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NEW PERSPECTIVES ON THE STRATIGRAPHY, VOLCANOLOGY, AND STRUCTURE OF ISLAND-ARC VOLCANIC ROCKS IN THE ORDOVICIAN ROBERTS ARM GROUP, NOTRE DAME BAY[1]

A. Kerr
Newfoundland Mapping Section

ABSTRACT

Mapping during 1995 shows that previous 1:50 000-scale maps of the Roberts Arm Group by the Geological Survey of Canada are very detailed and accurate in terms of unit distributions. However, key regional relationships and structural patterns support a new stratigraphic and structural interpretation. The Roberts Arm Group is divided into five basalt-dominated "terranes" (s.l.), *which are separated by variably steepened, south- to southeast-dipping, north-directed thrust faults. The structural base of the group is the Boot Harbour terrane, which contains well-preserved submarine felsic volcanic rocks, possibly erupted under deep marine conditions. The structurally overlying Pilley's Island terrane contains distinct felsic rocks of more fragmental (shallow-water?) character, associated with VMS mineralization and alteration. These are structurally overlain by basalts of the Mud Pond terrane, which have a regional hematite (± epidote) alteration signature. The structural top of the calc-alkaline sequence is the Triton terrane, containing fresh basalts and voluminous mafic intrusive rocks. These four terranes are probably, in turn, structurally overlain by tholeiitic basalts and associated sedimentary rocks of the Crescent terrane.*

The Roberts Arm Group may represent a reversed stratigraphic sequence, or it may represent a collage of two or more unrelated, spatially discrete, volcanic sequences. The structural polarity in the area is directly opposite to previous proposals, and the calc-alkaline terranes are viewed as the disrupted, lower limb of a northward-overturned anticlinal nappe structure. The Springdale Group rests unconformably upon different Roberts Arm Group terranes, suggesting some pre-Middle Silurian deformation and imbrication. Later deformation is largely brittle, and is related to dextral transcurrent and/or southeast-directed reverse motions along the Lobster Cove Fault and similar structures. The Pilley's Island terrane is considered to have the highest potential for VMS mineralization, and the new interpretation highlights areas where it may be structurally repeated, or hidden beneath overlying thrust sheets.

INTRODUCTION

PROJECT OVERVIEW

This study is part of a multidisciplinary project to prepare a digital data compilation from the Buchans–Robert's Arm belt, and integrate these data with new geological, metallogenic and surficial studies. Field work during 1995 consisted of mapping, examination of key relationships, and systematic lithogeochemical sampling, aimed mostly at calc-alkaline volcanic rocks in the northern part of the belt. Previous mapping by Bostock (1988) proved extremely accurate and detailed. However, field work supports a new view of regional relationships that has significant implications for regional geology and mineral exploration. This new model will be further tested through petrographic, geochemical and geochronological studies planned for the winter of 1996.

REGIONAL GEOLOGICAL FRAMEWORK

The Lower Ordovician Buchans–Robert's Arm belt (Strong, 1977) is interpreted as a mature island-arc sequence (Swinden *et al., in press*), and includes large volcanogenic massive sulphide (VMS) deposits at Buchans, and smaller examples at Lake Bond, Gullbridge and Pilley's Island (Figure 1). The Roberts Arm Group *(s.s.)* extends from the Gullbridge area to the coast (Figures 1 and 2). In the study area, it is bounded to the west by the Mansfield Cove Fault, which

[1] Buchans – Robert's Arm multidisciplinary project: bedrock mapping

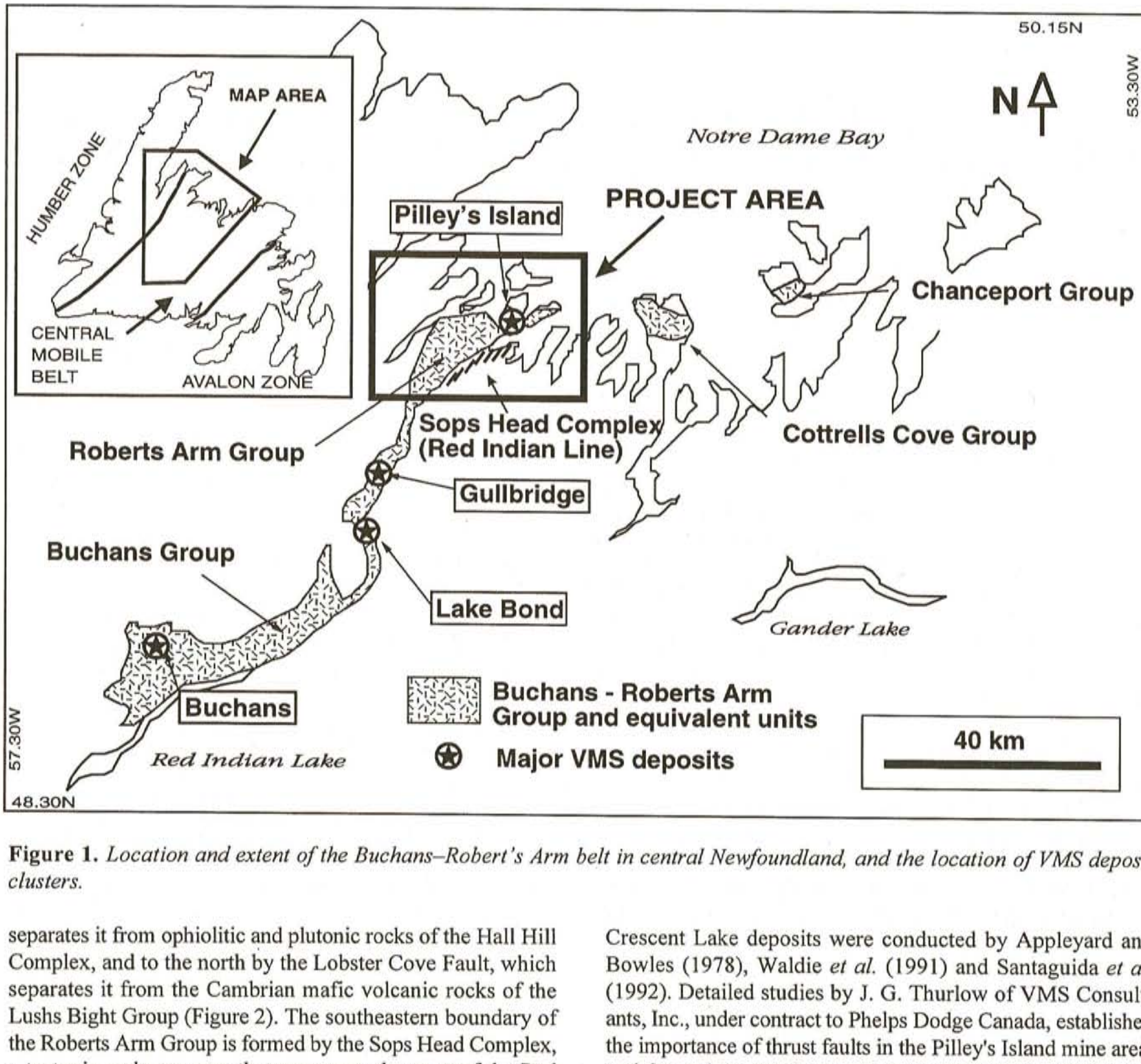

Figure 1. *Location and extent of the Buchans–Robert's Arm belt in central Newfoundland, and the location of VMS deposit clusters.*

separates it from ophiolitic and plutonic rocks of the Hall Hill Complex, and to the north by the Lobster Cove Fault, which separates it from the Cambrian mafic volcanic rocks of the Lushs Bight Group (Figure 2). The southeastern boundary of the Roberts Arm Group is formed by the Sops Head Complex, a tectonic melange zone that represents the trace of the Red Indian Line, separating the Notre Dame and Exploits subzones of the Dunnage Zone (Williams *et al.,* 1988). Bostock (1988) recognized that the Roberts Arm Group included mafic volcanic rocks of both tholeiitic and calc-alkaline affinities.

PREVIOUS WORK

Previous geological mapping in this area includes the work of Espenshade (1937), Hayes (1951a and b) and Dean and Strong (1976). The most recent and comprehensive 1:50 000-scale mapping was by Bostock (1978, 1988), and major mineral occurrences were summarized by Swinden (1987, 1990) and Tuach (1984, 1990). More detailed studies of alteration and mineralization in the Pilley's Island and Crescent Lake deposits were conducted by Appleyard and Bowles (1978), Waldie *et al.* (1991) and Santaguida *et al.* (1992). Detailed studies by J. G. Thurlow of VMS Consultants, Inc., under contract to Phelps Dodge Canada, established the importance of thrust faults in the Pilley's Island mine area, and formed the starting point for regional structural studies discussed here (see Thurlow, *this volume*).

DESCRIPTIVE FRAMEWORK FOR THE ROBERTS ARM GROUP

The new view of the stratigraphy and structure of the Roberts Arm Group provides the descriptive framework for this report, and is presented at the outset. Bostock (1988) recognized that there were discrete belts of volcanic rocks within the group, and defined three terranes. This terminology is partly retained, but additional terranes are defined, and the boundaries of Bostock's terranes are revised. Five main terranes are now defined, and the boundaries between them are marked by faults interpreted as steepened south- to southeast-dipping thrusts. The term terrane is used throughout

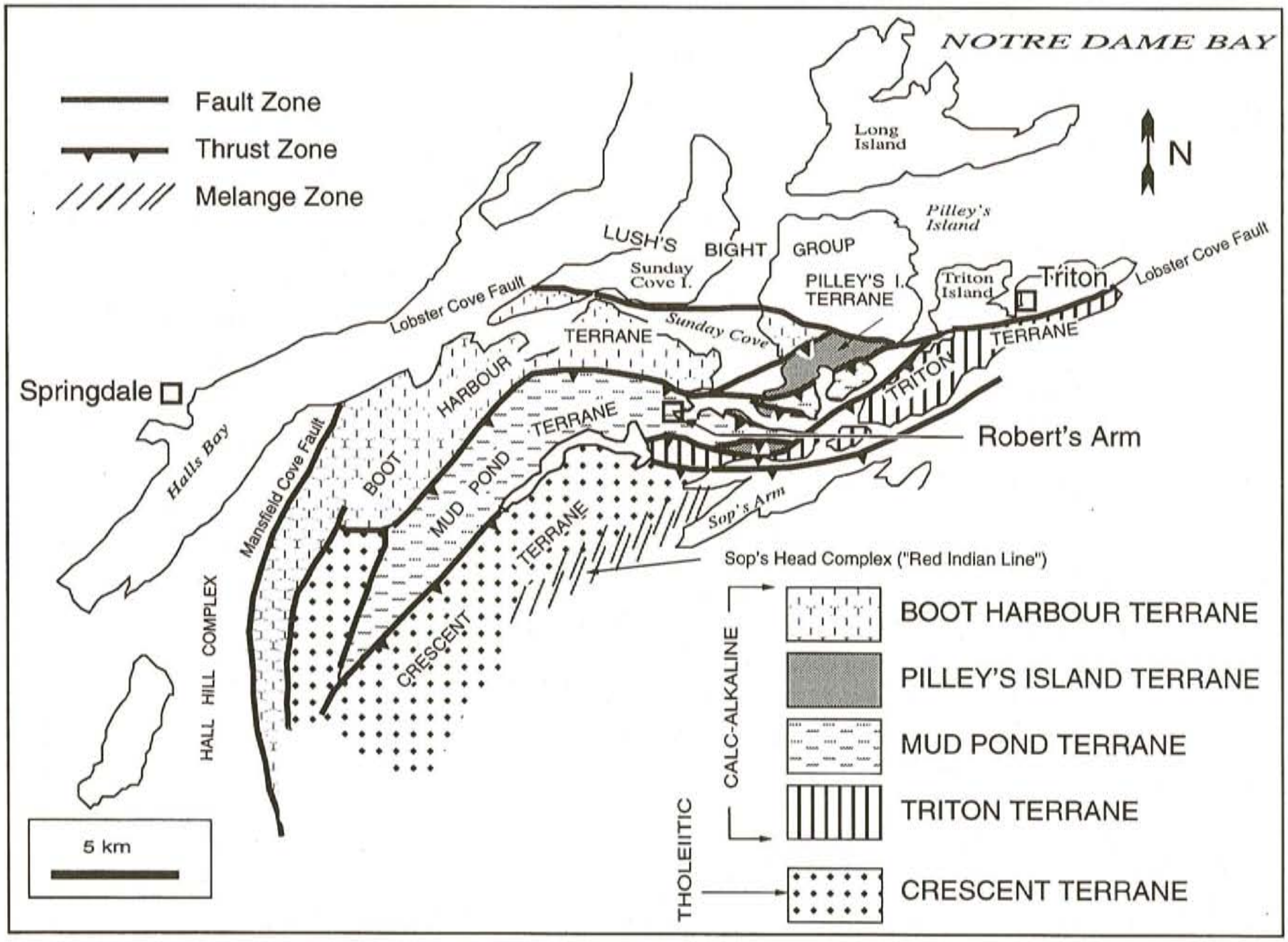

Figure 2. *Summary map showing the distribution of the five main tectonic terranes defined within the Roberts Arm Group, which are used as a descriptive framework in this report.*

in an informal sense as "a region where a particular rock or group of rocks predominates" (Bates and Jackson, 1987).

In ascending structural order, the calc-alkaline portion of the Roberts Arm Group comprises the Boot Harbour, Pilley's Island, Mud Pond and Triton terranes (Figure 2). The tholeiitic volcanic rocks are grouped as a single terrane, termed the Crescent terrane (Bostock, 1988). The original stratigraphic and/or geographic relationships between tholeiitic and calc-alkaline rocks, and between various terranes, are uncertain. Along the trace of the Lobster Cove Fault, small outliers of the Silurian Springdale Group locally sit unconformably upon the Roberts Arm Group. Descriptions in this report are confined to the Roberts Arm and Springdale groups, and refer to a simplified geological map (Figure 3). For details of rock units that bound the Roberts Arm Group, see Bostock (1988).

ROBERTS ARM GROUP

Boot Harbour Terrane

The Boot Harbour terrane is very well preserved, and contains most of the felsic rocks within the Roberts Arm Group, and also includes two small granitoid plutons. It resembles the synonymous terrane of Bostock (1988), but is here redefined to exclude mineralized felsic rocks and associated basalts of the Pilley's Island mine area. The western and northern boundaries of the Boot Harbour terrane are defined by the Mansfield Cove and Lobster Cove faults respectively, and its southern boundary is defined by the Sunday Cove – Bear Cove thrust on the mainland, and on Pilley's Island by an inferred fault termed the Swimming Hole thrust. The nature of the Boot Harbour terrane – Crescent terrane boundary near Loon Pond is unclear. Detailed coastal

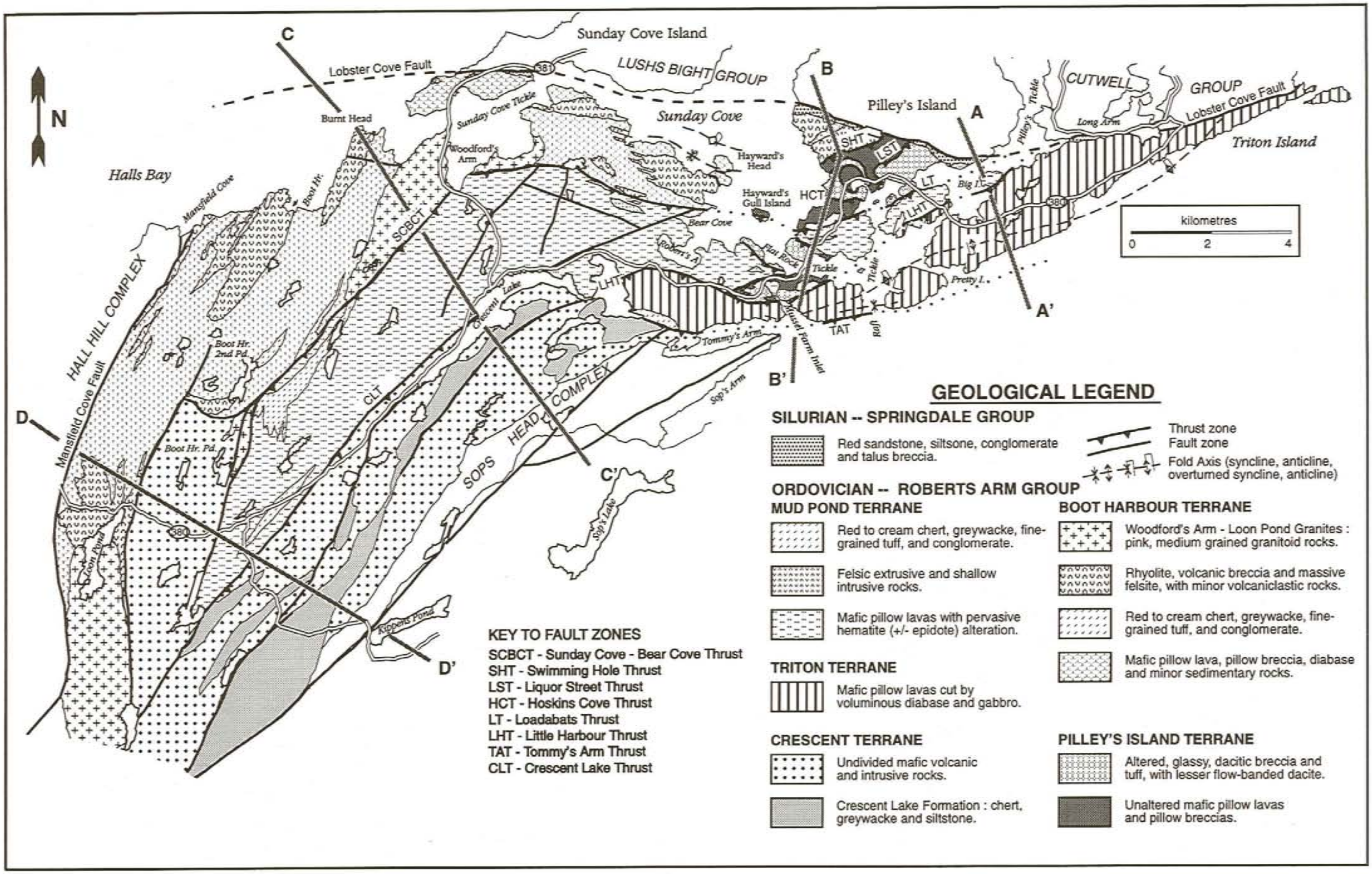

Figure 3. *Simplified geological map of the northeastern part of the Roberts Arm Group. Outcrop and unit distribution mainly after Bostock (1978, 1988) with modifications based on 1995 field work. Revised unit designations, and pattern of major terrane boundary faults, based on 1995 field work.*

mapping suggests that the Boot Harbour terrane is largely intact stratigraphically, but much of it is vertical to steeply inverted.

Submarine Mafic Volcanic Rocks

Pillow lavas are black- to purple-weathering, grey to grey-green, fine-grained, aphanitic rocks that lack signs of pervasive alteration or recrystallization, although hematitic alteration locally imparts a maroon colour. They are mostly well preserved, and some outcrops reveal lava tubes and other primary flow-related structures (e.g., Williams and McBirney, 1979; Walker, 1992) The basalts are locally plagioclase or augite-porphyritic, and commonly contain calcite amygdules, particularly on upper flow surfaces. Interpillow material consists of massive to layered red chert, or epidote – carbonate (± quartz) patches. Vesicular tops and pillow shapes provide good way-up criteria (e.g., Plate 1), but the original attitude is not always clear, as many pillows are probably tube-like flow structures developed on slopes. The best paleohorizontal indications come from thin intercalations of banded chert or fine-grained greywacke, which suggest that bedding is subvertical to steeply southeast-dipping in most areas.

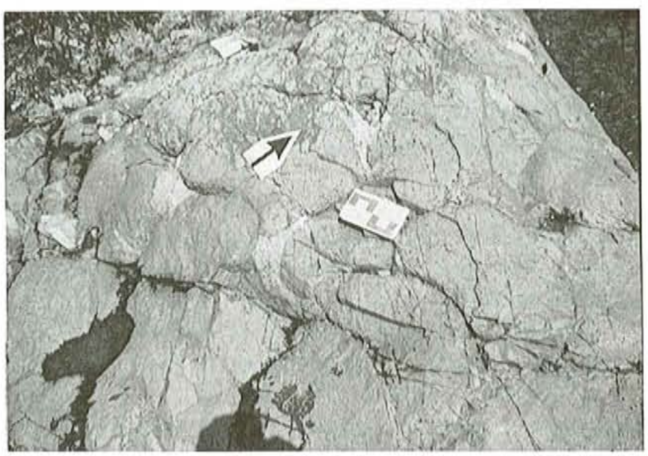

Plate 1. *Mafic pillow lava, showing well-developed pillow shapes, draping of pillows, and interpillow epidote – carbonate – quartz pods. Tops to right of photo, as indicated by arrow. Boot Harbour terrane, near Moorey Cove.*

Associated mafic volcanic breccias commonly consist of subangular amygdaloidal basalt fragments in a finer matrix, and most are interpreted as pillow breccias derived by submarine-flow or mass-wastage processes from partly solidified sources. On an outcrop scale, thin pillow breccia units are intercalated with pillow lavas, and may form the upper (or outer) parts of flows, affected by hydroclastic and autoclastic brecciation (cf., Carlisle, 1963; Dimroth *et al.,* 1979). Bostock (1988) suggested that several thick units of pillow breccia may have developed on slopes related to submarine felsic centres. This interpretation is supported by the presence of sporadic siliceous felsic volcanic clasts in some pillow breccias, which also suggest that the felsic volcanic rocks formed in an extrusive environment.

Sedimentary Rocks

Sedimentary rocks commonly form thin (< 2 m) units intercalated with the submarine mafic volcanic rocks. The most common rock types are finely laminated red, green and cream cherts, and lesser siltstones and greywackes. Thicker, mappable sedimentary units are present inland northeast of Boot Harbour Second Pond (Bostock, 1988), and include a white-weathering, chalky rock type interpreted as a fine-grained felsic tuff.

Felsic Volcanic Centres–Rock Types and Relationships

The Boot Harbour terrane contains most of the felsic volcanic and volcaniclastic rocks in the Roberts Arm Group. These are contained within three main centres, located at Boot Harbour itself, around Sunday Cove, and on the west side of Pilley's Island (Figure 3). Each centre contains two discrete accumulations of felsic rocks, separated by a sequence of basalts, and there may be broad stratigraphic correlations between them. A fourth felsic centre located in the Loon Pond area has not been examined in this study but is reported to consist of fine-grained pyroclastic and volcaniclastic material (Bostock, 1988).

Bostock (1988) was fully aware of the complexity of these felsic rocks, and used the nonspecific term *felsite* for most of them, and suggested that many of the larger bodies were of hypabyssal origin. Field work during 1995 suggests that the three main felsic centres contain both extrusive and intrusive components. The relationships between rock types are very confusing, and lateral facies variations are rapid. It is not possible to define mappable subunits, except at the outcrop scale, and the principal rock types are described in approximate order of abundance. Readers should note that names assigned to these rock types below are field terms only and have yet to be verified petrographically; some may require revision following laboratory studies.

Amygdaloidal Rhyolite. This most abundant felsic rock occurs by itself, and also as a component of other composite rock types described below. Typical amygdaloidal rhyolites are extremely fine grained to glassy, dark brown to purple, or locally red-weathering, and extremely hard, brittle and siliceous. Most are aphanitic, but tiny (1 mm or less) feldspar phenocrysts are locally evident. These rocks are characterized by abundant quartz-filled amygdules ranging from 5 mm to over 10 cm in length. The amygdules are flattened, lending a streaky appearance to outcrops (Plate 2), and commonly form discrete amygdule-rich and amygdule-poor zones. In detail, these amygdaloidal fabrics are chaotic and swirling, and are interpreted as a primary flow feature, rather than a tectonic fabric. Rare flow-banding, defined by dark and light layers, displays a similar contorted geometry. Although many amygdaloidal rhyolites appear massive and featureless, cut slabs commonly reveal a blotchy, fragmental appearance, which probably reflects incipient brecciation caused by ingress of sea water (termed hydrobrecciation). Several other lines of evidence also suggest that the amygdaloidal rhyolites include true extrusive rocks.

Plate 2. *"Amygdaloidal rhyolite" showing quartz-filled amygdules, and strong alignment interpreted as a primary flow fabric. Boot Harbour terrane, near Hayward's Bight.*

Spotty Rhyolite Breccia. Amygdaloidal rhyolites are everywhere associated with complex volcanic breccias, termed *spotty rhyolite breccia* in the field. Locally, the breccia zones form gradational layers, subparallel to regional strike, but the relationship is more commonly chaotic. The breccias consist of amoeboid to subangular rhyolitic fragments, commonly with amygdaloidal fabrics, in a matrix of apparently similar composition (Plate 3). Fragment-matrix boundaries range from sharp to diffuse, but variable fabric orientations in fragments demonstrate at least some mechanical disruption and rotation, in addition to hydrobrecciation. The matrix to the breccias is commonly pervaded by stockwork-like veins of amorphous, blue-grey silica. The breccias also contain rare pods of bright red, amorphous to banded silica, which locally resembles interpillow chert, suggesting that some breccias developed on the sea floor, and incorporated local sediments into their matrix. However, some red silica patches may be related to the stockwork veins.

Massive felsite. Amygdaloidal rhyolites and breccias are commonly associated with massive felsic rocks. These are

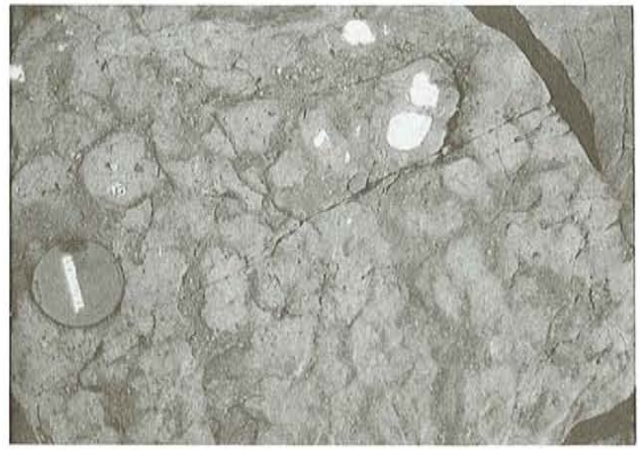

Plate 3. *"Spotty rhyolite breccia" showing amoeboid dark-coloured fragments in paler orange matrix. The opposite relationship (i.e., light fragments in dark matrix) is also seen. Boot Harbour terrane, northeast of Boot Harbour.*

also extremely fine-grained to glassy, but tend to be more homogeneous, and more obviously and consistently porphyritic, with small, lath-like feldspars from 1 to 5 mm in size. The relationships between amygdaloidal rhyolites and these 'massive felsites' are equivocal. Rare sharp contacts have a sinuous, lobate appearance, and lack obvious proof of an intrusive relationship, such as angular xenoliths. More commonly, amygdaloidal and massive variants are gradational. The massive felsites also resemble discordant dyke-like felsic bodies that clearly cut the associated mafic volcanic rocks.

Green Felsic Tuff. This is a pale to medium green, relatively homogeneous, medium-grained rock type having a variably schistose appearance. It is presently thought to be a volcaniclastic rock of intermediate to felsic composition, although J. G. Thurlow (personal communication, 1996) has suggested that it may record pervasive quenching and alteration of flows by seawater. It is associated with amygdaloidal rhyolites and related breccias, where it forms discontinuous layer-like zones up to 10 m thick, oriented subparallel to regional strike. However, it is more common in two distinctive composite rock types described below.

Tongue Rhyolite. This composite rock type consists of large, pancake-like masses of amygdaloidal rhyolite from 20 cm to 2 m in thickness, and 2 to 10 m in length, which are interlayered with green felsic tuff (Plate 4). The rhyolite tongues locally show textures suggestive of quenching and hydrofracturing. The proportion of the two rock types is variable, but amygdaloidal rhyolite normally makes up about 40 to 75 percent of the outcrop. This association was described by Bostock (1988), who used the term 'linguoid masses', from which the term tongue-rhyolite is derived.

Plate 4. *Typical "tongue-rhyolite", showing pancake-like masses of amygdaloidal rhyolite and friable tuff-like matrix. Note flow-like pattern in matrix around the rhyolite masses. Boot Harbour terrane, northeast of Mansfield Cove.*

Tongue-rhyolites are simply an outcrop-scale example of a relationship seen on a larger scale within the felsic centres. Some tongue-rhyolites that contain only small amounts of green felsic tuff may actually be longitudinal sections through pillow rhyolites.

Pillow Rhyolite. These spectacular rocks consist of large, rounded, masses of amygdaloidal rhyolite. Individual pillows range up to 3 m in diameter, and commonly have concentric amygdaloidal fabrics, indicating primary flow. Pillows are separated by narrow selvages of material that resemble green felsic tuff. The most spectacular example has pillows up to 3 m across that mimic typical pillow basalt shapes, show clear facing directions (Plate 5), and are overlain by a breccia that is analogous to a mafic pillow breccia. More commonly, rhyolitic pillows are round or elliptical masses without clear asymmetry or facing directions. Pillow-rhyolites are viewed as a variant of the more common tongue-rhyolites, but with a distinct morphology and much smaller amounts of the green felsic tuff. These structures were also described by Bostock (1988), who suggested analogies to structures described by Dimroth *et al.* (1979) from the Noranda area.

Volcaniclastic and/or Pyroclastic Breccia. Thin felsic units within the basaltic sequences are more obviously fragmental, and contain small, angular, brown to purple rhyolitic fragments (2 to 5 cm diameter) in a finer matrix. The variable colours and sizes of fragments suggest that these represent mass-flows, although the degree of sedimentary reworking is not clear. Volcaniclastic breccias and conglomerates also occur at stratigraphic transitions from felsic to mafic volcanism where they are associated with other sedimentary rock types including cherts and thin greywackes. Some volcaniclastic conglomerates contain rounded fragments of both basaltic and felsic (amygdaloidal rhyolite) composition (Plate 6), indicating that both rock types were simultaneously exposed on the sea floor.

Felsic Volcanic Centres–Environments of Formation

Several lines of evidence suggest that many of the felsic rocks are of extrusive or near-extrusive origin. In several areas, felsic rocks stratigraphically overlie pillow lavas, and are draped over the upper pillow surfaces, and appear to have settled into the depressions between pillows (Plate 7). In these instances, the felsic rocks are interpreted as mass flows. Some mafic – felsic contacts are marked by thin sedimentary intervals, indicating stratigraphic transitions representing quiescence, and amygdaloidal rhyolites are locally overlain conformably by cherts and volcaniclastic conglomerates containing both mafic and felsic fragments (Plates 6 and 8). Similarly, mafic debris flows locally include fragments of amygdaloidal rhyolite. Rhyolitic breccias locally contain interstitial red chert, suggesting formation at or near the subsea surface. These relationships indicate that amygdaloidal rhyolites were present at the subsea surface, and that some were directly extruded onto other rock types, or transported in debris flows. Intrusive contacts between mafic pillow lavas and felsic rocks do occur, but in most cases the latter are massive felsites that probably represent feeders. Pillow rhyolites with concentric amygdaloidal fabrics appear to be analogous to mafic pillow lavas, and interstitial green felsic tuff may represent sea-floor sediment, analogous to interpillow chert. The tongue-rhyolites are similar, but the proportion of rhyolites to sediment is lower. Similar pillow and tongue-like rhyolite structures have been described by Dimroth *et al.* (1979) as proximal parts of extensively brecciated submarine flows, and by other workers (e.g., Hanson, 1991; Hanson and Wilson, 1993) as products of rhyolite – wet sediment interaction in near-surface environments (so-called peperites).

Conversely, massive felsites are probably of shallow intrusive origin, as they locally show sharp contacts with

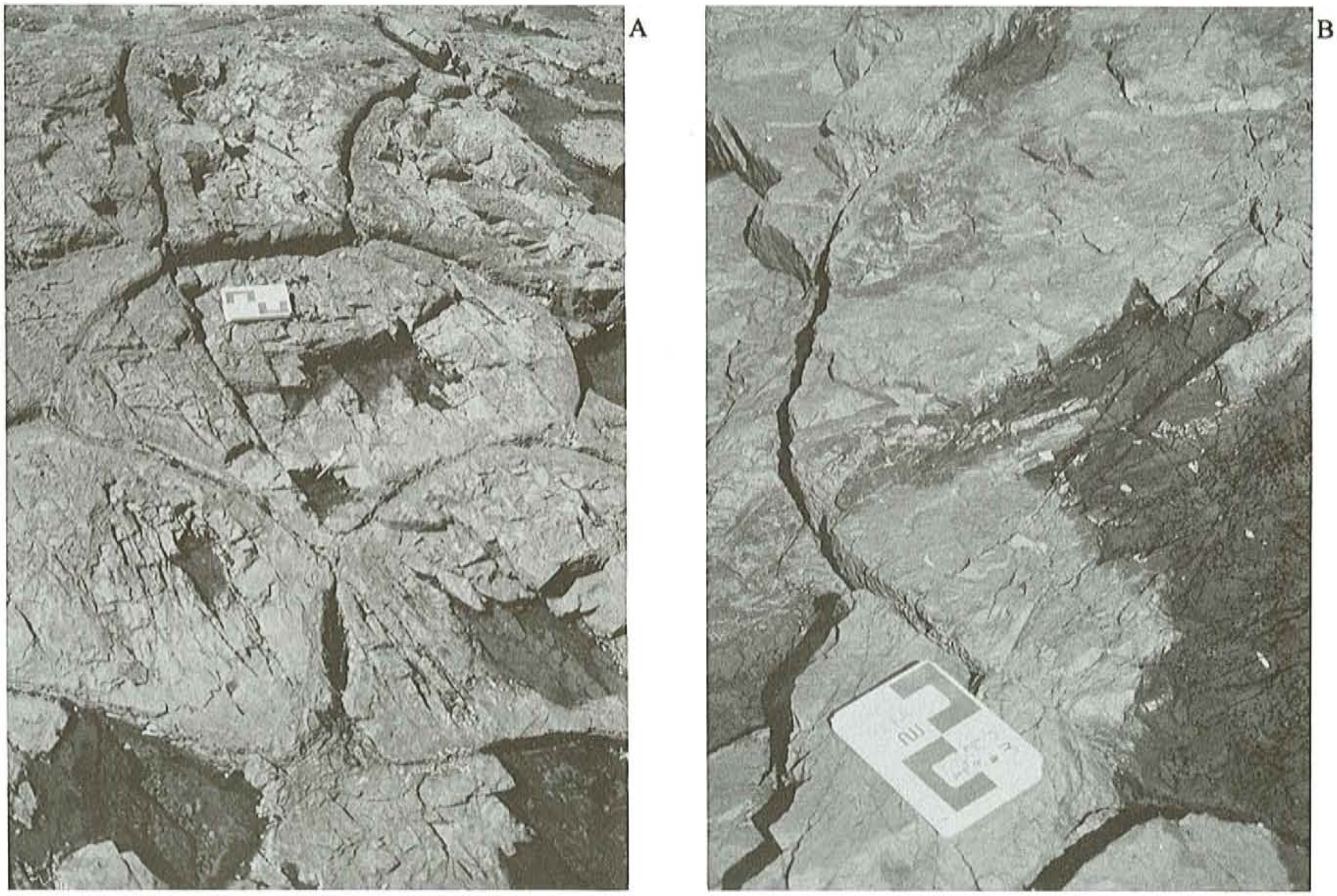

Plate 5. *Pillow-like structures in amygdaloidal rhyolites: (A) general view of rhyolitic pillows, showing mimicry of typical mafic pillow shapes, tops to top of photo; (B) detail of pillow margin, showing recessive weathering of interpillow green tuff and aligned amygdules indicating flow. Boot Harbour terrane, Boot Harbour Island.*

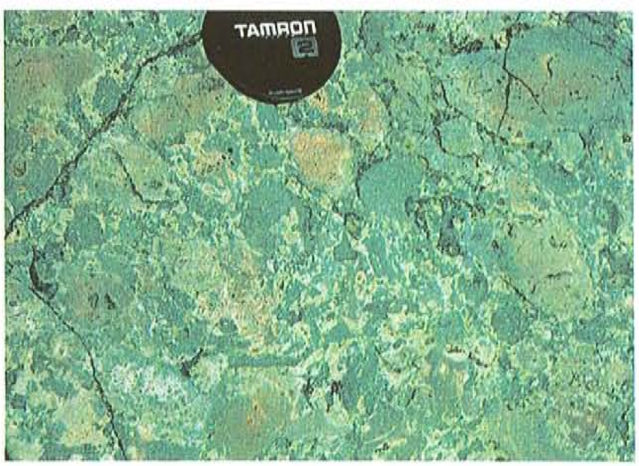

Plate 6. *Volcaniclastic breccia of mixed affinity, containing both basaltic (dark) and rhyolitic (pale-brown) fragments. Note pervasive epidotization of matrix. Boot Harbour terrane, Sunday Cove Island.*

amygdaloidal rhyolites, and resemble felsites that clearly intrude associated basalts. However, the massive felsites and amygdaloidal rhyolites are probably extrusive and shallow intrusive products of the same magmas. Thus, some massive felsites may represent deeper portions of thick flows, rather than discrete intrusions, and some amygdaloidal rhyolites may actually be volatile-rich portions of subvolcanic intrusions, rather than true flows. In a complex environment of episodic to continuous volcanism, the distinction between 'intrusive' and 'extrusive' becomes very blurred, as both components must be present, and some components inevitably fall into the grey area between end-members. Field relationships suggest broadly cyclic sequences, which commence with massive felsites, and grade upward into amygdaloidal rhyolites with strong planar fabrics, overlain by more heterogeneous rocks with chaotic, swirling amygdaloidal fabrics. The upper part of the cycle consists of a chaotic mixture of spotty rhyolite breccias and locally massive zones, which gives way to more massive rhyolites (or other rock types) across a relatively sharp contact. The complete sequence is only rarely preserved, and the relative thicknesses of the zones are highly variable. However, cross-strike alternations between massive rhyolitic rocks and chaotic mixtures of rhyolite and spotty breccia are common in all areas.

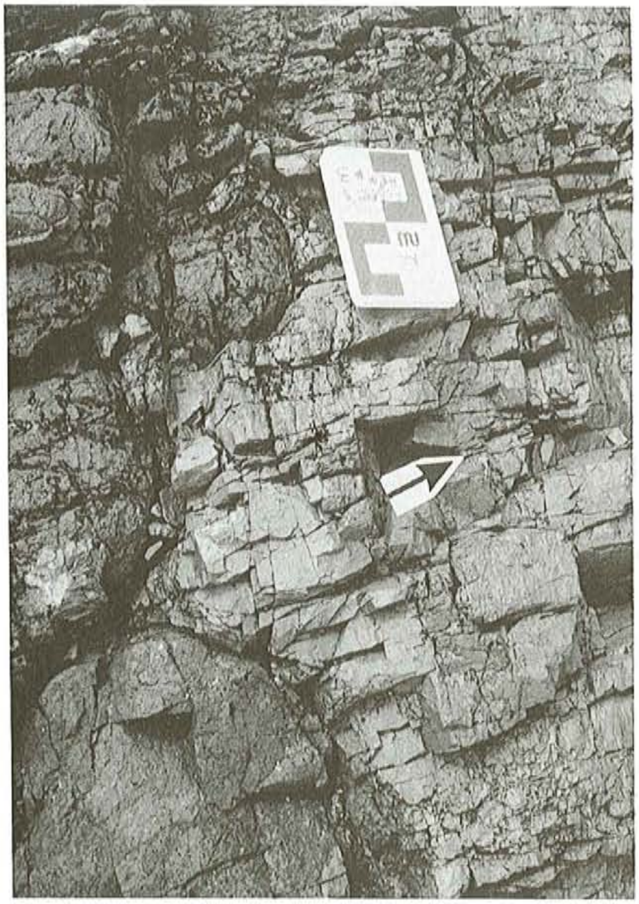

Plate 7. *Conformable contact of mafic pillow lava (left) and felsic rock of probable debris-flow origin (right). Tops to left of photo, as shown by arrow. Note accumulation of felsic material in depressions between pillows. Boot Harbour terrane, northeast of Mansfield Cove.*

Plate 8. *Conformable, original contact between amygdaloidal rhyolite (right) and laminated chert (left). Tops to left of photo, as shown by arrow. Complexity of contact is partly a surface effect, but also reflects original geometry of underlying flow. Boot Harbour terrane, Boot Harbour.*

This cyclic pattern is interpreted as a cross-section through a thick dome-like extrusion, in which upper and outer portions are brecciated through quenching and continued flow, whereas deeper sections behave plastically and develop flow-fabrics (Figure 4). Overlapping of flows or domes at the same horizon, coupled with "stacking" of flows within the stratigraphy, leads to the chaotic three-dimensional facies pattern observed in the field. Massive felsites are interpreted as feeder zones to younger eruptions, or as quasi-intrusive material in the base of dome-like extrusions. The finer pyroclastic and/or volcaniclastic breccias are interpreted as proximal debris flows derived from the outer brecciated zones, and the green felsic tuff as volcaniclastic material from more distal explosive eruptions. Tongue-rhyolites and pillow-rhyolites are here viewed as special cases where the felsic magmas were emplaced into or onto unconsolidated volcaniclastic sediments (cf., Hanson, 1991), and were affected less by seawater ingress. The differences between these two variants reflects the volume of rhyolite relative to sediment, and possibly also its rate of introduction.

Minor Intrusive Rocks

Dykes and sills of diabase, gabbro and felsite are present throughout the terrane. The majority of the larger mafic intrusions are oriented subparallel to strike, and were originally sills. Some display spectacular columnar structure, with rhythmic compositional layering at right angles to the column axes. The diabase sills and dykes are viewed as an integral part of the volcanic stratigraphy, probably representing feeders to flows and small subvolcanic magma chambers. Felsic dykes and sills are less common, and most resemble the massive felsite facies associated with felsic volcanic centres. Bostock (1988) noted that the greatest concentration of felsic dykes was associated with the Woodford's Arm granite pluton, suggesting that the two might be related. Observations in 1995 confirmed this pattern, but reddish felsite dykes near the granite contact appear subtly different from the brown, grey and purple varieties that resemble the felsic volcanic rocks. Thus, there may be two or

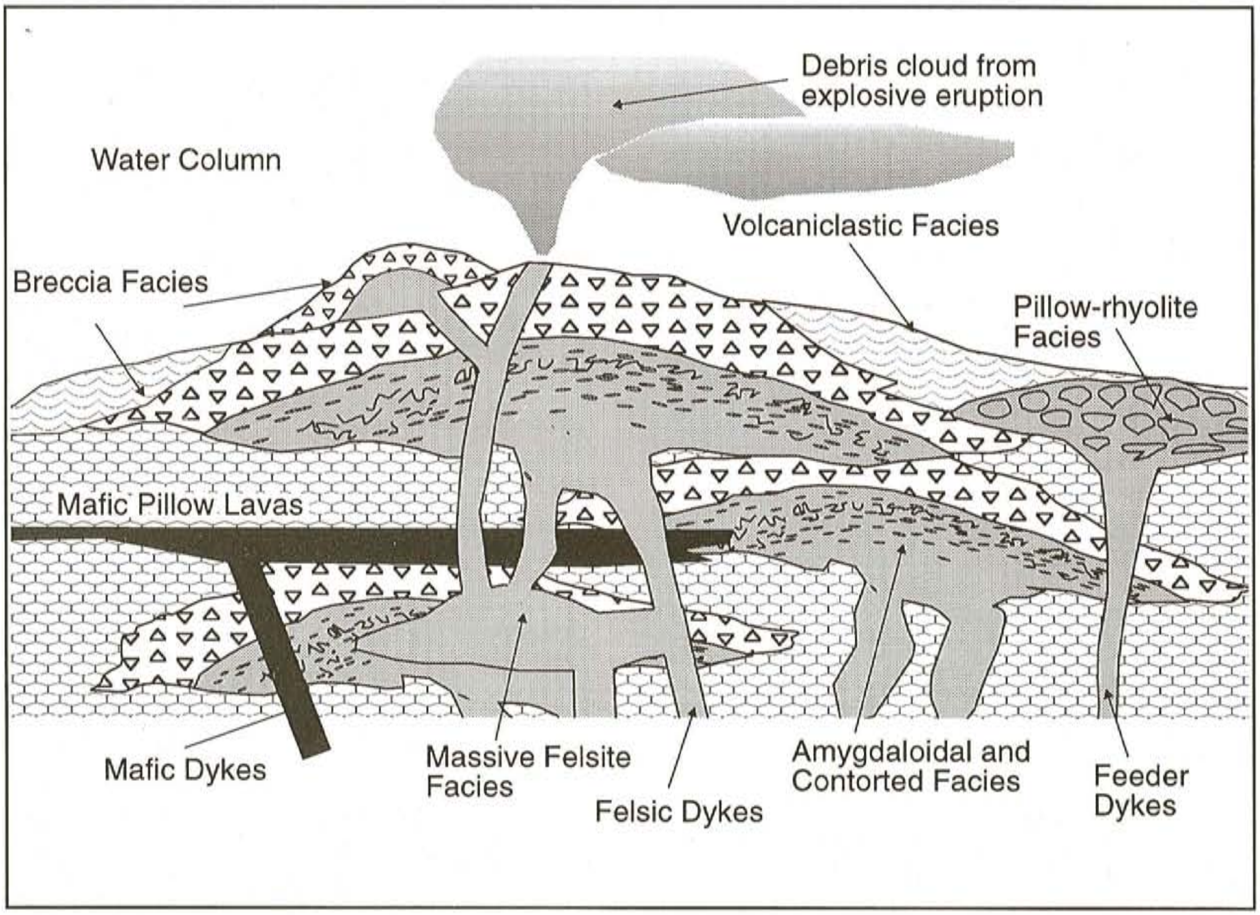

Figure 4. *Schematic illustration of spatial and stratigraphic relationships between various facies of submarine felsic volcanic rocks in the Boot Harbour terrane.*

more subpopulations of minor felsic intrusions. Felsic dykes and sills cut pillow lavas and diabase, but are themselves cut by diabase dykes, suggesting a spectrum of ages.

Woodford's Arm and Loon Pond Granites

The Woodford's Arm granite (Sunday Cove pluton of Bostock, 1988) consists of homogeneous pink to grey or buff-coloured, medium-grained, biotite granodiorite and granite, which locally contains amoeboid diabase-like inclusions. The northern margin of the pluton is fine grained and locally felsitic, and is cut by diabase dykes. Mafic volcanic rocks on the south shore of Sunday Cove Island appear hornfelsed, and are cut by numerous brown to red felsite dykes. These relationships suggest that the northern boundary is intrusive, although the contact itself is not exposed. Intrusion breccias with angular basalt and diabase xenoliths also indicate an intrusive relationship. Bostock (1988) considered the Woodford's Arm granite to be a subvolcanic intrusion related to, and synchronous with, stratigraphically overlying felsic volcanic rocks. The granite has yielded a Rb – Sr whole-rock isochron age of 464 ± 13 Ma (Bostock *et al.*, 1979). The Loon Pond granite pluton is very poorly exposed and has not been examined in this study. It is described as a massive, fine-grained, grey-green to pink granodiorite containing amphibole, epidote and chlorite, and is cut by mafic dykes (Bostock, 1988); its contact relationships are unknown.

Pilley's Island Terrane

The Pilley's Island terrane (Figures 2 and 3) hosts most of the significant VMS sulphide occurrences in the northeastern Roberts Arm Group. The main tract of the terrane occupies a 5- by 2-km area in the centre of Pilley's Island, and is bounded by the inferred Swimming Hole thrust in the north and the Loadabats thrust in the south (Figure 3). However, the position of the northern structural boundary is not definitive, as some of the mafic rocks may belong to the Boot Harbour terrane (see later discussion, and Thurlow, *this volume*). Smaller areas at the southern end of the island, and on the adjacent mainland, are viewed as structural repetitions of the ore-bearing rocks, although the details are not yet clear. The Pilley's Island terrane is dissected by internal thrust faults (Figure 3). The geology and structure of the area around the Pilley's Island mine are discussed in more detail by Thurlow (*this volume*), and the following is a general summary only.

Volcanogenic massive sulphide mineralization at Pilley's Island is discussed by Appleyard and Bowles (1978), Tuach (1984), Bostock (1988), and Thurlow (*this volume*).

Submarine Mafic Volcanic Rocks

Mafic pillow lavas and associated mafic breccias underlie the northern and southwestern parts of the main tract, and are separated from a central domain of altered and mineralized felsic volcanic rocks (termed the "ore-bearing sequence") by important thrust faults (Figure 3). In the north, mainly unaltered mafic rocks resemble their equivalents in the Boot Harbour terrane. These may also correlate with nearby mafic volcanic rocks in the core of a ring-like domain of felsic volcanic rocks. The mafic rocks may represent a structural culmination beneath a gently dipping thrust fault (Thurlow, *this volume*), rather than a fold interference structure, as suggested originally by Espenshade (1937). In the southwest, pillow breccias are more abundant. These mafic rocks probably correlate to the west with pillow breccias on the northern half of Hayward's Gull Island, immediately beneath the Loadabats thrust (Figure 3). The upper mafic sequence is cut out by the Loadabats thrust toward the east (Figure 3). Mafic pillow lavas, with abundant pillow breccias, also occur within the subarea south of Flat Rock Tickle (Figure 3). These include an unusual breccia unit consisting of bomb-like basaltic pumice fragments up to 10 cm in diameter in a fine tuff-like matrix. Bostock (1988) suggested that this represented spatter from subaerial basaltic eruptions, and noted that similar textures were locally present on the west coast of Pilley's Island.

Unaltered mafic pillow lavas are present at two locations within the ore-bearing felsic sequence on the west coast of Pilley's Island, where they are interpreted to be structurally imbricated with altered felsic rocks. Other mafic volcanic rocks in the ore-bearing sequence show hydrothermal alteration and disseminated pyrite mineralization, and may represent an original mafic interval within the sequence.

Ore-Bearing Felsic Volcanic and Volcaniclastic Rocks

Variably altered felsic volcanic and volcaniclastic rocks form the central thrust-bounded domain of the Pilley's Island terrane (Figure 3; Thurlow, *this volume*).

Flow-Banded Dacites. On the west coast, a pale grey, siliceous felsic volcanic rock displays spectacular, contorted, flow-banding (Plate 9). Previous workers (Strong, 1974; Appleyard and Bowles, 1978; Tuach, 1984) described this as "dacite", and the term is retained here. The texture locally resembles pahoehoe or "ropy lava", rather than the finer, delicate banding typical of flow-banded rhyolites. This ropy flow-banding is far more widespread than the rare flow-

Plate 9. *Pahoehoe-like, ropy flow-banding in dacite unit, Pilley's Island terrane. This is a regionally extensive feature at this location, and is also seen in blocks in associated breccias. West coast of Pilley's Island.*

banding seen in rhyolites of the Boot Harbour terrane. The flow-banded dacite grades northward into a breccia containing subrounded fragments from 5 to 10 cm in diameter, which also contains larger, angular fragments of flow-banded material with variable banding orientations, indicating mechanical disruption. However, much of the breccia texture is probably derived by quenching and water ingress. Both features suggest that this is the hydroclastic and autoclastic upper zone of the flow, and that it faces north, although the dip direction is not clear.

Complex Glassy Breccias. Most felsic volcanic rocks in the Pilley's Island terrane are complex breccias that defy concise description. These are dark grey to green, and contain clasts ranging from less than 2 mm to 10 cm or more in diameter. The larger clasts are commonly angular, and aphanitic to glassy in texture. The breccia matrix consists of myriad, small, lighter-coloured, jigsaw-like, glassy clasts separated by reticulate veinlets of amorphous silica. These smaller clasts appear to have been derived by *in-situ* fragmentation, and larger clasts show signs of incipient brecciation in the form of silica veinlets and pervasive blotchy devitrification (Plate 10). Some breccias contain arcuate, shard-like, glassy fragments, possibly derived by propagation of curved fracture systems (perlitic cracks ?). The breccias were probably formed by explosive interaction of felsic lava and seawater, i.e., by hydrobrecciation. This process appears to have been much more widespread and violent in the Pilley's Island terrane than in the felsic volcanic centres of the Boot Harbour terrane, where rocks showing evidence of hydrobrecciation are subordinate to massive amygdaloidal rhyolites. However, some of the brecciation effects may be hydrothermally induced (Thurlow, *this volume*).

Plate 10. *(A) Complex "glassy breccia" on cut surface. Note angular fragments of dark, glassy material, and matrix of small angular fragments with reticulate silica veinlets indicating hydrobrecciation. (B) Breccia with curved, shard-like fragments developed either through propagation of perlitic cracks or explosive vesiculation. Pilley's Island terrane, Pilley's Island.*

Identical glassy breccias, including large flow-banded dacite fragments, are present at the southern end of Pilley's Island (Figure 3), and probably correlate with those exposed across Flat Rock Tickle (Figure 3), which are clearly bounded to the south by a thrust. Widespread disseminated pyrite, and local Pb – Zn-bearing veinlets (Swinden, 1987) indicate that all these rocks were part of a mineralizing system. Nearby felsic rocks exposed on Route 380 and along Mussel Farm Inlet show evidence of hydrobrecciation and silicification, and are also grouped as part of the Pilley's Island terrane.

Minor Intrusive Rocks

Minor intrusive rocks of both mafic and felsic composition are not abundant in surface exposures on Pilley's Island, but are widely reported from drill intersections (J. G. Thurlow, personal communication, 1995 and *this volume*). At the southern end of the island, unaltered diabase dykes cut altered, pyritic, felsic breccias, suggesting that they are of post-mineralization age, perhaps representing feeders to higher parts of the volcanic sequence. However, clearly crosscutting unaltered mafic or felsic dykes are not abundant in the felsic sequence on the west coast of the island.

Mud Pond Terrane

The Mud Pond terrane corresponds with the synonymous terrane of Bostock (1988) in the southwest, but is redefined to include areas previously included in his "undivided Mud Pond–Boot Harbour terrane" (Figures 2 and 3). The northern boundary of the Mud Pond terrane is the Sunday Cove–Bear Cove thrust (west) or the Loadabats thrust (east), and it is bounded to the south by the Crescent Lake thrust (west) and the Little Harbour thrust (east), which separate it from the Crescent terrane and Triton terrane, respectively. There are internal thrust faults within the Mud Pond terrane, and its apparent thickness may be exaggerated. The Mud Pond terrane is defined by a weak magnetic signature on aeromagnetic vertical gradient maps (Geological Survey of Canada, 1990), which probably reflects its regional alteration.

Submarine Mafic Volcanic Rocks

Over 95 percent of the Mud Pond terrane consists of pillow lavas and associated pillow breccias, with lesser diabase. The mafic volcanic rocks are less well-preserved than those of other terranes in the Roberts Arm Group. Brittle deformation is much more prevalent than in the adjacent Boot Harbour terrane, and pillows are locally flattened. The basalts have a pervasive hematite alteration, which lends a distinct red-brown to maroon colour to many outcrops, and a later epidote-rich alteration is locally developed, which lends a pistachio-green colour to both weathered and fresh surfaces. The epidotization characteristically affects pillow centres, and produces a striking combination of bright green centres and maroon rims (Plate 11), best displayed along Route 381. According to Swinden and Wilson (1994), the epidotization postdates early seafloor chloritic and hematitic alteration, and penetrated to pillow centres along radial cooling cracks (H.S. Swinden, personal communication, 1995). Mafic pillow breccia units in the Mud Pond terrane also display red hematite alteration, but they locally contain both altered and unaltered pillow fragments, indicating that the hematite alteration is early, and probably synvolcanic.

Alteration signatures are in general poor criteria for defining tectonostratigraphic terranes, as they are independent of stratigraphy. Local examples of similar hematite (± epidote) alteration are known from both the Boot Harbour and Triton terranes. Nevertheless, the alteration in the Mud Pond terrane appears to be of regional extent, as shown by its weak aeromagnetic signature, and it terminates sharply at bounding thrust faults, indicating that it predates deformation. The significance of alteration is less clear; it may imply some special conditions during formation, e.g., water depth or oxidation state. Alternatively, it may indicate conditions facilitating large-scale hydrothermal circulation (e.g., Swinden and Wilson, 1994).

Felsic Volcanic and Intrusive Rocks

Felsic rocks mostly occur as thin, discontinuous units northwest of Robert's Arm, near to the boundary with the Boot Harbour terrane. Felsic rocks examined near the microwave tower west of Robert's Arm are more homogeneous and coarser grained than typical Boot Harbour terrane rhyolites, and are therefore suspected to be hypabyssal intrusions. One of these units has given a U – Pb zircon age of 473 ± 2 Ma (Dunning *et al.,* 1987), which is generally taken as the age of the Roberts Arm Group. Distinctive tongue-rhyolites akin to those of the Boot Harbour terrane occur near the head of Tilley Cove (Figure 3).

Other Rock Types

Sedimentary rocks include cream, red and green cherts, greywackes, and minor siltstone and conglomerate, locally achieving thicknesses of a few hundred metres northeast of Boot Harbour Pond. This sedimentary belt also contains a white-weathering, chalky, rock type that may be a fine-grained sericitic tuff from distal explosive eruptions, also noted within the adjacent Boot Harbour terrane (see above). Minor intrusive rocks in the Mud Pond terrane include scattered diabase sills and dykes, and fine- to medium-grained gabbro.

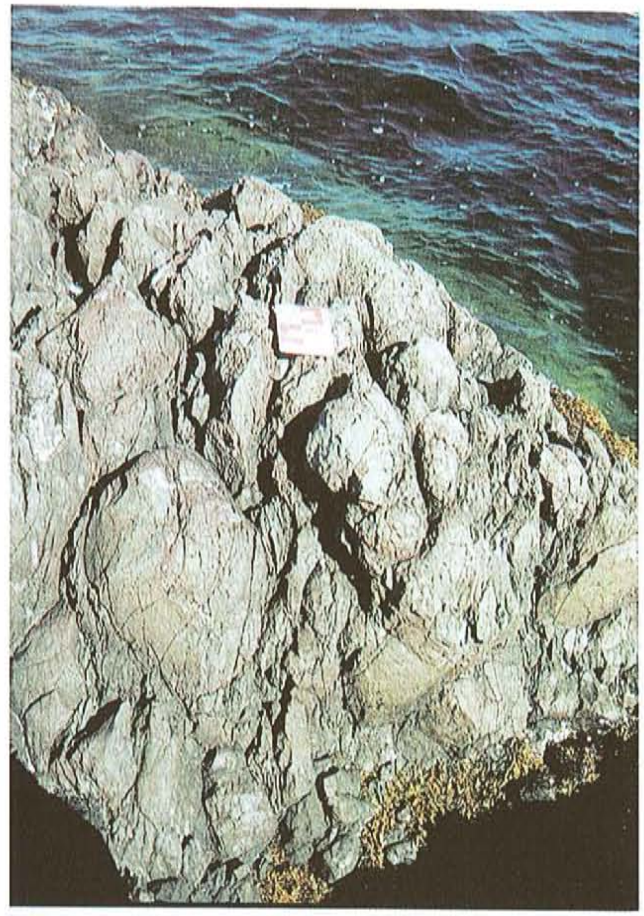

Plate 11. *Hematite – epidote alteration lending a distinctive purple and green colouration in mildly flattened pillow lavas of the Mud Pond terrane. Hayward's Gull Island.*

Triton Terrane

The Triton terrane is the structurally highest portion of the exposed calc-alkaline sequence. Most of it was previously grouped as "undivided Mud Pond–Boot Harbour terrane" by Bostock (1988). The northern boundary of the terrane is defined by the Little Harbour thrust (Figure 3). To the southeast, this structure merges with the Crescent Lake fault under Crescent Lake. The southern boundary of the terrane is defined by the Tommy's Arm thrust, which extends along the linear south coasts of Pretty Island and Triton Island. Small faults possibly representing internal thrusts were noted at two localities but, given its general lack of deformation, the terrane is thought to be largely stratigraphically intact. The Triton terrane is also delineated by a regional magnetic high on aeromagnetic vertical gradient maps (Geological Survey of Canada, 1990), probably reflecting the high proportion of shallow intrusive material.

Submarine Mafic Volcanic Rocks

Pillow lavas are massive, dark grey to black, generally unaltered, variably amygdaloidal, and locally coarsely pyroxene-phyric. They are very well preserved, and show delicate features such as concentric amygdule rings (Plate 12). In addition to interpillow red chert, many outcrops contain interstitial fine-grained diabase, derived either from ruptured pillows, or percolation of magma through interconnected voids to feed later eruptions. The excellent primary features of these rocks contrast strongly with the altered and cleaved basalts of the underlying Mud Pond terrane. However, local hematite – epidote alteration is seen at the south end of Raft Tickle, where it predates deformation, as it is transposed in the Tommy's Arm thrust.

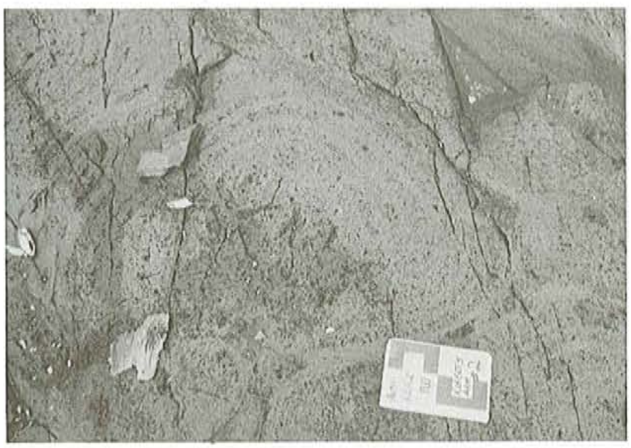

Plate 12. *Well-preserved mafic pillow lava showing superb vesicular ring-structure and dark, quenched glassy rims, Triton terrane, Bridges Island.*

Diabase and Gabbro

Almost every outcrop of pillow lava is cut by locally sheeted diabase dykes and sills, and some outcrops consist dominantly of diabase and gabbro, with only screens of pillow lava. The dykes are generally fine-grained, aphanitic, rocks and show excellent intrusive contacts, locally with delicate flow-laminations in their chilled margins (Plate 13). Medium-grained, variably plagioclase-porphyritic gabbro is present on a local scale, notably on the south side of Pretty Tickle, where it has been described in detail by Bostock (1988). The high proportion of diabase and gabbro in the Triton terrane probably causes its distinct regional magnetic signature.

Plate 13. *Contact of diabase dyke (top) and pillow lava (bottom) showing delicate flow-banding in dyke margin, continuous around delicate apophysys at centre of photo. Direction of magma flow was probably normal to the outcrop surface. Triton terrane, Bridges Island.*

Other Rock Types

Minor amounts of felsic rocks occur in several coastal outcrops, and include mixed volcaniclastic breccias, with amygdaloidal rhyolite fragments, and discordant felsitic dykes. Red cherty sediments are very poorly exposed east of Crescent Lake.

Crescent Terrane

The tholeiitic Crescent terrane (Bostock, 1988) is mostly exposed to the southeast of the Crescent Lake–Tommy's Arm thrust. According to Bostock (1988), it is dominated by pillow lavas, commonly finer grained and less vesicular than those of the calc-alkaline sequence, intercalated (or interleaved ?) with thick units of greywacke, slate and chert (Crescent Lake Formation). Observations along logging roads suggest that the basalts are cut by large volumes of diabase. Small areas of felsic volcanic rocks are also present, of which only one body located near Route 380 was examined. This is a relatively coarse-grained rock containing broken to subhedral plagioclase crystals and round quartz eyes in an indeterminate matrix. Delicate, layer-like zones of red chert, locally containing scattered quartz eyes, suggest that it is a crystal tuff, and not an intrusive rock.

SPRINGDALE GROUP

Conglomerates and other sedimentary rocks of the Springdale Group form a narrow, discontinuous outlier along

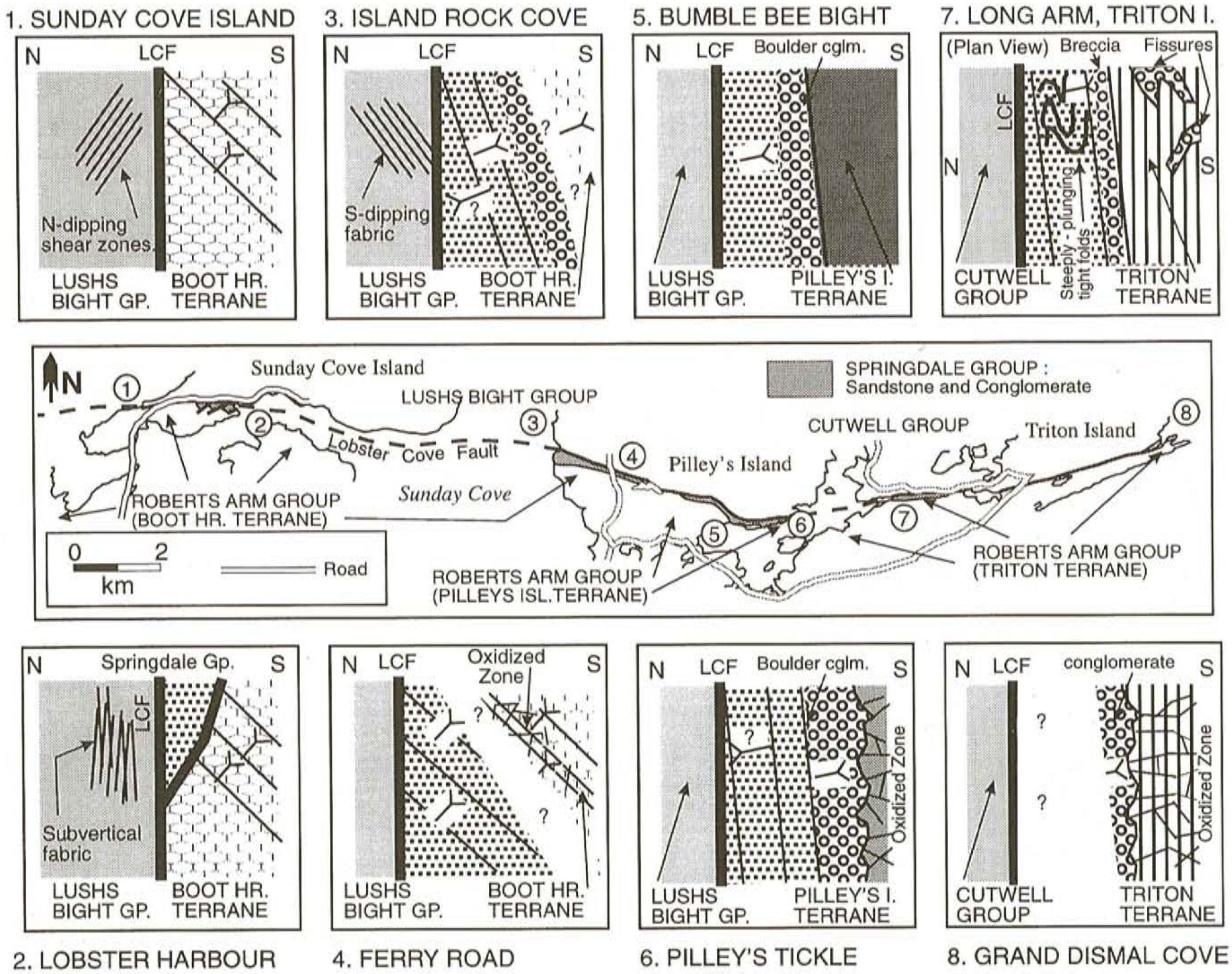

Figure 5. *Index map of the Lobster Cove Fault and associated Springdale Group outliers, showing key locations discussed in text.*

the trace of the Lobster Cove Fault (Figure 3). The discussion below is organized from west to east, and emphasizes its relationship to the Roberts Arm Group in several key locations (Figure 5). The Springdale Group is generally considered to be of mid-Silurian (Llandovery) age, based on a ca. 427 Ma U – Pb age from a rhyolite (Chandler *et al.*, 1987).

At Lobster Harbour on Sunday Cove Island, the contact between the sandstones and the Roberts Arm Group (Boot Harbour terrane) is a small brittle fault on the shoreline, and cannot be seen clearly in inland outcrops. At Island Rock Cove on the west side of Pilley's Island, south-dipping sandstones and minor conglomerates are exposed for almost 400 m, and are north-facing (i.e., upside-down) for the most part, except close to the Lobster Cove Fault, where they appear to be south-facing. The contact with reddened felsic volcanic rocks of the Boot Harbour terrane is concealed, but there is conglomerate on the Springdale Group side, containing fragments of basalt, red rhyolite, vein quartz and bedded sandstone. On the road leading to the Long Island ferry terminal, sandstones are strongly overturned, dipping 40° south, and felsic volcanic rocks of the Boot Harbour terrane are extensively reddened and altered. Although these are now structurally above the Springdale Group, they must originally have been located just below the basal unconformity.

The best exposures of the unconformity are on the east coast of Pilley's Island. At Bumble Bee Bight, boulder conglomerates include entire pillows, complete with amygdaloidal rings, and large, fresh amygdaloidal rhyolite cobbles with flow-fabrics, characteristic of the Boot Harbour terrane. At a nearby locality on Pilley's Tickle, the basal unconformity is clearly seen, and a network of fine hematitic fractures pervades underlying felsic volcanic rocks of the Pilley's Island terrane (Plate 14). The unconformity is steeply inverted, but there is some evidence that sandstones and scattered conglomeratic beds farther to the north are right-way-up. At Long Arm on Triton Island, thinly bedded, upside-down sandstones and minor breccia beds are in contact with reddened basalts across a small fracture. However, adjacent basalts and diabase dykes of the Triton terrane contain irregular zones of red breccia containing sandstone fragments that appear to be filled fissure systems in the erosion surface. At Grand Dismal Cove, Bostock (1988) reports that a breccia grades through altered basalt into fresh basalt over several metres. This locality was not visited, but the Roberts Arm Group here is thought to be part of the Triton terrane.

Plate 14. *Steeply inverted unconformable contact between Roberts Arm Group felsic volcanic (right) and Springdale Group conglomerate (left). Note hematization and fracturing beneath the unconformity, and also that bedding in the Springdale Group is not parallel to the unconformity surface; Pilley's Island.*

To summarize, the basal unconformity is preserved on the Boot Harbour terrane, the Pilley's Island terrane, and the Triton terrane, but there are no potential sites on the Mud Pond terrane, as its extension is concealed beneath Pilley's Tickle. At one of these locations, the basal conglomerate sits upon Pilley's Island terrane rocks, but contains cobbles of fresh amygdaloidal rhyolite, characteristic of the structurally underlying Boot Harbour terrane. Assuming that the model for juxtaposition of these terranes along thrust faults presented below is valid, these relationships suggest that assembly and at least some deformation of the Roberts Arm Group occurred before deposition of the Springdale Group.

STRUCTURAL GEOLOGY

PREVIOUS WORK

Espenshade (1937) initially recognized that many of the rocks in the Pilley's Island area were overturned, and stated that "....the compressive forces were directed from south to north". In contrast, Bostock (1988) suggested that the Roberts Arm Group was affected by southeast-directed thrusting, but without major displacements of volcanic terranes. This model was influenced by Nelson (1981), who suggested that clastic sedimentary rocks to the southeast were derived from an advancing thrust sheet, and also by Dean and Strong (1977), who interpreted several major faults in Notre Dame Bay as folded, southeast-directed thrusts. Szybinski (1988) documented north-directed thrusting in the adjacent Cutwell Group, and suggested that this was also recorded in the Roberts Arm Group. However, a subsequent interpretation (Szybinski *et al.,* 1992) emphasized regional southeastward transport as part of a Notre Dame Bay nappe. Thurlow (*this volume*) reinterpreted surface geology and drill sections in the Pilley's Island area, and concluded that the ore-bearing felsic volcanic sequence was dissected by gently southeast-dipping thrust faults. This key observation provided a starting point for the wider interpretation presented in this section.

DESCRIPTIVE FRAMEWORK

A new interpretation provides the descriptive framework for this section, and must be summarized at this point. The structural development of the Roberts Arm Group is broadly a two-stage process, although each stage may have been polyphase. Stage 1 is viewed as dominated by broadly northward-directed thrusting, and produced terrane boundary faults, related lesser structures, and northward-overturned folds. This event, at least, partly preceded deposition of the Springdale Group. Stage 2 entirely postdates the Springdale Group, and produced the regional Z-shaped flexure within the belt, and numerous minor brittle faults. It also steepened earlier Stage 1 structures, particularly in the west. The Mansfield Cove and Lobster Cove faults, which bound the Roberts Arm Group, mainly record Stage 2, but may have an earlier Stage 1 history. Similarly, Stage 1 thrust faults were locally reactivated during Stage 2 events and their earlier history is locally obscured. Following Calon and Szybinski (1988), Stage 2 is viewed as mainly related to Silurian or younger dextral motion along major fault systems such as the Lobster Cove Fault.

Stage 1 Terrane Boundary Thrust Faults

The boundaries of terranes within the Roberts Arm Group are defined by zones of intense deformation manifested by strong schistosity, flattening and local transposition, which are interpreted as variably steepened thrust faults. However, direct kinematic evidence for the sense of motions is rarely present. Outside these fault zones, most of the Roberts Arm Group is only weakly deformed, and many outcrops lack penetrative cleavage development. The major terrane boundary thrust faults are described in ascending structural order.

Sunday Cove–Bear Cove Thrust

This zone defines the Boot Harbour–Mud Pond terrane boundary in the west, and was partly mapped by Bostock (1988) as the Sunday Cove fault. The best exposures are at Woodford's Arm, where flattened hematitic pillow lavas of the Mud Pond terrane give way northward to an intensely deformed hematitic rock in which all pillow structure has been eradicated. The fault zone contains veins of fine-grained, deformed, felsite-like material that appear to locally crosscut the strong fabric, and may constrain the age of early motions. Examination of thin sections suggests that the vein margins are sheared and strongly foliated, but interior portions are massive and crosscut the marginal fabric, implying that they were emplaced synchronously with deformation. The fabric in the fault zone has been refolded, and its orientation is locally variable, but is mostly subvertical to steeply south-dipping. The fault zone is bounded to the north by weakly deformed Woodford's Arm granite.

Swimming Hole Thrust

A thrust fault is presently inferred to mark the top of the Boot Harbour terrane on Pilley's Island, where felsic volcanic rocks show an anomalously strong southeast-dipping (~40°) cleavage. This structure is believed to pass north of Hayward's Gull Island, and merge into the Sunday Cove–Bear Cove thrust (Figure 3). An alternative explanation is that mafic rocks in the northern part of the Pilley's Island terrane are part of the Boot Harbour terrane, and that the Liquor Street thrust (see later discussion of intraterrane thrust faults) actually marks the terrane boundary. More work is required to resolve this uncertainty.

Loadabats Thrust

This fundamental structure defines the base of the Mud Pond terrane in the east of the area, and is best exposed on Hayward's Gull Island and on Pilley's Island; in the latter area, it was recognized as an important fault by Espenshade (1937), Tuach (1984) and Bostock (1988). The most intense deformation is developed within Mud Pond terrane basalts, which are transposed into a red-and-green striped rock, with an east – west fabric dipping about 40° south (Plate 15). On eastern Pilley's Island, intense deformation is also seen in the underlying felsic volcanic rocks. As in the Sunday Cove–Bear Cove thrust, there is evidence of later refolding and crenulation, and the fabric orientation is locally variable. The eastward continuation of the Loadabats thrust is hidden beneath Pilley's Tickle (Figure 3).

Plate 15. *Strongly flattened and deformed pillow basalts in the Loadabats thrust, showing disk-like relict pillows. The alteration of reddish and greenish layers results from attenuation of hematite ± epidote alteration typical of Mud Pond terrane basalts; Pilley's Island.*

Little Harbour Thrust

The Little Harbour thrust defines the Mud Pond–Triton terrane boundary. It is best exposed on Mussel Farm Inlet, and along Flat Rock Tickle, where it dips about 60 to 80° south, with no obvious signs of refolding. The fault runs through Little Harbour (J. G. Thurlow, personal communication, 1995), and then between Big Island and Triton Island (Figure 3), where it separates gently southeast-dipping, upside down, hematitic pillow lavas of the Mud Pond terrane from unaltered, upside down Triton terrane basalts and dykes. In the west, the thrust merges with the Crescent Lake thrust beneath the lake itself.

Tommy's Arm Thrust

The Tommy's Arm thrust locally marks the boundary between the Crescent and Triton terranes, and continues

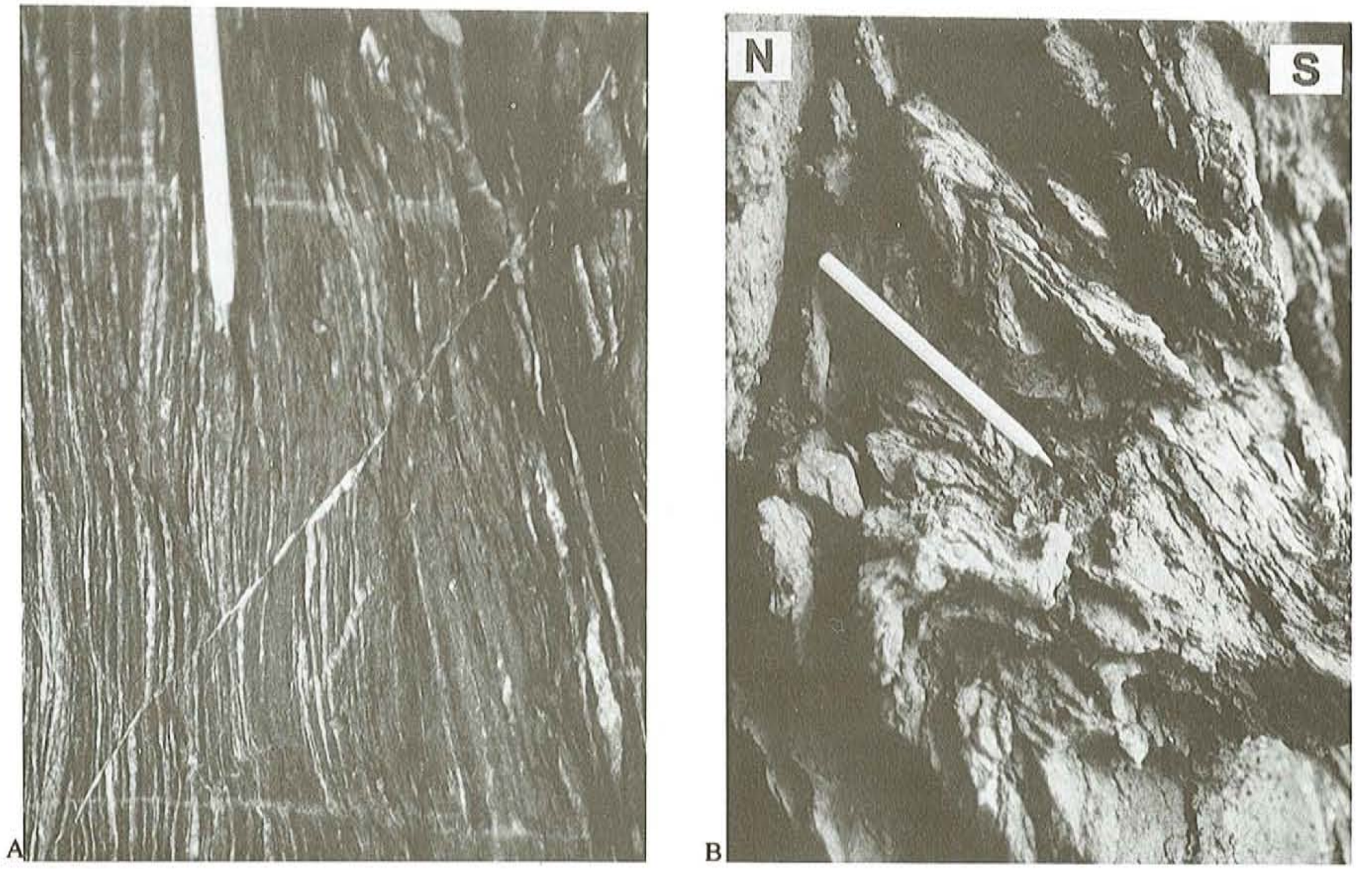

Plate 16. *(A) Mylonite-like rock produced by attenuation and transposition of carbonate veins and variably hematitic basalts in the Tommy's Arm thrust. (B) Northward-overturned minor folds in strongly deformed basalts (?) within the Tommy's Arm thrust; Tommy's Arm, 1 km west of Raft Tickle.*

southwestward as the Crescent Lake thrust (Figure 3). It is best exposed around Raft Tickle, where red-and-green striped rocks with concordant calcite seams (Plate 16A) were derived by transposition of hematite – epidote altered basalts. Minor folds in the fault zone (Plate 16B) are overturned to the north, and plunge to the east at about 40°. The pattern suggests reverse or thrust motion, with an eastward component, although more than one episode of movement is probably recorded. The nature of the offshore geology southeast of the Tommy's Arm thrust is unknown; it may comprise Roberts Arm Group rocks, or part of the complex tectonic melange of the Sop's Head Complex. In the latter case, the thrust may actually be a bounding fault to the Roberts Arm Group, representing its structural top.

Crescent Lake Thrust

A major fault defines the Crescent–Mud Pond terrane boundary through much of the area, juxtaposing tholeiitic and calc-alkaline sequences (Bostock, 1988). In most areas, this is defined by a wide subvertical zone of brittle fracturing. In one location on Route 380, strongly flattened, hematitic, epidotized pillow lavas are cut by schistose zones that dip about 70° southeast, and contain asymmetric folds overturned to the northwest, suggesting reverse motion. Southeast of this zone, distinctive coarse-grained, quartz-phyric felsic crystal tuffs are unlike any felsic rocks associated with the calc-alkaline sequence. This fault probably represents part of an original thrust that placed Crescent terrane over the Mud Pond terrane. Along most of its length, the Crescent Lake thrust is obscured by later brittle deformation.

Stage 1 Intraterrane Thrust Faults

Intraterrane thrust faults are recognized within all Roberts Arm Group terranes, excluding the Boot Harbour terrane, which appears to be stratigraphically intact. In the Pilley's Island terrane, the Liquor Street thrust and Hoskins Cove thrust, respectively, define the structural base and structural top of the ore-bearing felsic volcanic sequence. These thrust faults, and other lesser structures, are flat-lying to gently south-dipping, and locally have a complex, arcuate outcrop pattern (Thurlow, *this volume*). The Mud Pond terrane is believed to contain numerous internal thrusts, particularly near its structural base, where deformation is most intense. A prominent fault from Moorey Cove to Crescent Lake (Figure 3) may be a thrust linking the Sunday Cove–Bear Cove and Crescent Lake structures, dividing the Mud Pond terrane into two halves. A fault exposed on Route 380, just north of Crescent Lake, trends at 120° / 37° south, and preserves good evidence of thrust motion in the form of an internal C – S fabric, footwall tectonic brecciation, and northward-overturned hanging-wall folds (Plate 17; note that folds are too small to be seen in photo). Intraterrane thrust faults in the Triton terrane are spatially associated with the Tommy's Arm thrust. One example, exposed in a cliff face on Pretty Island, shows dip variations from 30° south to 60 to 70 °south, indicating a sigmoidal, "ramp and flat" geometry.

Plate 17. *Thrust fault exposed within Mud Pond terrane basalts. Note C – S fabric in hanging wall, suggestive of thrust motion, and extensive footwall brecciation. Highway 380, 3 km west of Robert's Arm.*

Stage 1 Regional Folding Patterns

There is little direct evidence of folding, due to the massive, monotonous, volcanic rocks, and the absence of marker horizons. Bostock (1988) recognized kilometre-scale folds in parts of the Boot Harbour and Triton terranes, and 1995 field work added little to this inventory. However, facing directions are relatively common throughout the Roberts Arm Group, and their regional consistency argues against the presence of any large-scale regional fold structures.

As documented by Bostock (1988), virtually all of the Boot Harbour terrane youngs north or northwest, and much of it is upside down. The degree of overturning is greatest at its northern extremity, where northwest-facing pillow lavas dip about 50° southeast (Plate 18). In the Hayward's Head area (Figure 3), facing reversals define a northeast-overturned syncline (Bostock, 1988), presumably coupled with an

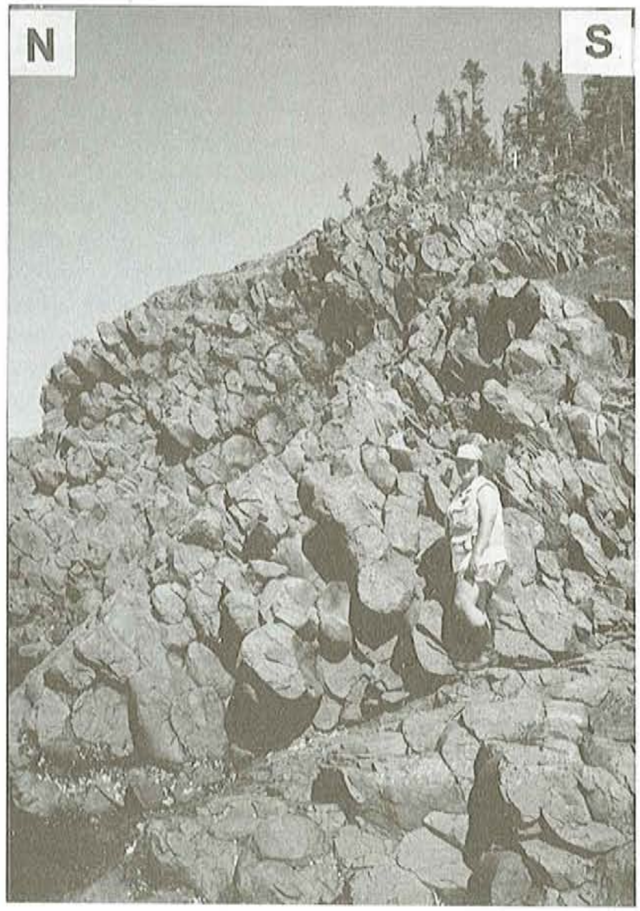

Plate 18. *Upside-down pillow lavas, dipping some 50° southeast, but facing northwest. This type of structural attitude is typical of large areas of the Roberts Arm Group. Boot Harbour terrane, Sunday Cove Island.*

unexposed anticline beneath Sunday Cove. In contrast, the Pilley's Island terrane contains very few way-up indicators. The mafic volcanic rocks structurally beneath and above the ore-bearing felsic volcanic rocks are considered to be upside down, and gently south dipping (see also Thurlow, *this volume*). Within the felsic volcanic rocks, the progression from quenched and flow-brecciated dacite into massive flow-banded dacite on the west coast implies that at least part of the sequence is north facing and inverted, as suggested by Espenshade (1937). Conversely, Appleyard and Bowles (1978), Tuach (1984) and Santaguida *et al.* (1992) argue that the felsic volcanic sequence is right-way-up, on the basis of alteration facies, which fit the geometric model for Kuroko-type mineralization. If the orebodies are right-way-up, it implies that there must be a northward-overturned fold within the ore-bearing sequence, as suggested by Espenshade (1937). However, the recognition of thrust faults (Thurlow, *this volume*) raises the possibility that the apparent relationships between orebodies and various alteration facies may not be stratigraphic. This important question is currently open, but it has obvious implications for exploration strategies.

The Mud Pond terrane is similarly north facing, and mostly south dipping (i.e., upside down). At its northeast extremity, on Big Island, hematitic pillow lavas are approximately flat lying, and upside down (noted also by Bostock, 1988). The Triton terrane is also mainly north facing, and variably overturned, especially along the south side of Pilley's Tickle, where pillow lavas dip southeast at around 40°. However, local south-facing domains suggest at least one paired anticline and syncline (Bostock, 1988). These folds are northward-overturned at Raft Tickle, become southward-overturned on Triton Island, and return to northward-overturned at the northeastern extremity of the Roberts Arm Group. This regional warping of fold axes may be related to Stage 2 deformation.

Facing directions are poorly known through most of the Crescent terrane. However, the area west of Boot Harbour Pond, sandwiched between Boot Harbour and Mud Pond terranes, is southeast-facing (Bostock, 1988). This is the only part of the Roberts Arm Group with this regional attitude. Southeast of the Crescent Lake thrust, regional alternations of volcanic and sedimentary rocks of the Crescent Lake Formation may indicate repetition by isoclinal folding, or by thrusting. The rocks of the Crescent terrane exhibit more intense penetrative deformation than those of the calc-alkaline terranes, and structural complexity should be expected. Bostock (1988) shows regional bedding and foliation attitudes as steeply dipping to both north and south.

The relationships between Stage 1 thrust faults and folding are not entirely clear. There is no evidence that the tight Stage 1 folds affect the major thrusts, although outcrop-scale northward-overturned folds in the Tommy's Arm thrust affect the schistosity, indicating that they postdate the first fabric development. Provisionally, Stage 1 folds are viewed as parasitic structures developed on the overturned northern limb of a regional anticlinorium, essentially synchronously with early thrusting events.

Stage 1 Folding of the Springdale Group ?

The outliers of the Springdale Group, and its basal unconformity, have the northward-overturned attitude typical of much of the Roberts Arm Group. However, the Springdale Group may be locally south facing (i.e., right-way-up), in two locations adjacent to the Lobster Cove Fault (Figure 4). This inference is based only on apparent facing directions, which may not be reliable in coarse sediments of probable alluvial origin, and it requires further examination. Such a pattern may indicate local Stage 2 folding along the trace of the Lobster Cove Fault, seen also on an outcrop scale (see below), but it could also suggest northward-overturned folds analogous to those seen in the Roberts Arm Group. Thus, it is possible that some of the north-directed thrusting in the Roberts Arm Group postdates deposition of the Springdale Group. However, the presence of the basal unconformity upon different tectonic terranes implies that some thrusting predates deposition of the Springdale group.

Stage 2 Bounding Faults of the Roberts Arm Group

Mansfield Cove Fault

This zone juxtaposes the Roberts Arm Group with the Hall Hill Complex, mostly represented in the study area by the Mansfield Cove trondhjemite pluton. It is best exposed at the type locality on Halls Bay, where there are subvertical to steeply east-dipping brittle faults trending at about 10°, with prominent subhorizontal slickensides. There are also minor east-dipping brittle faults with evidence of reverse motion, including a small-scale imbricate zone, or so-called "schüppen structure" (B. O'Brien, personal communication, 1995), and west-dipping brittle faults of uncertain character. All of these structures are viewed as related, possibly as part of a regional "flower structure" associated with the main strike-slip fault (B. O'Brien, personal communication, 1995).

Lobster Cove Fault

The Lobster Cove Fault juxtaposes Lushs Bight Group and Cutwell Group against either Roberts Arm Group or Springdale Group rocks. On Sunday Cove Island, the Lushs Bight Group is cut by schistose zones that resemble Stage 1 structures seen in the Robert's Arm Group, but these are subvertical to northward dipping (55 to 80°). B. O'Brien (personal communication, 1995) suggests that there may also be an earlier south-dipping fabric in the Lushs Bight Group here, but its attitude is uncertain. On the west coast of Pilley's Island, metatuffaceous Cutwell Group rocks, about 200 m north of the Lobster Cove Fault, have a "gneissic" appearance, and a strong fabric trending at 050° / 45° south. This deformation is absent on the east coast of Pilley's Island, where only 2 or 3 m separates Springdale Group sandstones from fractured metavolcanic rocks of the Lushs Bight Group. Minor faults that may be associated with the main Lobster Cove Fault were mapped on Sunday Cove Island by Bostock (1988), and were also observed on Pilley's Island. One such fault trending at 200°/ 70° west, places the Springdale Group structurally above the Roberts Arm Group, indicating east-directed reverse motion.

Folding in the Springdale Group is seen clearly only on Triton Island, where tight, vertically plunging folds are present in thinly bedded intervals, but not in adjacent thickly bedded sandstones. However, the Cutwell Group north of the Lobster Cove Fault contains vertical schistose zones indicating an earlier, more intense, deformation.

Observations suggest major strike-slip motion and associated brittle deformation along the Lobster Cove Fault, but more intense, ductile deformation in the adjacent Lushs Bight and Cutwell groups suggests an earlier history. A regional study of the Lobster Cove Fault (Calon and Szybinski, 1988) suggested dextral strike-slip motion, and that the Springdale Group may have been deposited in small, pull-apart basins. However, it has also been suggested that the Springdale Group was derived from, and deposited ahead of, a large-scale nappe structure advancing toward the southeast (Szybinski *et al.,* 1992).

Stage 2 Minor Faults

The area contains numerous brittle, minor faults of uncertain character that are characteristically associated with pervasive brown iron carbonate alteration. In the Hayward's Head area, these overprint northward-overturned Stage 1 folds. On Hayward's Gull Island, subvertical brittle faults bound an outcrop of strongly schistose material, apparently derived from a nearby Stage 1 thrust fault. Such relationships demonstrate that this brittle deformation postdates Stage 1 thrusting and folding. These minor structures are potentially important in property-scale exploration, e.g., vertical faults offset the Pilley's Island orebodies by up to 60 m (Appleyard and Bowles, 1978).

Stage 2 Folding

Stage 2 folding is seen on an outcrop scale in the Springdale Group adjacent to the Lobster Cove Fault. The regional sigmoidal flexure of the entire Roberts Arm Group, including its contained Stage 1 thrusts, may be a large-scale structure of similar origin. A strong north-northeast-trending brittle fracturing observed along the north side of Tommy's Arm is probably axial planar to this regional bend (B. O'Brien, personal communication, 1995), and warping effects may be responsible for shifts in the attitudes of Stage 1 fold axes on Triton Island.

DISCUSSION AND IMPLICATIONS

REGIONAL GEOLOGICAL AND STRATIGRAPHIC IMPLICATIONS

Age and/or Spatial Relationships of Terranes

The Roberts Arm Group has been divided into five main fault-bounded terranes, that are separated by broadly south-dipping thrust faults (Figure 6a). The four calc-alkaline terranes mostly young north or northwest, and are partially upside down. Thus, the present configuration of the Roberts Arm Group may represent an inverted stratigraphy, in which older rocks were thrust above younger rocks (Figure 6b). This model explains the voluminous diabase in the Triton terrane as feeder systems to higher parts of the volcanic edifice, and is consistent with evolution toward a mature arc with local felsic volcanic centres. It also implies that a mafic sequence with pervasive regional alteration originally lay stratigraphically below felsic rocks associated with VMS mineralization. This model of regional older-over-younger thrusting may not apply everywhere, as the Pilley's Island terrane is locally structurally above Mud Pond terrane around Flat Rock Tickle, and altered and unaltered rocks are imbricated within the ore-bearing sequence. These local complexities are presently unresolved, and could be explained by several models, e.g., by a second generation of thrusts that disturb an already imbricated sequence, or by later normal faulting. However, these are important questions in the context of mineral exploration.

Alternatively, the Roberts Arm Group may represent two or more assemblages that were developed in different locations, and brought together by thrusting (Figure 6c). In this model, the Sunday Cove – Bear Cove – Loadabats thrust system is a candidate for a fundamental boundary, as it separates terranes with felsic volcanism from those dominated by mafic rocks. The tholeiitic Crescent terrane could fit into either model, as an underlying volcanic sequence (Figure 6b), or a spatially discrete tholeiitic package (Figure 6c). The apparent juxtaposition of Crescent terrane, Boot Harbour terrane and Mud Pond terrane northeast of Loon Pond requires a separate structural explanation, discussed later.

Possible tests of these models include U – Pb zircon geochronology and geochemical studies. For example, if dykes cutting the Crescent terrane tholeiitic volcanics are of calc-alkaline affinity, it would support (but not prove) the stratigraphic model. Wide variations in isotopic compositions between tholeiitic (ϵ_{Nd} = +4 to +8) and calc-alkaline (ϵ_{Nd} = -10 to +2) rocks (Swinden *et al., in press*) may favour the non-stratigraphic model.

Contrasting Types of Felsic Volcanism

Bostock (1988) grouped felsic rocks as a single unit, and suggested that many were of hypabyssal origin, whereas the present study concludes that both extrusive and shallow intrusive components are present, but that the former are dominant. A more important conclusion is that the felsic rocks of the Boot Harbour and Pilley's Island terranes are of different character.

In the Boot Harbour terrane, well-preserved and generally unaltered felsic rocks display features analogous to subglacial rhyolites in Iceland, and Archean submarine rhyolites in the Canadian Shield (Dimroth *et al.,* 1979; De Rosen-Spence *et al.,* 1980; Furnes *et al.,* 1980) . The

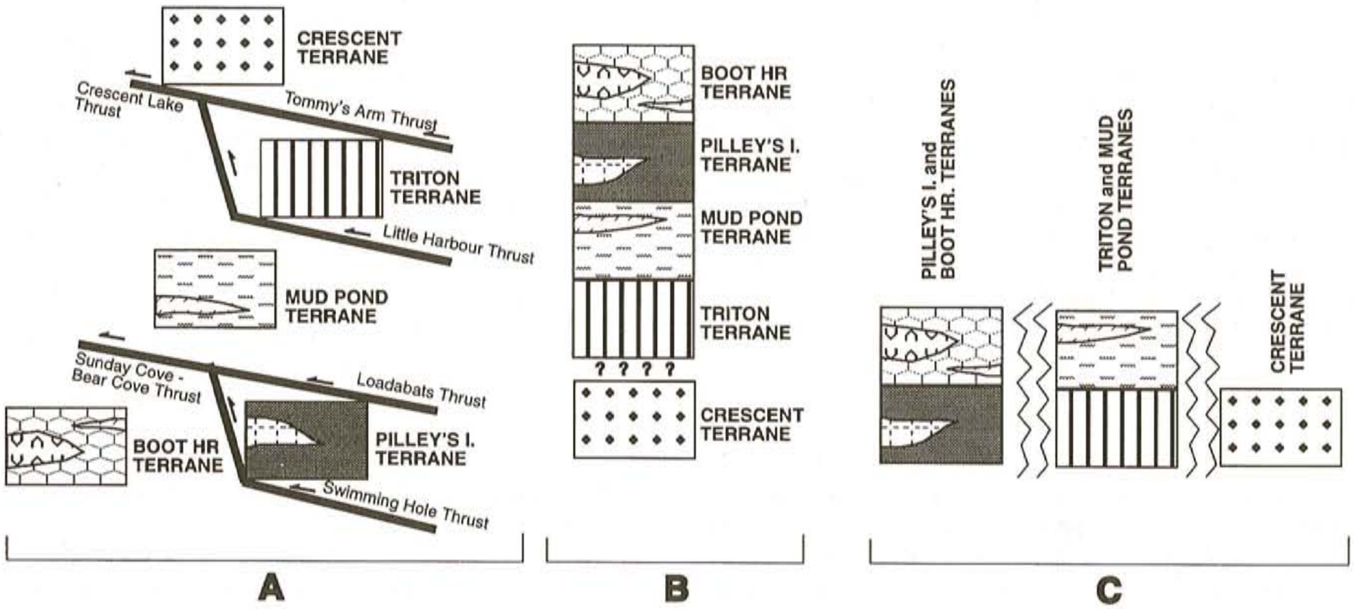

Figure 6. *Schematic illustration of structural relationships between terranes in the Roberts Arm Group, and their possible original stratigraphic and/or spatial relationships: (a) Present configuration; (b) "Stratigraphic" option, implying a reversal of original sequence by thrusting; (c) "Exotic" option, implying separate, unrelated development of at least some terranes. Note that these models are not mutually exclusive.*

amygdaloidal rhyolites, with flow structures, are particularly characteristic of the Boot Harbour terrane. Vesicles may have nucleated by shear stress in viscous, flowing material (McDonald, 1972; De Rosen-Spence *et al.,* 1980), or flow may have been localized in volatile-rich zones due to their lower viscosity, or incipient bubble development (Williams and McBirney, 1979, page 125). Volatile retention in magmas leads to reduced viscosity, and would facilitate massive flows, and unusual associated facies such as pillow-rhyolites (Dimroth *et al.,* 1979). Inhibition of large-scale vesiculation could reflect a deep-water environment, or a low initial volatile content. Paradoxically, the amygdaloidal flow textures are widely preserved because the volatile phase did not completely separate from the magma. Mafic pillow lavas of the Boot Harbour terrane are characteristically amygdaloidal, which could be taken as an indication of shallow conditions (Williams and McBirney, 1979). However, these spherical vesicles may have formed after much of the pillow was solidified, from a residual volatile-enriched component. In this respect, vesicles in the mafic rocks differ from those in the rhyolites, which were *early* and affected by flow-related deformation. Also, the original volatile contents of mafic and felsic magmas may have been different, and felsic lavas are not necessarily more volatile-rich than calc-alkaline basalts.

In the Pilley's Island terrane, felsic rocks have a very different appearance. This, in part, reflects widespread alteration but, they are considered also to be texturally and compositionally distinct from those of the Boot Harbour terrane. The complex, glassy, breccias have undergone violent and explosive brecciation partly related to water ingress. Preserved amygdaloidal textures are less common than in the Boot Harbour terrane, but vesiculation may have been more widespread and catastrophic, contributing to lava fragmentation. For example, arcuate fragments observed in some glassy breccias may be bubble rims, rather than shards developed via perlitic fracturing. The polylithic tuff-breccias within the ore-bearing sequence, which include ore fragments, are also potential products of explosive submarine volcanism. These differences may indicate a shallower water depth, favouring large-scale vesiculation and violent steam expansion during hydrobrecciation. Mafic volcanic breccias with scoriaceous, bomb-like clasts at two locations within the Pilley's Island terrane may also be a indication of subaerial mafic eruptive activity. Tuach (1984) also suggested locally emergent conditions based on "welding" in some tuff horizons. Alternatively (or additionally), felsic magmas at the Pilley's Island centre may have had higher primary volatile contents than those of the Boot Harbour terrane, or were enriched in volatiles by association with an active hydrothermal system. The extensively flow-banded, non-amygdaloidal dacitic unit is an exception to this pattern. However, it is possible that it was extruded after a volatile-rich upper section of the magma chamber was depleted through explosive eruptions (c.f., Fisher and Schminke, 1984).

The answers to these questions lie in petrographic and geochemical studies. Bostock (1988) noted that the felsites around Pilley's Island were chemically distinct, but it is not clear if this reflects their alteration alone. More comprehensive trace-element data, including REE, may help to resolve this question, which has obvious implications for mineral exploration.

Structural and Tectonic Implications

Regional Structural Configuration. The polarity of Stage 1 thrusting in the Roberts Arm Group is toward the north or northwest. This sense is opposite to most previous conceptual models (e.g., Dean and Strong, 1977; Bostock, 1988), and also opposite to thrusting documented at Gullbridge and Buchans (Pope *et al.,* 1990; Thurlow, 1990). The regional configuration is envisaged as a stack of north-verging, largely upside-down thrust sheets, some of which contain overturned folds developed broadly synchronously with thrusting (Figure 7). In the east, the original low-angle geometry is partly preserved (Figure 7a and b). In the centre of the area, the Swimming Hole thrust merges with (or is overridden by ?) the Loadabats thrust, to form the Sunday Cove–Bear Cove thrust, and the Pilley's Island terrane is absent at surface (Figure 7c). Attitudes are steeper in this region. The Woodford's Arm granite could either be a early (pre-thrusting) subvolcanic pluton (c.f., Bostock, 1988), or a a younger intrusion that exploited the thrust, but was cut off by subsequent brittle motions. The south-facing area of Crescent terrane bounded by Mud Pond and Boot Harbour terranes near Loon Pond is envisaged as a downfaulted section of structurally overlying Crescent terrane (Figure 7d)

The calc-alkaline portion of the Roberts Arm Group is viewed as the disrupted, overturned (lower) limb of a large-scale north-verging anticlinal nappe, and the kilometre-scale overturned folds within individual terranes are viewed as parasitic structures (Figure 8). The complementary right-way-up (upper) limb is not seen in the calc-alkaline sequence, but may be preserved within the poorly known Crescent terrane. The pattern of strike-parallel faults and repetition of metasedimentary units in this region suggest that it is also a thrust stack. The south-facing area of Crescent terrane northeast of Loon Pond is viewed as a downfaulted segment of this upper limb, most of which has now been removed by erosion. The regional steepening of Stage 1 structures is attributed to a combination of southeast-directed reverse motion and dextral transcurrent motion during Stage 2, associated with structures such as the Lobster Cove Fault. Based on the attitudes of bedding and Stage 1 thrusts, steepening seems to have been most prevalent in the west of the area.

Relationships to Surrounding Terranes. Szybinski (1988) and Kean *et al.* (1995) describe a similar two-stage structural history in the Cutwell Group, i.e., early north-directed thrusting, followed by brittle deformation along dextral transcurrent faults. However, these rocks are partly south facing and right-way-up, indicating that they include a series of folds (Szybinski, 1988; Kean *et al.,* 1995). These may represent the upper limb of another northwest-overturned anticlinal structure, originally structurally below the Roberts Arm Group terranes (Figure 8). This interpretation implies that the Lobster Cove Fault may have originated as a north-directed thrust that brought the Roberts Arm Group over the Lushs Bight and Cutwell groups, rather than the south-directed thrust suggested by previous workers (e.g., Dean and Strong, 1977). The ancestral Mansfield Cove Fault may have started life as a similar northwest-directed thrust that brought the Roberts Arm Group over the Hall Hill Complex. This interpretation contrasts with suggestions that the Lobster Cove Fault represents part of the sole thrust to a southeast-verging "Notre Dame Bay Nappe" (e.g., Szybinski *et al.,* 1992), and it is difficult to reconcile these conflicting views, unless there is large transcurrent displacement along the fault, such that it juxtaposes regions with very different structural histories.

Timing of Stage 1 and Stage 2 Deformation. The unconformable relationship of the Springdale Group with three different terranes of the Roberts Arm Group implies that the latter were assembled by thrusting prior to the Middle Silurian. Thus, some Stage 1 deformation may be of Ordovician age. There is presently no evidence for deformation that predates this northward translation. The Springdale Group basal unconformity has locally been rotated through 135° (assuming that it was originally a horizontal datum, rather than a scarp), and it has also been deformed. There are three possible interpretations.

First, Stage 1 north-directed thrusting may have resumed after deposition of the Springdale Group, creating a structural style similar to that of the Roberts Arm Group, but with much less intense deformation. A second, related option is that the Springdale Group formed synchronously with thrusting, by erosion ahead of the thrust stack, and was then eventually overriden, folded and overturned. This resembles the suggestions of Szybinski *et al.* (1992), but with a diametrically opposite sense of motion. Both interpretations imply at least some post-Middle Silurian Stage 1 deformation. Alternatively, inversion of the unconformity may entirely be a local Stage 2 process related to motions on the Lobster Cove Fault, and all Stage 1 deformation is pre-Middle Silurian (and possibly Ordovician). Stage 2 brittle deformation, comprising folding and faulting related to strike-slip motions, affects Stage 1 structures and the Springdale Group, and must be entirely of post-Middle Silurian age

Mineral Exploration Implications

Felsic volcanic rocks and associated VMS deposits on Pilley's Island are located in a different tectonic terrane than

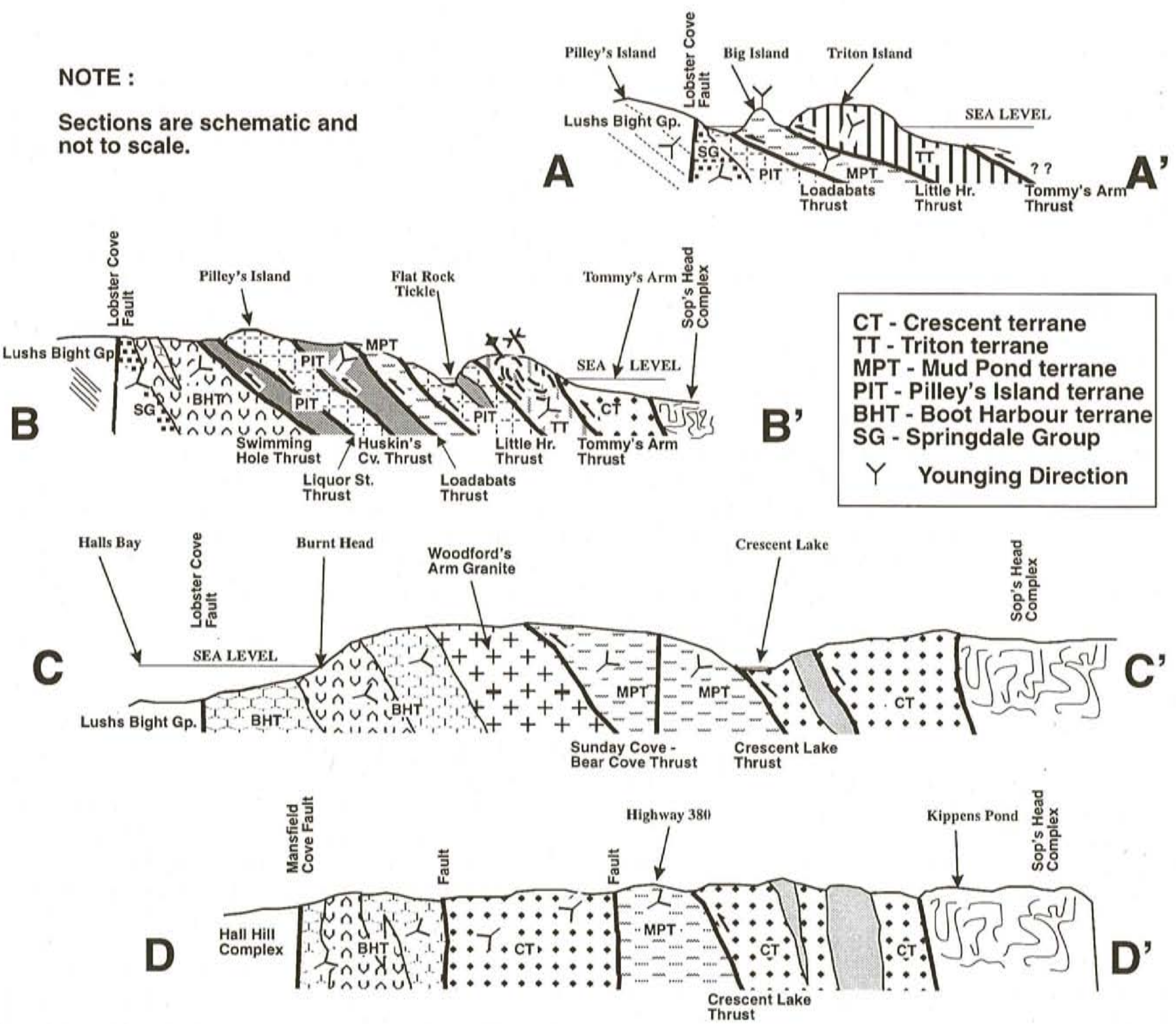

Figure 7. *Interpretative, schematic structural cross-sections through the Roberts Arm Group: (a) Pilley's Tickle area; (b) West Coast of Pilley's Island and adjacent areas; c) Woodford's Arm–Crescent Lake area; (d) Mansfield Cove–Tommy's Arm River area; For locations of section lines, see Figure 3. Legend for units as for Figure 3.*

the more abundant felsic rocks of the Boot Harbour terrane. The environments of felsic volcanism were apparently distinct in these two terranes, and the magmas may also have been compositionally different. Also, there is little or no evidence of pervasive hydrothermal alteration in Boot Harbour terrane felsic volcanic rocks. At face value, these conclusions are not encouraging for mineral exploration around felsic volcanic centres in the Boot Harbour terrane. Mineralization in the Boot Harbour terrane at Sunday Cove Island is mainly in mafic rocks cut by felsite dykes, and is apparently epigenetic (Evans, *this volume*). There may be some potential around the poorly known Loon Pond felsic centre, where Swinden (1987) describes "lean volcanogenic sulphide showings", or in inland areas, where alteration is more difficult to recognize.

The Pilley's Island terrane is the most prospective area for VMS mineralization, but it is discontinuous. If the assignment of pillow breccias on northern Hayward's Gull Island is correct, it extends for some 2 km west of Pilley's Island, beneath Sunday Cove. Farther to the west, it is missing at surface, and the Sunday Cove – Bear Cove thrust places the Mud Pond terrane directly above the Boot Harbour terrane. However, the Mud Pond terrane may have completely overridden the Pilley's Island terrane, which may still be present at depth. Eastward of Pilley's Island, Mud Pond terrane basalts are flat lying to gently southeast-dipping, and upside-down. The ore-bearing felsic volcanic sequence probably sits with a similar attitude beneath the Loadabats thrust, and may continue in the subsurface beneath Triton

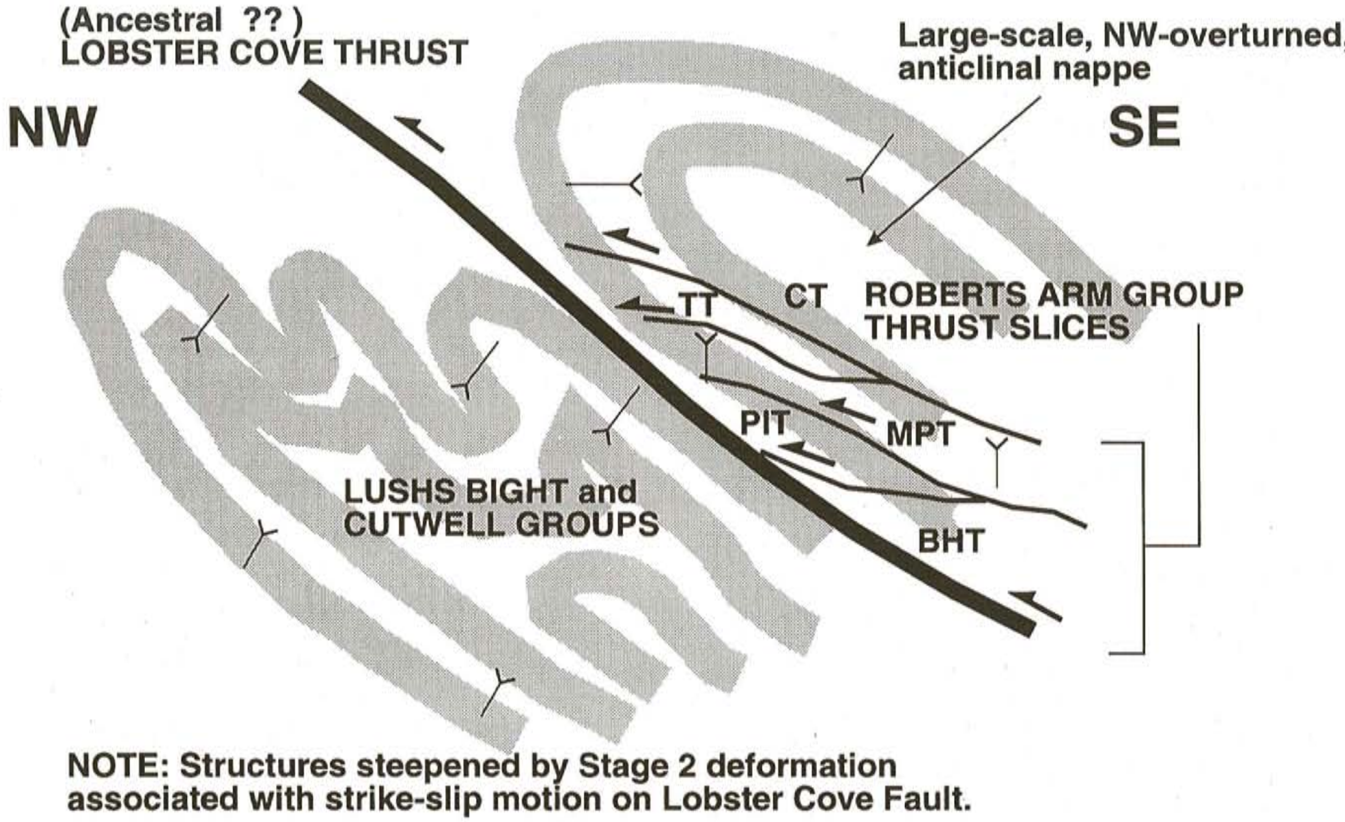

Figure 8. *Schematic illustration of interpretation of the Roberts Arm Group as the disrupted, overturned, lower limb of a large-scale, north-verging nappe structure, and its possible relationship to terranes north of the Lobster Cove Fault.*

Island. The potential area for blind exploration here is almost as large as the exposed segment of the Pilley's Island terrane.

The southern part of Pilley's Island also has potential for exploration, as the ore-bearing sequence should be present in the subsurface, beneath the Loadabats and/or Hoskin's Cove thrusts. There is also structural repetition of ore-horizon-like felsic rocks at the southern tip of Pilley's Island, and on the adjacent mainland, in areas that have not received concentrated exploration. Thus, there is potential for multiple subsurface intersections of the ore-bearing sequence south of the Pilley's Island mine area. However, the three-dimensional structural pattern of this area is complex and unresolved, and the lateral extent and plunge direction of the repeated panels is uncertain. More work is required here to develop a detailed structural model that could guide any deep drilling efforts. As the individual thrust faults probably have a sigmoidal "ramp-and-flat" pattern in 3 dimensions, it is presently difficult to predict depths to favourable horizons on the basis of regional data.

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