pyroclastic rocks as well as sediments, and the sub-amphibolite grade of metamorphism strongly suggest that the Hand Camp prospect occurs in rocks related to the Robert's Arm Group rather than Rowsell Hill basalts. The presence of plagioclase-phyric as opposed to pyroxene-phyric basalts and the explosive nature of felsic volcanism shown by these rocks suggests that they are specifically related to those of Crescent terrane to the northeast. On the other hand plutonic rocks likely related to the Mansfield Cove pluton are the nearest rocks mapped during the present project along strike to the north. This suggests that either or both 1) a southwesterly trending fault, possibly related to the Burnt Creek Fault zone has produced some thousands of metres of right lateral offset of the southern Crescent terrane; or 2) the Robert's Arm Group lies unconformably upon the Hall Hill Complex within the Hall Hill terrane. The existence of faults of right lateral offset within the Robert's Arm Group appears to favour the former interpretation, whereas the absence of a fault lineament and perhaps the apparent low metamorphic grade of rocks at the Hand Camp property in contrast to those of both Hall Hill Complex and southern Crescent terrane appear to favour the latter.

Lushs Bight terrane

Occurrences of sulphide mineralization are abundant within western Lushs Bight terrane northwest of the map area in contrast to the dearth of them in the Hall Hill terrane. This does not appear to be entirely explicable in terms of the greater accessibility and better exposure of Lushs Bight terrane because excellent exposures of Hall Hill rocks exist along the shores of Halls Bay. Examination of the Springdale and Botwood Mineral Occurrence Maps (No. 76-32, and 80-4; Newfoundland Department of Mines and Energy) suggests that parts of the Lushs Bight terrane about Halls Bay and farther west are particularly well endowed in this respect. The major occurences according to Dean (1978) are "Cyprus Type" base metal sulphide deposits with simple (pyrite-chalcopyrite-(sphalerite)) mineralogy. Within the map area the only known occurrence of this type of mineralization is on the west coast of Sunday Cove Island where pyrite with traces of chalcopyrite and chalcocite are reported (Map 80-4).

Crescent terrane

Rust Pond - 4th Pond zone

The most important mineralized zone known in the Crescent terrane is that extending from Rust Pond in the south through Round Pond to the vicinity of 4th Pond in the north, a distance of about 3.5 km. Interest was first attracted to the zone in 1957 with the discovery of traces of chalcopyrite in cuts along an adjacent part of the old Robert's Arm highway. In the following two decades a series of outcrops and float occurrences containing Cu-Zn-Pb mineralization have been found along the zone, and drilling targets delineated with auxilliary data from geochemical and geophysical surveys.

According to MacQuarrie (1976), basalts, which form the major lithological type in this area, are divisible into hematized and non-hematized types with irregular and gradational boundaries that do not precisely correspond to bedding. Mineralization is associated with felsic to intermediate pyroclastics in a more mafic pyroclastic unit within the basalts, but the best mineralized zone, at Rust Pond, is within the more mafic rocks. Fryer (1982) believed the most interesting mineralization found in the zone to date comprises a Cu-Zn-rich stockwork grading up to 2% Cu over 10 foot intersections with disseminated sulphides in overlying beds.

Sandy Pond south

Attention was drawn to the area south of Sandy Pond with the discovery of Pb-Cu-Zn-rich float and geochemical anomalies in this region in 1970-71 (MacQuarrie, 1976). The area of interest is underlain by basalts which intertongue with felsic rocks at the southwest margin of a small felsic volcanic centre with an extensive volcano-sedimentary apron to the north. It is transected on the west by the Sunday Cove Fault which has an associated Cu anomaly in the South Brook section. No mineralization has been found in place.

Loon Pond area

According to Mannard (1960) prospecting in 1959 discovered disseminated pyrite and sparsely distributed tiny patches of sphalerite and galena scattered through a rhyolite unit intersected by the old highway north of Loon Pond. Two veinlets less than 2 cm thick containing pyrite, sphalerite, galena and chalcopyrite were found in blocks blasted from the road cut. Four blocks of rhyolite found in a bulldozer strip south of the highway were found to contain pyrite, sphalerite and galena either disseminated or in tiny white quartz veinlets. Adjacent agglomeratic rhyolite outcrops are cut by a maze of basalt dykes. One of these outcrops displays a poorly defined northeast trending zone containing 1% of disseminated small blebs of black sphalerite over a width of 1.2 m. A number of other outcrops show pyrite with minor sphalerite and traces of chalcopyrite. Farther south near the east contact of Loon Pond pluton, malachite stain was observed in association with small pyrite concentrations along a poorly exposed contact between basalt and red chert and within adjacent chert blocks.

Mud Pond - Boot Harbour terrane

Pilley's Island Mine

Ore mineralization was discovered at Pilley's Harbour on Pilley's Island in 1875, and was subsequently developed as a source of pyrite for sulphur in 1887. The ore zone near the surface had a strike length of 150 m and was up to 15 m thick. It was followed southeastward down dip for some 210 m where the length had contracted to 30 m. At that point the ore was cut off by a northeast trending more steeply southeast dipping fault, the Mine Fault. As a result mining ceased in 1908 after shipment of 500 000 tons of ore.

Drag along the fault suggested that the ore zone had been down-dropped to the southeast and a drilling program under the supervision of N.O. Lawton in 1919-20 was successful in finding additional ore in the hanging wall. A further 600 000 tons of ore were indicated of which 200 000 tons assayed 3-3.5% Cu. Parts of the new ore, however, were found to extend dangerously close to the sea floor beneath Pilley's Island Harbour.

The ore zone in the foot wall consisted of overlapping lenses composed respectively of brown ore (massive pyrite), white ore (pyrite and gangue), and some hard ore (Cu-rich ore). Later drilling and investigation of cores has shown that some parts of the ore bodies contain substantial lead, zinc and some silver. Pyrite commonly shows colloform texture. Quartz, carbonate and less commonly barite and fluorite are the typical gangue minerals. Reserves were estimated by Brinex in 1970 at 1 277 850 tons grading 1.23% Cu and 26.4% S (Tuach, 1984).

The Pilley's Island ore bodies occur conformably within pyroclastic horizons within a felsic volcanic sequence in the upper part of the Robert's Arm Group. These pyroclastics include both tuffs and felsic breccia containing fragments of felsite up to 15 cm in diameter. In this respect felsites about the Pilley's Island Mine appear unlike other major centres in Mud Pond-Boot Harbour terrane and more like smaller centres in the Crescent terrane. Chemical analyses of felsites on the footwall side of the Mine Fault indicate that these rocks belong to a distinctive chemical group which is more altered than other felsites in the region. Felsites in the hanging wall include some rocks with compositional features like similar rocks in the Crescent terrane.

A more detailed interpretation of geology in the mine area has been made by Tuach (1984), Appleyard and Bowles (1978) *in* Tuach (1984) and Lemon (1982), based on recent mapping and diamond-drill data. They suggest that basal basalts west of Mine Pond were succeeded by effusion of a dacite dome. Fused dacite breccias with fragments reaching more than 1 m in diameter were deposited on the east margin of this dome. Massive sulphide lenses formed near the base of these pyroclastics and possibly beneath the dome. An extensive sericite alteration blanket developed within the dome and pyroclastics centered on the massive sulphide lenses. The dome related rocks are overlain by a second similar dacite flow which postdates this alteration.

Structure in the mine area is obscured by rapid variation in stratigraphy typical of felsic volcanics, by faulting, and by a dearth of pillow structures in basalts within the mine area possibly due to emergent conditions during volcanism. Espenshade (1937) believed the felsite about the mine to lie at the core of a large westward-plunging anticline, however, the pillows in the bluff at Pilley's Island Village (Fig. 36) do not support this interpretation. Rather these pillows, and the surface trace of the basalt-felsite contact combined with the fact that drilling in the mine area bottomed in basalt, seem to indicate that the footwall part of the mine area forms part of a northward-overturned eastward-plunging syncline. It is possible that this fold may correlate with a better documented eastward-plunging synclinal structure exposed along the south shore of Sunday Cove between Heywards Head and Stag Cove.

Recently published maps and sections (Tuach, 1984) indicate that the volcanic stratigraphy in the mine area is part of a moderately southeast-dipping, southeast-facing homoclinal sequence truncated on the southwest and west by complex faulting. It is possible that the reversal of facing directions between this sequence and basalts immediately to the southwest (Fig. 36) follows an irregular fault corresponding to the fold axis interpreted above.

East of the Mine Fault, Bursnell (1968) observed flat lying cleavage, which he assumed genetically related and axial planar to northeast-trending folds. This, and the fact that pillow lavas to the east on Big Island (east of Bumble Bee Cove) are flat lying and upside down, suggests that the Mine Fault, and perhaps other northeasterly trending lineaments about Pilley's Island have accommodated rotational movements that allow substantial changes in fold pattern between fault blocks.

Chess's showing

Chess's showing is located along the dacite-basalt contact at the west end of the spur road west of Mine Pond. According to Tuach (1984) disseminated and stringer pyrite, chalcopyrite, sphalerite and galena occur in chloritized and sericitized basalt and dacite agglomerate at the base of the dacite dome.

Henderson showing

The Henderson showing is located just above tide level on the north shore of Bumble Bee Cove about 0.8 km northeast of the west end of the cove. It was one of the first mineral occurrences found on Pilley's Island in 1885, the same year that mineralization was discovered in Pilley's Harbour. According to Horsburgh (1967) two pits and an old shaft have been excavated on the showing, but the best exposure now accessible is an outcrop at the shore. This displays fragments of felsite, felsite breccia, chert, basalt, and rounded masses of pyrite up to 2-4 m in diameter in altered fine grained breccia containing disseminated pyrite. Minor chalcopyrite, sphalerite and galena are present. Exploration in the surrounding bush has been disappointing and the possibility exists that the deposit is limited within a breccia pipe.

Bull Road showing

The Bull Road showing comprises a slumped trench some 45 m in length on the hillside at the north end of Heads Pond. Discovery of gossan float in this area in 1966 led to a geochemical survey and eventual trenching by bulldozer (Grimley, 1968). This work uncovered steeply dipping felsic breccia and tuff units containing some disseminated pyrite, cut by a high grade 'vein' of pyrite, sphalerite, chalcopyrite and galena.

According to Strong (1974b) part of the breccia contained small fragments up to several centimetres in diameter of basalt, dacite, chalcopyrite and cupreous pyrite. These fragments were consolidated by a cement consisting predominantly of sphalerite and galena. A grab sample of this material assayed 45.9% Zn, 0.29% Pb, and 4.15 oz./ton of Ag. When the writer visited this area in 1974 only a few metres of bedrock at the showing were well exposed in the bottom of the trench. These comprised 0.7 m of nearly massive fine grained brown sphalerite with 1 m of pyrite to the north and felsic breccia to the south. A steep dipping foliation trends 115°.

Mansfield showing

In a saddle on the hill top 0.25 km east of the old Pilley's Island Mine two trenches some 8 and 10 m long and up to 1.2 m deep have been excavated in felsite. Galena with a little chalcopyrite occurs in local disseminations, as minor fracture fillings, and in scattered amygdules in these trenches.

Freemans claim

South of a small island near the south shore of Bumble Bee Cove and some 15 m up the hillside from the shore, a poorly exposed gossan extends for about 8 m. The host rock is felsite lying near the contact with basalt to the southeast. The gossan is due to weakly disseminated pyrite with traces of chalcopyrite.

Crescent Lake Mine

The Crescent Lake Mine is located about 1.5 km southwest of Robert's Arm village on the west side of the prominent peninsula that projects southward into Crescent Lake from its northeast corner. According to Murray and Howley (1881) mining started in 1878. The mine was pumped dry in 1924 and over the following 2 years 2000 tons of 12% Cu ore were shipped (Hatch, *in* Espenshade, 1937). Shafts sunk over the life of the mine reached a maximum depth of 55 m.

The ore (according to Espenshade, 1937) was obtained from a quartz vein striking N 60° E and dipping 30-35° south within basalt flows and breccias. The vein was exposed for about 60 m on the surface varying from 1 to 4.5 m but averaging 1.5 m in width. It consisted of chalcopyrite and pyrite in a quartz gangue with minor pyrrhotite and sphalerite. The wall rocks are chloritized and veined by thin stringers of quartz. Several other minor veins containing similar gangue and ore mineral assemblages were discovered in the vicinity of the main vein.

The Crescent Lake Mine area was investigated by drilling by Brinex under the supervision of Glenn (1971). Six holes totaling 1567 ft. were drilled. Two holes intersected narrow zones with low grade copper values (0.38 and 1.65% Cu) in silicified mafic volcanics. Glenn (1971) suggested that the results of this work are consistent with the view that the mineralization is localized in the silicified top of a mafic breccia pile. Chemical analyses of ore from the Crescent Lake Mine dump (Bruce, 1951) indicate average Cu contents at 0.78 to 1.02% and average Ag at 0.33 to 0.36 oz. per ton. An average of 250 ppm Co is also reported.

Robert's Arm area

A large number of minor base metal sulphide occurrences have been found over the years in the vicinity of Robert's Arm. West of the harbour they extend westward along the fault valley toward Crescent Lake as far as the small gabbro pluton. To the east they include minor showings at Hammer, Measles, and Tilley coves. Only those marked on the map were seen by the writer.

According to MacQuarrie (1976) the rocks west of the arm comprise primarily mafic lavas and breccias with minor lenses of felsic to intermediate volcanics. Most of the base metal occurrences consist of sphalerite, chalcopyrite or galena in amygdules or in narrow quartz or calcite veins. Bornite was observed at two localities. Minor disseminated base metal sulphides occur locally in association with the felsic volcanics, and MacQuarrie reported black argillite at one locality containing stringers of chalcopyrite along cleavage in a zone about 40 cm wide above and between pillows in a dacite lens.

East of Robert's Arm, Horsburgh (1967) described two showings at Hammer Cove. One southwest of the cove consists of chalcopyrite with malachite and azurite in thin quartz-calcite veins within sheared pillow lava. The vein is said to be little more than 6 m long and of unknown width. The second showing, 230 m south of the cove comprises, a well defined 1 m vein which is brecciated and riddled with quartz veinlets containing chalcopyrite, pyrite and galena. On the southwest shore of Measles Cove a small body of felsite contains minor quartz stringers. These display local patches of pyrite and chalcopyrite. On the east shore of Tilley Cove a felsite lens 3 by 4.5 m in basalt contains quartz veins and disseminated pyrite-chalcopyrite. The Tilley Cove occurrence is of interest because felsite from the west shore of the Cove has chemical characteristics like that which surrounds the Pilley's Island Mine.

The central and northern parts of Crescent section, which crosses Mud Pond and Boot Harbour terranes and passes through the Robert's Arm area, include several stations which display minor pyrite in basalt. Traces of chalcopyrite were observed at one station within the rotated block south of Sunday Cove Fault, where mineralization is associated with a minor felsite body in the basalts.

Rocky Chute

A long straight series of rock cuts is present along the new Robert's Arm highway (Route 380) where it climbs westward over the scarp that follows the northwest side of Crescent Lake-Tommy's Arm Fault. This was appropriately referred to as "Rocky Chute" by MacQuarrie (1976).

Rocky Chute cuts obliquely through an assemblage of greywacke, chert and some basalt within the mafic volcanics at the base of the Mud Pond Fault belt. The greywackes are distinctive in that they contain scattered chips of chert up to 10 cm diameter and are interbedded locally with mafic greywacke or tuff. Thin section study shows that the greywacke commonly consists of fragments of quartz and feldspar crystals in a fine grained siliceous matrix. Locally quartz fragments retain partial haloes of fine grained quartz or foreign felsic matrix indicating that they are fragments of phenocrysts. One small fragment of felsite was observed. These features suggest that the greywacke is of proximal felsic volcanic or tuffaceous origin. Malachite stain is locally present and traces of chalcopyrite were observed along tiny fractures in chert and disseminated in a thin mafic unit.

MacQuarrie, who supervised detailed mapping in this area, states that disseminated chalcopyrite occurs within and adjacent to a persistant felsic tuff horizon about 15 m thick, and grab samples taken from this unit assay up to 6.9% Cu. Later work (Fryer, 1982) has indicated that the chalcopyrite mineralization is stratigraphically controlled and has been traced along strike for some 820 m in surface outcrop. Disseminated pyrite was observed in greywacke along the same scarp some 4 km to the northeast and MacQuarrie (1976) reported minor disseminated chalcopyrite on Island Pond Brook in association with minor occurrences of similar rocks. A minor occurrence of chalcopyrite not seen by the writer is shown in the same zone on Newfoundland Department of Mines and Energy Map 80-4 and listed as "Fourth Pond Trail".

The presence of substantial amounts of felsic volcanic debris containing at least some quartz grains of phenocrystic origin suggests comparison with similar felsic units in Crescent terrane and is uncharacteristic of the larger felsite centres in the upper Boot Harbour terrane. The position of Rocky Chute near the base of Mud Pond terrane suggests that the conditions of petrogenesis which in a general way set the various terranes apart, in fact overlap.

Sunday Cove Island

A small region of Boot Harbour terrane is exposed on the southewest tip of Sunday Cove Island west of Port Anson and south of the Sunday Cove Fault. These rocks more closely overlie the Sunday Cove granite pluton than their position on the map would suggest, because the epidote-amphibolite facies isograd lies inland from the shore all along the south coast west of the causeway. Like rocks to the southeast in Crescent section, and unlike similar rocks along strike to the southwest which also overlie the pluton, numerous small showings of disseminated pyrite and two minor occurrences of chalcopyrite have been observed in these rocks.

Minor disseminated pyrite and chalcopyrite occurs in a dyke-like mass of basalt apparently intrusive into felsite along the shoreline just west of the causeway. Minor chalcopyrite and pyrite with malachite stain are disseminated in a mafic breccia lens beneath felsite about 110 m inland from the north shore and 400 m west of the point at which the Lobster Cove Fault reaches the coast.

Discussion

Examination of the distribution and variation of all mineral occurrences in the Robert's Arm region has shown that these occurrences in a general way differ between terranes. The Hall Hill terrane west of Robert's Arm Group is characterized by a dearth of base metal sulphide occurrences. Lushs Bight terrane is characterized by numerous pyrite-chalcopyrite-(sphalerite) showings of the "Cyprus type" commonly associated with ophiolitic assemblages (although few occur within the map area). The Robert's Arm Group, by contrast, is characterized by Cu-Zn-Pb-Ag-(Au) occurrences of the "Buchans Type" bearing similarities to the Kuroko deposits of Japan.

Two petrochemical terranes have been recognized within the Robert's Arm Group: a presumably older tholeiitic terrane (Crescent terrane) characterized by submarine tholeiitic basalts accompanied by (except in Crescent Hump) relatively small, commonly quartz-phyric felsic centres with voluminous associated volcano-sedimentary debris; and a younger, locally barely emergent terrane (Mud Pond-Boot Harbour terrane) characterized by more calc-alkaline basalts with large quartz-amygdaloidal felsic centres in its upper part, and which mostly displays higher felsite/volcaniclastic ratios than found in the Crescent terrane. Contrasts in chemistry of basalts and in eruptive character of the felsites between these two terranes does not appear to have contributed greatly to generation of base metal-bearing hydrothermal fluids reponsible for ore deposition because in both terranes ore mineral occurrences tend to be of Buchans type.

Contrast in ore mineral occurrences between Lushs Bight and Robert's Arm terranes on the other hand have been well established, those of the Lushs Bight terrane being of Cyprus type, whereas those of Robert's Arm are of Buchans type. This difference is presumably related to deep seated factors because the volcanic rocks within which the deposits of these terranes occur are both substantially tholeiitic basalts, even those of Boot Harbour terrane being only transitional to calc-alkaline in character. The principal deep seated contrast between Robert's Arm and Lushs Bight terranes is likely the presence of a greater sialic element in the crust underlying the former, possibly reflecting the difference in setting between back-arc and ocean floor setting. This is indicated by upfaulted inliers of trondhjemitic plutonic rocks and perhaps by gravity (Karlstrom, 1983) within the Dunnage Zone, although the latter argument may not apply if Dunnage Zone is allochthonous, having been emplaced in post Middle Ordovician time (Coleman-Sadd and Swinden, 1984). Hydrothermal fluids responsible for ore deposition were therefore likely significantly affected by processes taking place at depth within the basement.

Concentrated release of ore-fluids in the Pilley's Island Mine area indicates that the region subjacent to Pilley's Island was unique either because felsic magmatism there was of a unique variety, or because the structural configuration was unique, permitting deep access of circulating brines into the subjacent crust in the vicinity of the magma chamber from which the Pilley's Island felsites were derived. Evidence for or against the existence of a distinctive Pilley's Island magma type is inconclusive, because the rocks have been extensively altered, but at least some felsites in the mine area (east of the Mine Fault) closely resemble those elsewhere in the Robert's Arm Group. On the other hand the structural complexity of the Robert's Arm Group on Pilley's Island is in contrast to that about any of the other major felsic centres in the group. If this deformation began before volcanism was complete, then it may have been a controlling factor in siting of the Pilley's Island Mine.

The distribution of altered rocks, particularly of the Mine felsites which include the most strongly altered felsites in the Robert's Arm Group, probably reflects the distribution of hydrothermal vent zones from which the ore-bearing fluids of the Pilley's Island area were derived. These rocks are predominant in the western mine area (west of the Mine Fault), in the Spencers Dock area, at Tilley Cove, and perhaps among the felsites at Raft Tickle. This distribution suggests a search for further concentrations of base metal mineralization along strike from these felsites immediately off the west coast of Pilley's Island. East of the Mine Fault, additional alteration zones may be more deeply buried. This is suggested by indications of eastward plunge, apparent increase in galena-sphalerite showings, and lower degree of alteration of felsite samples collected east of the Mine Fault. No other alteration zones commensurate with those of Pilley's Island have been discovered in the Robert's Arm Group during this project or apparently in previous work.

Following volcanism and deposition of exhalative ore mineralization, continued deformation included thrusting of the Robert's Arm Group southeastward over a shale-greywacke sequence now exposed in the Sops Head Complex. This thrusting likely resulted in expulsion of lithium-bearing brines along permeable zones in the overlying basalts. These brines, however, do not appear to have introduced base metals. Base metal occurrences in the area about Robert's Arm, which are associated with quartz-carbonate veining, may be related to remobilization of these elements in the zone of maximum deformation.

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APPENDIX I

Chemical Analysis

A. XRF method

XRF analyses were made for major and minor rock-forming elements in the laboratories of the Geological Survey of Canada using one gram of sample mixed with 5 grams of Li_2B_4O, and 0.30 grams of LiF. Single readings of 20 minutes per disc were made and matrix effects corrected by alpha coefficients. Table 17 provides a list of ranges and errors to be expected.

B. Spectrographic method

Spectrographic analyses for trace elements were made in the laboratories of the Geological Survey of Canada using the 12B-DR analytical system developed by W.H. Champ. The ranges for which this method is calibrated are given in Table 18. Within these ranges the anticipated error is plus or minus 25% of the value quoted, but will be greater near the lower limit of the range. In particular an error of plus or minus 25 ppm is considered realistic at the lower limit of 20 ppm for Zr analyses.

C. Screw rod method

Analyses for Li, Rb and Cs were carried out in the laboratories of the Geological Survey of Canada by the screw rod method. Recent assessments in the Geological Survey laboratories indicate that errors in determination of Rb and Cs and to a lesser extent Li by this method are greater than originally thought. Revised estimates of error are given in Table 19.

Repetition of 20 lithium analyses, representing the full range determined by the screw rod method was carried out using atomic absorbtion. The mean discrepancy in the range 25 to 160 ppm was 14 ppm for a mean of 11 analyses of 65 ppm. The worst case yielded a relative discrepancy of 56% of the lesser of the values determined by the two methods. Overall means at 39 and 40 ppm Li determined by screw rod and atomic absorbtion methods respectively, were not significantly different.

D. Selective ion method

Fluorine and chlorine were analyzed in the laboratories of the Geological Survey of Canada by the selective ion method. Estimates of potential error for this method are given in Table 20.

E. Electron microprobe

Mineral analyses by electron microprobe were carried out in the laboratories of the Geological Survey of Canada. All analyses were obtained using a Materials Analysis Company model 400 electron microprobe equiped with a Kevex 5000A energy dispersive spectrometer and automated to produce simultaneous multi-element analysis and data reduction (Plant and Lachance, 1973). Operating conditions were as follows: 20 kV accelerating voltage, specimen current of 10 nA (nanoamperes) measured on a standard kaersutite, and a spectrum acquisition time of 100s. As well as data reduction for matrix effects, the program calculates mineral formulae and molecular proportions of end-member constituents. With the exception of sodium, the determinations have a relative accuracy of plus or minus 1-2% for minor elements. For sodium, the relative accuracy is plus or minus 10%.

Table 17.. Accuracy of the XRF method

Element	Calibration range %	Maximum error absolute +	relative %	Determination limit	Standard deviation
SiO_2	0 - 100	0.40	1	0.40	0.53
TiO_2	0 - 3	0.02	1	0.02	0.02
Al_2O_3	0 - 60	0.40	1	0.40	0.40
Cr_2O_3	0 - 4	0.02	1	0.02	0.02
Fe_2O_3	0 - 90	0.10	1	0.10	0.10
FeO	0 - 30	0.05	8	0.03	
MnO	0 - 1	0.01	2	0.01	0.01
MgO	0 - 50	0.10	1	0.10	0.14
CaO	0 - 35	0.10	1	0.10	0.15
Na_2O	0 - 10	0.50	0	0.50	0.50
K_2O	0 - 15	0.05	1	0.05	0.16
P_2O_5	0 - 1	0.02	1	0.05	0.02
H_2O	0 - 5	0.05	5	0.02	
CO_2	0 - 20	0.02	3	0.02	
S	0 - 3	0.02	5	0.02	
Rb	0 - .0600	0.002	5	0.002	0.002
Sr	0 - .2000	0.002	10	0.002	0.002
Ba	0 - .3000	0.002	1	0.002	0.002
Zr	0 - .2000	0.002	10	0.002	0.008
Zn	0 - .0200	0.002	10	0.002	0.002
Ni	0 - .3000	0.003	10	0.003	0.004

Table 18. Ranges for elements determined by the 12B-DR system

Element	ppm range	Element	ppm range
Sr	10 - 7000	Zn	200 - 7000
Ba	5 - 4000	Co	10 - 1000
V	20 - 1250	Ni	10 - 2000
Zr	20 - 1750	Cr	5 - 7000
Cu	7 - 1250		

Table 19. Revised error estimates for the screw rod method

Element	Mean (ppm)	2 sigma	Range (ppm)
Li	20	4	17 - 24
Rb	96	23	57 - 156
Cs	0.8	2	0.1 - 1.8

Table 20. Error estimates for the selective ion method

Element	Mean (wt %)	2 sigma	Range (wt %)
F	.057	.01	.05 - .06
Cl	.024	.02	.01 - .03

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*Principal reference