Sedimentation in a subaqueous arc/back-arc setting: the Bobby Cove Formation, Snooks Arms Group, Newfoundland

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Abstract

The Bobby Cove Formation of the Snooks Arm Group, north-central Newfoundland, displays cycles of lava- and sediment-dominated successions. The formation, located between pillow basalts and black graptolite-bearing mudstones, was deposited in a subaqueous setting. Volcaniclastic rocks were produced by calc-alkaline volcanism that either occurred during quiescence of, or was synchronous with, periods of tholeiitic volcanism. Variation in rock chemistry supports a change in tectonic setting from an expanding fore-arc oceanic crust to a progressively more mature magmatic arc/back-arc system. Combined chemical, sedimentological and detailed petrographic studies define several types of volcaniclastic sedimentary rocks of pyroclastic, epiclastic, and mixed origin. The volcaniclastic rocks were divided into three groups based on clast components and textures: (1) a monogenic facies with minor mudstone interbeds, composed of basaltic to basaltic andesite clasts, is interpreted to have originated from subaqueous vertically-directed, pyroclastic eruptions; (2) a polygenic facies with abundant mudstone interbeds composed of rounded fragments and a lack of vesicular mafic fragments, was probably derived from chemical weathering and mechanical erosion of volcanic rocks (i.e. epiclastic volcanolithic sandstone); and (3) a second polygenic facies with minor mudstone interbeds is characterized by diverse clast compositions and textures, and is interpreted as remobilized deposits from previously deposited, fresh and/or altered, pyroclastic debris. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Intense arc-related volcanism, high sea-level, and abundant volcanogenic mineralization characterize both the Ordovician and the Archean (e.g. Tiley, 1993). These conditions result in environments where subaqueous deposits of pyroclastic debris are likely to form. Ordovician subaqueous pyroclastic deposits have been described previously (Francis and Howells, 1973; Kokelaar et al., 1984; Fritz and Howells, 1991)

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and are easier to interpret than Archean deposits, because actualistic plate tectonic models can be applied with fewer assumptions, and because fossils provide better constraints on the paleogeographic context (i.e. water depth, salinity, etc.). Nevertheless, there are considerable similarities between Ordovician and Archean volcaniclastic deposits. Plants and animals had not yet colonized the land in the Ordovician, so that erosion rates were more similar to the Archean than to the modern period. Recent work implies that subduction of pelagic sediments plays an important role in the geochemistry of arc-related volcanic rocks (e.g. Davidson, 1987; White and Dupré, 1989; Brenan et al., 1995; Elliott et al., 1997; Turner et al., 1997; Plank and Langmuir, 1998; Bédard, 1999). During the Ordovician, the deep-sea floor had begun to be covered by pelagic biogenic siliceous ooze (radiolarians), whereas organisms producing present-day carbonate ooze had not yet evolved. Thus, the similarity of Ordovician and Archean sedimentation patterns could lead to a similarity in the geochemistry of arc-related rocks.

This study examines a volcaniclastic-rich formation of Ordovician age from north-central Newfoundland. Distinguishing between primary deposits of pyroclastic origin, and secondary deposits of epiclastic origin is difficult, but crucial, for the paleogeographic reconstruction of ancient deposits. The distinction between primary and secondary deposits may be subtle because both tend to be emplaced by mass-flows with high concentrations of debris and limited turbulence (Fisher and Schmincke, 1984; Cas and Wright, 1987; Stix, 1991; McPhie et al., 1993). Freshly deposited pyroclastic debris is readily remobilized by rain, wind and ice in subaerial environments, and by density currents of various origin in marine environments.

The distinction between primary and secondary deposits in subaqueous settings is generally based on petrography and sedimentary structures (Walker and Croasdale, 1972; Dimroth and Yamagishi, 1987; Stix, 1991). Both provide information on the nature of constituents, on the mode of fragmentation, on mechanisms of transport, and about sedimentation processes. It is possible to identify the composition and origin of individual pyroclasts, and clast populations are preserved in both primary and rapidly resedimented deposits. However, the brittle nature and metastable mineralogy of pyroclasts do not favor their preservation in deposits resulting from epiclastic weathering and erosion of previously sedimented pyroclastic deposits. Our understanding of subaqueous eruptions and their deposits is currently limited, as a result of imperfections in theoretical modeling, and a paucity of well documented examples. A combined geochemical and stratigraphic approach using facies analysis is employed to distinguish eruption-related facies and secondary resedimented deposits.

The Bobby Cove Formation is part of a sequence of alternating flow-dominated and sediment-dominated successions. Basaltic volcanism is characterized by the accumulation of thick (400–500 m) sequences of pillow lavas and sheet flows (Bédard et al., 1999b). These basalt-dominated events alternate with periods of relative quiescence and erosion marked by tilting of fault blocks, erosion, and/or deposition of thick epiclastic and debris flow deposits (Bédard et al., 1999c; Kessler and Bédard, this volume). There are also periodic influxes of pyroclastic and epiclastic debris and lavas from a nearby calc-alkaline volcano (Bédard et al., 1999b). Calc-alkaline volcanism may have occurred during basaltic quiescence, leading to alternating sequences of basaltic flows and calc-alkaline deposits; or to mixed sequences of calc-alkaline tuffs and volcanogenic epiclastic deposits derived from erosion of the tholeiitic flows (Bédard et al., 1999a). Alternatively, calc-alkaline activity may have occurred synchronously with basaltic volcanism, leading to interfingering between tholeiitic basalts and calc-alkaline tuffs. The more explosive style of calc-alkaline sequences is probably related to differences in lava chemistry and volatile content (Gill, 1981; Arculus, 1994).

2. Geological and tectonic setting

The Bobby Cove Formation is part of the Snooks Arm Group in the Notre Dame Bay area
of Newfoundland (Fig. 1; Hibbard, 1983; Bédard et al., 1999b). Rocks of this group overlie the obducted oceanic crust of the Middle Ordovician Betts Cove Ophiolite sub-conformably, which probably formed in a marginal basin adjacent to the Laurentian margin (Tremblay et al., 1997). The oceanic crust at Betts Cove is dominated by rocks of boninitic affinity (Coish et al., 1982; Bédard et al., 1998, 1999b; Bédard, 1999), and so formed in a supra-subduction zone environment, either in response to arc splitting, or to extreme fore-arc extension leading to seafloor-spreading (Stern and Bloomer, 1992; Tremblay et al., 1997; Bédard et al., 1998). Recent mapping has revealed the presence throughout the Snooks Arm Group of numerous high-angle cross-cutting normal faults (Bédard et al., 1999a,b). Rapid changes in thickness and facies on either sides of these faults, an up-section decrease in the magnitude of lithological offsets along individual faults, and the local presence of basalt within fault breccias and talus breccias, together suggest synvolcanic and synsedimentary faults. Extension was synchronous with eruption and sedimentation. Basaltic eruptions in the Snooks Arm Group were subaqueous, as indicated by the dominance of pillow lavas and pillow breccias. Interbedded black mudstones locally contain graptolites (Snellgrove, 1931; Williams, 1992) and indicate deep-water. The Snooks Arm Group consists of three repeated cycles of basaltic lavas and volcanogenic sediments whose geochemistry document basin changes of tectonic regime (Fig. 2). The repeated alternation of these distinct volcanic suites collectively imply a long-lived, extensional, subsiding back-arc setting with a simultaneous development of nearby, mature arc volcanoes.

Fig. 1. Geological map of part of the Betts Cove ophiolite and its cover rocks, showing the overall stratigraphy of the Snooks Arm Group. Adapted from Bédard et al. (1999b).
The lower Snooks Arm Group (Mount Misery, Scrape Point and Bobby Cove Formations) forms the lowermost lava-sedimentary cycle. The Mount Misery Formation is dominated by basaltic pillowed and sheet flows of arc tholeiite composition, geochemically transitional between the boninitic lavas of the ophiolite and the evolved, undepleted, overlying tholeiites. This reflects a transition from the arc-dominated system of the ophiolite to a more mature back-arc system (Bédard et al., 1999b). The Scrape Point Formation consists of interfingering volcanic and sedimentary rocks. The flows have only a weak arc signature and are interpreted to represent mature back-arc basin basalts. The sedimentary rocks are very similar in mineralogy, texture and geochemical signature to those of the overlying Bobby Cove Formation and are interpreted as precursors or distal equivalents of the conformably overlying Bobby Cove Formation. They show a dominant calc-alkaline affinity and, thus, the interfingering of tholeiitic and calc-alkaline rocks suggests stabilization and maturation of an arc system synchronous with back-arc spreading.

The Bobby Cove Formation is the first mappable unit of formational rank dominated by sedimentary rocks, and was emplaced during a hiatus in tholeiitic volcanism. The formation is dominated by a lower member that is about 400 m thick and contains a diverse suite of mafic to felsic calc-alkaline volcaniclastic rocks whose chemistry implies that they represent a mature arc volcano. Analyses of flows, dikes, and of individual clasts suggest that there are two magmatic lineages: a High-Ti and a Low-Ti series (Fig. 2; Table 1). The High-Ti series is essentially indistinguishable from underlying (Mt. Misery) tholeiites, suggesting a genetic link with these magmas. The Low-Ti series exhibits a characteristic calc-alkaline trend of depletion of FeO and TiO₂, and SiO₂-enrichment; a trend that cannot result from anhydrous crystallization of these magmas. Felsic volcaniclastic rocks become proportionally more significant upwards. The felsic rocks show considerable scatter, but most fall along the extension of the Low-Ti series trend.

The lower member of the Bobby Cove Formation records the principal calc-alkaline eruptive
Table 1
Average analyses (normalized to 100%) from different lithofacies\(^a\)

<table>
<thead>
<tr>
<th>Unit facies</th>
<th>BCLM</th>
<th>BCUM</th>
</tr>
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<tbody>
<tr>
<td>High-Ti lavas</td>
<td>Low-Ti lavas</td>
<td>Dyke</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>50.3</td>
<td>52.1</td>
</tr>
<tr>
<td>TiO(_2)</td>
<td>1.28</td>
<td>0.86</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>17.2</td>
<td>15.9</td>
</tr>
<tr>
<td>Fe(_2)O(_3)</td>
<td>12.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Na(_2)O</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>MgO</td>
<td>5.51</td>
<td>7.40</td>
</tr>
<tr>
<td>CaO</td>
<td>8.64</td>
<td>9.00</td>
</tr>
<tr>
<td>K(_2)O</td>
<td>3.95</td>
<td>3.55</td>
</tr>
<tr>
<td>K(_2)O</td>
<td>0.26</td>
<td>0.91</td>
</tr>
<tr>
<td>Fe(_2)O(_3)</td>
<td>0.80</td>
<td>0.52</td>
</tr>
<tr>
<td>Fe(_2)O(_3)</td>
<td>3.44</td>
<td>3.87</td>
</tr>
<tr>
<td>Total</td>
<td>78.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

\(^a\) 'BCLM' and 'BCUM', Bobby Cove lower and upper members, respectively.
episode in the Snooks Arm Group. Sharply contrasting patterns of geochemical evolution (Fig. 2), and distinct geochemical signatures imply that the Bobby Cove magmas were not cogenetic with the undepleted back-arc basin tholeiites (Scrape Point or Venam’s Bight formations), though they may be cogenetic with the arc tholeiites (Mt. Misery Formation). Consequently, the Snooks Arm Group appears to record two distinct magmatic suites. There probably were two distinct volcanic plumbing systems fed by two different types of basalt.

The upper member of the Bobby Cove Formation is about 200 m thick and consists principally of volcanogenic turbidites, with rare rhyolitic tuffs (Bédard et al., 1999b). The contact between the upper and lower members is presumed to be conformable, although the contact is commonly occupied by thick (up to 100 m) tholeiitic ferrogabbro sills comagmatic with the tholeiitic rocks of the overlying cycle (Bédard et al., 1999a,b). Presumably the magmas exploited the mechanical weakness represented by this contact. The turbidites themselves have bulk compositions reflecting derivation from calc-alkaline rocks similar to those of the lower Bobby Cove (Table 1; Fig. 2), suggesting erosion and redeposition of unconsolidated, possibly originally subaerial tuffs. Notwithstanding, the absence of interbedded tholeiitic basalt implies that deposition of the Bobby Cove Formation took place during a period of quiescence in the back-arc tholeiitic basaltic system.

The entire upper Snooks Arm Group consists of alternating or simultaneous deposition of: (1) back-arc basin tholeiites; (2) arc tholeiites and calc-alkaline basalts to rhyolites; and (3) the erosion products of these two volcanic sequences during periods of volcanic quiescence. The distinction between the first and second volcano-sedimentary cycles lies mainly in the nature of volcaniclastic rocks found at their summits. The volcaniclastic rocks capping the first cycle (the Bobby Cove Formation) are a mixture of epiclastic and pyroclastic rocks, and in part represent the direct products of calc-alkaline volcanism. Those capping the second cycle (Balsam Bud Cove Formation) are principally epiclastic rocks emplaced by mass-flow currents following slope failure.

These deposits probably reflect a gradual waning of basaltic volcanic activity and incipient erosion of the basaltic volcanic edifice, though interbedded felsic tuffs in the basal part probably represent a brief recrudescence of activity from the calc-alkaline volcano responsible for the Bobby Cove deposits. Clast compositions in the large-scale volcaniclastic mass-flow deposits (debrisites; Kessler and Bédard, this volume) also suggest that erosion was not limited to the freshly erupted tholeiitic lavas and felsic pyroclastic debris, but also included deeper parts of the volcanic stratigraphy. The third cycle is incomplete, and only consists of tholeiites (Round Harbour Formation) essentially identical to some underlying tholeiites (Venam’s Bight Formation), though cross-cutting felsic dikes of calc-alkaline affinity similar to the Bobby Cove felsic magmas suggest a subsequent pulse of calc-alkaline magmatism.

3. Classification and petrography of pyroclasts

Pyroclast-rich rocks can be classified according to schemes proposed by Fisher and Schmincke (1984), whereby classification is based on grain-size: tuff (< 2 mm), lapilli tuff (2–64 mm), pyroclastic breccia (> 64 mm). In contrast, rocks with polygenic clast compositions, lack of vitric and vesicular clasts, and which have rounded clast shapes, are most easily considered and classified as epiclastic rocks: mudstone (< 0.06 mm), sandstone (0.06–2 mm), conglomerate (> 2 mm). The terms volcanogenic or volcanolithic may be added to distinguish them from other non-volcanic rocks. Rocks with intermediate features (i.e. with some pyroclasts, angular clast shapes, and a large vitric component) are classified according to Schmid’s (1981) classification which employs the epiclastic grain-size scheme, but with the added term tuffaceous: tuffaceous mudstone, sandstone and conglomerate. Deposits with abundant juvenile vitric and vesicular debris tend to be classified as pyroclastic, in comparison to those that contain abundant accessory and accidental lithic debris.

Rocks of the Bobby Cove Formation were affected by post-depositional hydrothermal circula-
tion, regional greenschist metamorphism, and syn- to post-obduction deformation. Chemical analyses were performed on relict fresh minerals, and by sampling large clasts (conglomerate, breccia, and lapilli in size). In the Betts Cove Complex (which includes the Snooks Arm Group), deformation was concentrated in the weak serpentinites and shales, so that the original sedimentary structures, clast morphologies and internal textures are nearly always preserved in the Bobby Cove rocks, especially in the coarser grained conglomerates and sandstones (Figs. 3 and 4). These primary structures and textures show little evidence of pervasive shearing, or extensive compactional flattening. It is common for both delicate scoria fragments with angular shapes, and angular crystal fragments in tuffaceous sandstones, to be perfectly preserved (Fig. 3A, B).

Table 2 summarizes the descriptions and interpretations of the various petrographic constituents observed in the tuffs of this study. Most significant are three types of mafic fragments. Types 1 and 2 fragments are aphanitic, non-vesicular to moderately vesicular, and tend to have a blocky shape. The clasts are finely crystalline or glassy basalt fragments, interpreted as juvenile pyroclasts produced by steam explosions. Type 3 fragments are scoriaceous and are also interpreted to be juvenile pyroclasts produced by magmatic explosions (Heiken and Wohletz, 1985; Kokelaar, 1986). Many of these mafic fragments are elongated (Fig. 3B), which can be interpreted as a diagenetic feature, the result of post-alteration compaction as a result of lithostatic pressure. However, many deposits contain equant clasts and scoria fragments (Fig. 3A,B; Fig. 4D–F), an observation that appears at odds with pervasive flattening as a result of compaction. Furthermore, fragments with equant shapes may contain elongated vesicles, some of which show elongation normal to the bedding planes. This appears to indicate that flattening of vesicles is not as a result of compaction, but is a primary feature of the clasts.

Crystals of feldspar, pyroxene and hornblende are abundant in the Bobby Cove deposits. These crystals typically have shapes, sizes, proportions and compositions similar to those of phenocrysts found in the dominant lithic and scoriaceous fragments in the same beds. The crystals were derived from sources similar to those of the mafic clasts. Some of the crystals are partly to completely surrounded by thin turbid rinds of altered vesicular glass (Fig. 3A). The extremely angular shapes of the crystals, and the preservation of thin ‘glassy’ coatings are consistent with a mechanism by which most of the crystals were separated from their matrices during explosive eruptions. In addition, they suggest limited transport by currents.

Constituents of the finer grained material associated with coarse-grained tuffs cannot be distinguished optically. Their composition seems uniform and we infer that the fine-grained tuffs probably had compositions similar to those of the coarser-grained tuffs, which are mainly composed of fine glassy mafic debris with admixed free crystals of clinopyroxene, plagioclase and hornblende. The finer-grained tuffs locally display spherulitic structures (Fig. 3C). Such spherulites often form during early to late diagenesis of glass in lavas and tuffs (Lofgren, 1971).

4. Description and interpretation of facies

The Bobby Cove Formation forms a continuous band of volcaniclastic rocks, 16 km long, with an average thickness of about 500 m. The unit appears to thicken westwards (Fig. 1). Subdivision of rocks into facies is based on (1) petrography; (2) sedimentary textures and structures; and (3) rock-type association. The lower member of the Bobby Cove contains numerous facies and sub-facies with complex stratigraphic relationships. Coarser-grained facies (i.e. conglomerate and/or breccia) are better developed at the base of the formation. Coarse-grained facies with abundant felsic deposits are located only near the dacite tuff facies, in the central part of the formation. No transition to a felsic lava dome can be documented in the Bobby Cove Formation, though some of the rhyolites of the Balsam Bud Cove may represent such a feature. The upper member
Fig. 3. (A) Photomicrograph of coarse grained tuff turbidite TT1 bed (plane light, bar scale is 1 mm). Abundant fresh pyroxenes (X: medium light gray) and plagioclase (P: white to light gray) crystals, with type 1 light-colored non-vesicular basalt fragment (1; light gray), type 2 dark-colored basalt fragment (2; black), and type 3 vesicular to pumiceous basalt fragment (3; back with light gray dots). Note also coating of type 3 fragments on large pyroxene crystal marked X. (B) Photomicrograph of basaltic lapilli of the tuff lapilli tuff facies (crossed nicols, bar scale is 1 mm). A large type 3 fragments shows changes of vesicle shape from flattened along its edge (lower left) to elliptical (white dots, upper left); also note the rounded shapes of vesicles within the fragment (upper left corner) between adjacent pyroxene crystals (X). Type 2 fragments (2; lower one with small pyroxene crystals and some vesicles) are present, as well as type 1 fragments with the blurred contacts. (C) Devitrification spherulites aligned parallel to lamination in the upper part of a tuff turbidite bed; larger spherulites are developed in the finer-grained upper part of a TT1 bed. Scale in centimeters. (D) Tuff turbidite bed (TT1) with massive base overlain by diffuse parallel laminations. (E) Upper part of a TT1 bed with a protruding clast of basalt overlain by sets of TT3 beds. Lowermost TT3 bed begins by a fine grain sand division overlain by a mudstone division whose upper part is brecciated, scoured, and filled by angular to rounded mud pebbles, some imbricated. (F) Close-up of mud-rich TT3 beds that show parallel to undulating laminations and low angle scouring. Width is 10 cm.
### Table 2
Petrographic constituents of tuff turbidite and related facies

<table>
<thead>
<tr>
<th>Lapilli and coarse ash</th>
<th>%</th>
<th>Phenocryst</th>
<th>Vesicle</th>
<th>Size and texture</th>
<th>Nature</th>
<th>Origine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lithic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>20–40</td>
<td>CPX</td>
<td>No</td>
<td>&lt;0.25 mm, indistinguishable; 0.25–0.50 mm, blocky</td>
<td>Finally crystalline or glassy basalt</td>
<td>Steam explosion; thermal</td>
</tr>
<tr>
<td>Type 2</td>
<td>&lt;10</td>
<td>CPX, PL</td>
<td>&lt;15%; small</td>
<td>&gt;0.50 mm, irregular</td>
<td></td>
<td>Fracturing</td>
</tr>
<tr>
<td>Type 3</td>
<td>&lt;10</td>
<td>CPX, PL</td>
<td>&gt;70%</td>
<td>Irregular</td>
<td>Scoraceous basalt</td>
<td>Magmatic explosion</td>
</tr>
<tr>
<td><strong>Crystal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clinopyrone</td>
<td>5–40</td>
<td></td>
<td></td>
<td>Idiomorphic to broken; &lt;15.0 mm</td>
<td></td>
<td>Magmatic</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>5–20</td>
<td></td>
<td></td>
<td>Idiomorphic to broken; &lt;2.0 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amphibole</td>
<td>0–10</td>
<td></td>
<td></td>
<td>Broken; &lt;5.0 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine ash</td>
<td>10–15</td>
<td></td>
<td></td>
<td>Indistinguishable</td>
<td>Devitrified and recrystallized basaltic fine ash</td>
<td>Cannot be determined</td>
</tr>
</tbody>
</table>
of the Bobby Cove Formation only contains one facies. Vertical or lateral changes in the ratio of constituent rock-types are too insignificant to merit subdivision of the upper member into subfacies. Small, representative stratigraphic columns of the various facies described are presented with a map of the central part of the formation where all facies crop-out (Figs. 5–8 and 10).
4.1. Tuff turbidite (TT) facies of the lower member

The TT facies constitutes about 50% of the formation. This facies can be further subdivided into three sub-facies that are intimately interbedded with one another. The TT facies occurs at all stratigraphic levels and interfingers with all other facies present within the lower member of the Bobby Cove Formation (Fig. 5). TT beds have a monogenic composition with abundant mafic crystals and clasts interpreted to be pyroclastic in origin. This allows these rocks to be classified as either vitric or crystal tuffs (Schmid, 1981).

The most widespread TT subfacies is TT1 (Fig. 6), which consists predominantly of beds a few centimeters to several decimeters thick composed of medium to very coarse sand-sized debris. The TT2 subfacies is composed of thicker-bedded (up to a few meters) and coarser-grained (composed of coarse sand- to granule-sized) debris. Both TT1 and TT2 beds (Fig. 3D) exhibit a massive base or crude normal grading that passes up to crude and/or to well-defined parallel laminations at the tops. Dune- or ripple-sized cross-laminations are rare and laterally discontinuous in TT1 beds, whereas TT2 have bases with either clast- or matrix-supported pebble-size clasts. Typically, the massive division of TT2 beds is overlain by diffuse millimeter-thick laminae. These laminae are subparallel to one another, but laterally discontinuous on the scale of a few ten’s of centimeters. Debris within the laminae alternates between medium sand to granule in size. Some laminae also have trains of isolated or grouped sub-angular pebble-size clasts. Locally, large fragments protrude from the top of the beds (Fig. 3E). Pebble compositions are similar to those in the tuff breccia with some intraclast pebbles from TT1 and TT3 beds. TT3 beds are thinner (0.5–10 cm) and are composed of very fine- to medium-sand sized debris and mud. TT3 beds commonly show an incomplete set with a lower, medium-grained, normally graded division, overlain by finer-grained, parallel to low angle cross-laminated sands, followed by a laminated, muddier upper division. The upper division is laterally discontinuous and commonly fills, or is cut by low-amplitude arched surfaces (Fig. 3F). Other common sedimentary
Fig. 6. Stratigraphic column for a portion of the lower member of the Bobby Cove Formation, showing beds of the tuff turbidite facies.
structures in the tuff turbidite facies include slumps as well as numerous syn-sedimentary normal faults, indicating that deposition was syn-extensional. Load casts and flame structures are locally present at the contacts between overlying coarser-grained and underlying finer-grained beds. Well-bedded TT3 beds may pass within a few meters into a brecciated layer with angular to rounded mud pebbles, and then to a train of mud pebbles and granules within a thick bedded tuff turbidite (Fig. 3E).

TT1 beds are similar to those associated with decelerating flows containing a high concentration of sand-size debris, such as massive sandstones in proximal turbidites (Walker, 1978). Similarly, TT3 beds are interpreted to have formed as classic to distal turbidites by more dilute turbulent flows. Thicker TT2 beds were also emplaced by flows with a high concentration of debris. High particle concentrations can damp turbulence within flows and lead to en-masse freezing, thus producing massive divisions (Lowe, 1988). Alternating diffuse laminations of different coarse grained-size debris (sand to granule), as well as trains of isolated pebbles, are not solely produced by traction in low density turbulent flows (i.e. Tb). The laminae are thin and do not show well developed structures typical of traction carpets. However, large oversized clasts or trains of clasts, found either within the laminae or at the top of beds, imply mechanisms such as limited differential settling, dispersive pressure, and/or kinetic sieving (Lowe, 1980, 1988; Postma et al., 1988; Smith and Lowe, 1991; Kneller and Branney, 1995; Iverson, 1997). Whatever mechanism was dominant, the thickness of the diffuse lamination division requires rapid vertical aggradation with a high par

Fig. 7. Stratigraphic column for a portion of the lower member of the Bobby Cove Formation, showing contacts from the lapilli tuff-breccia facies to the tuffaceous conglomerate facies. Note channel feature (dotted line; center) and tuff turbidite interbeds in lapilli tuff — breccia. Upper contact of lapilli tuff — breccia with tuffaceous conglomerate is gradual. Both facies show similar structures, and distinction between them is based on composition. Lower contact between tuffaceous conglomerate and lapilli tuff — breccia is, however, sharp and both beds have markedly different texture and composition. Pie diagrams of clast counts show a higher proportion of accessory fragments in the tuffaceous conglomerate facies.
particle concentration. These flows probably had higher concentrations of particles and higher fallout rates than those that produced the TT1 beds.

Sedimentation from high- to low-density turbulent flows probably best accounts for the sedimentary textures and structures of the Bobby Cove pyroclast-rich TT facies. In marine turbidite models, coarse-grained beds are episodic events that alternate with background sedimentation, often pelagic mudstones. Pelagic non-volcanic mudstones are absent in the lower member of the Bobby Cove Formation. Furthermore, had pyroclasts rested for some time before resedimentation they would likely have been altered to some degree, and have been more prone to destruction during resedimentation. One would not expect delicate glassy rims or fragile scoria to be preserved. Most of the features found in the Bobby Cove tuff turbidites imply rapid, repeated, and sustained high sedimentation rates from pyroclast-rich flows, and suggest syn-eruptive deposition.

4.2. Breccia and conglomerate facies

Coarse-grained facies in the Bobby Cove Formation include a lapilli tuff-breccia (LTB), a tuffaceous conglomerate (TC), and a subordinate basaltic tuff-lapilli tuff (TL). Individual breccia and conglomerate beds are several meters to decameters thick, and can form compound sequences of tuff breccias and tuffaceous conglomerates up to 120 m thick. Individual beds can be traced a few hundred meters laterally. Clast compositions were determined both petrographically and geochemically.

The lapilli tuff-breccia (LTB) contains cobble- to block-sized clasts (Fig. 4A) that differ from one another by the proportion of vesicles and phenocrysts (Fig. 7). Decimeter-thick, crude- to well-defined bedding is accentuated by centimeter-thick tuff interbeds or by reverse, reverse-to-normal and normal grading of fragments. The beds are matrix- and clast-supported and show variation in structures or textures up section. Lapilli tuff-breccia beds (LTB) may pass vertically or laterally into the TC or TT facies. At one locality, LTB and TC beds abut a thin basaltic flow that is compositionally almost indis-
tistinguishable from the clasts in the LTB (Table 1). Locally, the lapilli tuff-breccia is cut by small, weakly chilled dikes with irregular contacts, suggestive of emplacement in soft sediment. These dikes are compositionally similar to those of the clasts and interbedded flows (Table 1).

The LTB facies is characterized by a monogenic composition with fragments that are possibly juvenile pyroclasts. Fragments in the LTB have a sub-equant, angular shape, commonly with a vesicular, plagioclase + clinopyroxene + hornblende-porphyritic core, and a partial rim of finer-grained, weakly-phyric, weakly-vesicular material. The finer-grained rims are inferred to have resulted from chilling of magma in water. Small fragments of detached rim material constitute a sub-population of clasts, giving a false impression of a bimodal clast population. Because the irregularly outlined fragments do not mold each other (Fig. 4B), their shape is almost certainly not a result of late diagenetic or tectonic processes, but probably records the evolving shape of hot pyroclasts as they cool and fragment during transport and deposition. Some LTB beds contain high proportions of elliptical or amoeba-shaped clasts characterized by complete fine-grained rims (Fig. 4C). Such shapes are similar to fragments in hyaloclastite breccias and seamounts (Cousineau and Dimroth, 1982; Doloz and Ayres, 1991). The LTB facies is not associated with pillowed or massive flows, nor emplaced hyaloclastite breccias, but rather pyroclast-rich mass flows. Clast shapes are interpreted as products of subaqueous fire-fountains (Kokelaar, 1986), with fragmentation produced during subsequent mass-flow emplacement.

Sedimentary structures in the LTB reflect rapid sedimentation from a succession of flows, or a succession of pulses within a flow. The monogenic clast population and sedimentary structures imply rapid, repeated, and sustained high sedimentation rates of pyroclast-rich flows, which would be best achieved if sedimentation was concurrent with eruption. Gravity and fluidization flow transformations could then explain in part the development of matrix-poor deposits as well as the presence of sandy interbeds by elutriation of finer grained debris from within the flow (Fisher, 1983; Huppert et al., 1986).

The basaltic tuff-lapilli tuff facies (TL) is less abundant than the LTB facies. TL beds are less than a few meters thick, and are composed of lapilli- and tuff-sized deposits with poorly defined upward thinning and fining sequences. Individual beds are mostly massive and poorly sorted, though sorting improves up section with development of normal grading and parallel laminations. Compared with the LTB facies, TL beds contain a greater amount of matrix and scoriaceous fragments. These features support an origin from a magmatic eruption, with sedimentation from subaqueously-erupted pyroclastic mass flows (Fiske and Matsuda, 1964; Stix, 1991; Cousineau, 1994).

The tuffaceous conglomerate (TC) facies (Fig. 4D, Fig. 7) differs from the LTB and TL facies in the following ways: (1) clasts are polygenic (presence of tuff turbidite, intermediate volcanic, dacite, mafic cumulates, mudstone fragments); (2) a clast-supported texture is common; (3) clasts are typically more angular or show a greater diversity in degree of roundness (attributed to mechanical abrasion); and (4) beds are generally thicker. There is a reduction in the diversity of mafic clast types in the sand-sized matrix, and a greater difficulty in identifying their morphology. Local derivation of clasts is probable because beds with abundant dacite fragments are located below and next to a dacite tuff (Fig. 5), and some large clasts have very high aspect ratios. Beds of the TC were emplaced by high density mass-flows, however, the compositions and textures indicate that the TC facies represents resedimentation of debris, which is only partly composed of juvenile pyroclasts. Schmid’s classification scheme can be applied in this case. TC beds could result from slope failure of a volcanic apron and/or of a dacite dome. High variability in clast composition and lack of background pelagic sedimentation imply that: (1) sedimentation occurred repeatedly and at brief intervals, possibly triggered by syn-volcanic tremors; and (2) that more than one stratigraphic level, or more than one source was sampled.

4.3. Mudstone-tuffaceous sandstone (MTS) facies

The mudstone-tuffaceous sandstone (MTS) facies represents less than 5% of the lower member
of the Bobby Cove Formation and is transitional to the upper member. This facies consists of centimeter- to decimeter-thick beds of sand-sized and mud-sized clasts (Fig. 8). Local beds of conglomerate, siliceous mudstone, and felsic crystal tuffs are also present. Less polygenic beds of sand-sized deposits are similar to those of the tuff turbidite facies. More polygenic beds are like those of the volcanolithic facies of the upper member. There are fewer scoriaceous fragments, but abundant altered quartz- and feldspar-phryic rhyolitic to dacitic fragments. Consequently, the MTS deposits are classified as tuffaceous sandstones and conglomerates. Sedimentary structures are similar to those found in sandy proximal turbidites (Fig. 4F); with structures such as normal grading overlain by parallel laminations and then mudstone (Table 2). The MTS facies could have formed by epiclastic processes in environments where turbidity currents are prominent, such as deep-sea fans. The violet color of the mudstones (partial oxidation of iron) and presence of siliceous mudstones, both suggest that these rocks formed near a volcano, where hydrothermal activity might have been operative.

4.4. Other facies of the lower member

A single thick (~150 m) lenticular body of dacite tuff caps the basal member near the East Pond outlet. The rock contains 15% fragments of basalt, diabase, and feldspathic hornblendite (1–2 cm in size). These are set in an entirely recrystallized matrix of quartzo-feldspathic composition with 40–80%, 1–3 mm-size, euhedral crystals of highly sericitized plagioclase, hornblende, magnetite and quartz. The virtual absence of visible sedimentary structures and intense recrystallization limits interpretation of depositional processes. The presence of this facies at the top of an otherwise mafic tuffaceous succession and its association with TC beds rich in clasts of similar composition suggests a shift towards more felsic volcanism.

Basaltic to andesitic, massive to pillowed lava flows compose only a few percent of the Bobby Cove Formation. The lavas are petrographically and geochemically (Fig. 2, Table 2; Bédard, 1999) almost indistinguishable from the dominant porphyritic basalt/andesite clasts of the TC and LTB facies.

4.5. Volcanolithic turbidites (VL) in the upper member of the Bobby Cove Formation

Rocks in the upper member of the Bobby Cove Formation (Fig. 9A) exhibit sedimentary structures typical of distal turbidites (i.e. Tabce, TbcF, Tce), with occasional thick to very thick, more massive beds (3–4 m) of coarser-grained material. There are no consistent upward fining or coarsening cycles (Fig. 10). The composition of the
coarser-grained sedimentary rocks throughout the volcanolithic (VL) facies is uniform. Mafic volcanic rock fragments, feldspar grains, felsic volcanic rocks, and volcanic quartz grains are all abundant (Fig. 9B). Mudstone beds are more abundant in the VL than in the MTS facies. The VL mudstones are typically dark gray, rather than violet, greenish or yellowish as in the lower member. Similarly, sandstones in the VL facies are medium gray, rather than greenish as in the TT and MTS facies. Grains in VL sandstones are also better rounded than in the lower member. The abundance of rounded grains of different composition supports an epiclastic origin. Successions of sedimentary structures (Tabcde, Tcde, Tae) and mudstone:sandstone ratios (about 1:1) are typical of classic turbidite deposits, and imply similar sedimentation processes and depositional environments.

5. Evolution of the sedimentary basin

Problems relative to the interpretation of the Bobby Cove Formation are similar to those of most ancient volcaniclastic rocks. Most important are: (1) the source volcano is not exposed; and (2) rocks are metamorphosed, folded and faulted. Emplacement models for these rocks may be constrained by several factors. The overall tectonic and paleogeographic setting is provided by the geochemistry of these rocks and of those from the bounding formations, and by the fossils contained in bounding formations. These data confirm and supplement information gathered by petrography and facies analysis.

Petrographic analysis of the various facies in the Bobby Cove Formation allows distinction of three groups on the basis of clast diversity and texture. Monogenic facies (TT, LTB, LT) are composed nearly exclusively of basaltic to basaltic andesite clasts. Clast morphologies in TT, LT, and possibly LTB facies are reminiscent of those reported from several other mafic volcanogenic deposits (Kokelaar, 1986; Ross, 1986; Cas et al., 1989; Dolozi and Ayres, 1991; Doucet et al., 1994) which were also interpreted as having formed by subaqueous pyroclastic eruptions of
phreatomagmatic origin. The polygenic VL facies, with its rounded fragments and lack of vitric vesicular mafic fragments, forms a second group which was probably derived through chemical weathering and mechanical erosion, as are many other epiclastic volcanolithic sandstones (e.g. Archer, 1984). The polygenic TC and MTS facies constitute the third group, which is characterized by diverse clast compositions and textures that vary from bed to bed. They are interpreted to have been derived from previously deposited, fresh and/or altered pyroclastic deposits with variable addition of accessory and accidental fragments.

Rocks of the Bobby Cove Formation were emplaced by mass-flow sedimentation. The absence of structures suggestive of terrestrial, nearshore or shallow-water sedimentation favors a deep-water basin. No fossils have been reported in this formation, though graptolites in bounding formations suggest a deep water environment. Sandstone beds of the VL and MTS facies regularly grade into, and alternate with mudstone beds. This could reflect alternating periods of mass-flow, triggered by episodic events, and more regular pelagic sedimentation. Mudstone interbeds are absent in the coarser-grained LT, LTB, and TC facies. Yellowish mudstone beds represent less than 5% of the TT facies and their close association with laminated medium- to very fine-grained tuffs favors sedimentation from a similar volcanic source rather than from pelagic suspension. Absence of mudstone interbeds in sets of successive near-identical beds of high density mass flow deposits can be interpreted as reflecting sustained sedimentation from rapidly succeeding flows, or from pulses within a single flow (Huppert et al., 1986; Iversen, 1997; Nemec et al., 1998). Mudstone-poor, pyroclast-rich facies could have been deposited from mass flows fed directly by subaqueous pyroclastic eruptions. Mudstone-poor facies with a more polygenic clast composition could result from repeated, earthquake-generated slumping of volcaniclastic debris originally deposited closer to the vent.

Pillow lavas and pillow breccias occur in all formations of the Snooks Arm Group, indicating that eruptions were persistently subaqueous. However, depth of eruption cannot be ascertained solely by studying the Bobby Cove Formation. Clasts in various facies of the formation are vesicular. The presence of abundant vesicles in flows and pyroclasts has previously been used to infer eruption at shallow depth (Jones, 1969; Williams and McBride, 1979; Lackschewitz et al., 1994), but vesicular to highly vesicular basalts appear to be a common component of deep-water submarine arc volcanoes (Burnham, 1983; Dudás, 1983; Gill et al., 1990; Wright, 1996; Fiske et al., 1998). The massive influx of coarse pyroclastic debris marking the base of the Bobby Cove Formation records an intense, explosive mafic volcanic event from a calc-alkaline volcano (Fig. 12). The complex lateral and vertical distribution of facies and sub-facies in the lower member of Bobby Cove Formation, together with the widespread evidence for synsedimentation extensional faulting and slumping, support models of rapid deposition within a basin characterized by a fault-controlled topography.

Several models can be proposed to explain the mafic pyroclast-rich facies of the Bobby Cove Formation. Some models could have operated concurrently or subsequently during a single eruption or an eruptive cycle. Vertically-directed, phreato-magmatic eruption fed by continuous magma supply best explains the mafic pyroclast-rich facies of the Bobby Cove Formation. Using this model, steam cupolas and fire-fountains formed above the vent during paroxysmal eruptions (Kokelaar, 1986). Expansion of the buoyant plume (umbrella) is limited and the plume is transformed into a cloud with a high particle concentration. Large ejected blocks and bombs that cross the steam cupola could retain a plastic shape and develop a chilled margin (Kokelaar, 1986; Mueller and White, 1992). Most ejecta, however, would be comminuted to finer-grained debris (Kokelaar, 1986; Lackschewitz et al., 1994) then fall back and accumulate near the vent. Collapse of the plume generates a mass-flow which is fed nearly continuously by the ongoing eruption. Pulses in the eruption could lead to repeated collapse events generating closely-spaced sets of similar flows. The pyroclast-rich facies of the Bobby Cove Formation (TT, LTB, LT) could
Fig. 11. Depositional model for the facies of the lower Bobby Cove member. (A) The lapilli tuff-breccia and basalt tuff — lapilli tuff facies with their abundance of juvenile fragments probably resulted directly from a phreatomagmatic subaqueous eruption (right side of diagram). Fragments generated during collapse of fire fountains and/or of magma bubbles were rapidly entrained in a subaqueous mass flow that moved downslope. A resedimentation model (left side of diagram) is inferred for the tuffaceous conglomerate, following post-eruption mass wasting from the flanks of the volcano. If resedimentation is nearly concurrent with eruption, this model could also explain deposition of the lapilli tuff — breccia facies. (B) The tuff turbidite facies could result from a primary subaqueous eruption (right side of diagram) by a process similar to A, but this would imply greater production of ash-size particles. Also present are vertical gravity flows issued from the ash-laden eruptive plume, which move downslope as they reach the flanks of the volcano. Both mass flow processes could have operated at the same time. Again, this facies could result from mass wasting (left side of diagram), that occurred soon after (if not contemporaneously with) the eruption.
have resulted from such eruptions and could represent beds sedimented at some distance within the basin, down-slope from the vent (Fig. 11). More powerful, vertically-directed eruptions are presumed to produce pumice and glass-rich deposits, typically with a massive base overlain by a doubly-graded succession of tuff turbidite beds (Stix, 1991). Such deposits are not present in the Bobby Cove Formation, though such a succession is weakly developed in the TL facies, which contains the most vesicle-rich pyroclasts.

Another possible model is one in which debris is fed rapidly to the eruptive plume (umbrella) by closely-spaced eruptions and explosions. As the plume breaches the water surface, debris accumulates and forms a cloud that spreads laterally. Gravity instabilities develop along the lower boundary of this debris-laden cloud that subsequently generate vertical gravity currents. Debris is thus delivered to the ocean bottom much faster than by individual particle settling (Carey, 1997; Fiske et al., 1998). These currents probably continued to flow down the slopes of the volcanic edifice as they reached the ocean bottom. This mechanism could also generate the succession of mass-flows that formed the TT facies (Fig. 11).

Debris that accumulates near the vent of a volcano following a pyroclastic eruption will lie on a steep surface, near the angle of repose. Such areas are prone to earthquakes generated by volcanic tremors and explosions that can rapidly remobilize freshly deposited debris and resediment it into deeper parts of a basin, without substantially modifying the general composition of the original deposit. In subaqueous environments, freshly erupted pyroclastic debris may rest in shallow water, where it is susceptible to reworking by tidal currents and waves (Kokelaar, 1986). Even water currents generated by the pyroclastic eruption itself may affect both recently formed deposits and those concurrent with the eruption. All of these scenarios could have produced mass-flows responsible for the pyroclast-rich facies of the Bobby Cove Formation.

Near vent deposits from previous eruptions can also be affected by these processes. Debris from various styles of eruptions could be incorporated into the remobilized mass, increasing the propor-
tion of accidental and accessory fragments. The time elapsed between successive eruptions may allow seafloor weathering of debris, reducing the amount of juvenile vitric material. Volcanic tremors are at a maximum during eruptions, thus resedimentation of near vent deposits from previous eruptions is probably most frequent during eruptions. This would lead to the formation of interbedded deposits of monogenic, pyroclast-rich facies with polygenic, pyroclast-poor facies, and with facies of intermediate composition. This is the most probable scenario to explain the TC facies and its relationship to the bounding pyroclast-rich facies.

The transition from the lower to the upper member of the Bobby Cove Formation appears to coincide with a shift towards more felsic volcanism. Frequency of volcanic activity was rapidly reduced, allowing for enhanced weathering of near-vent deposits. Earthquake-triggered resedimentation of previously erupted deposits may occur even if there is no eruption occurring. The area affected by seismic tremors is very wide, and could induce landslides from surrounding, possibly older and/or inactive volcanoes. With waning of volcanic activity in the area, deeper, more heterogeneous portions of the volcanic edifice would be exposed by erosion. Coarse-grained clastic sedimentation in the basin would become more polygenic, and background pelagic sediments would have the time to settle and form mudstone interbeds. Hydrothermal activity may persist for some time. This scenario could explain the transitional nature of the MTS facies. As the volcano became dormant, sedimentation in the basin became dominated by epiclastic deposits of the VL facies. This is further supported by the widespread distribution of this facies in the upper member of the Bobby Cove.

The period of quiescence ended by the massive outpouring of tholeiitic basalt (Venam’s Bight Formation), signaling the beginning of a new cycle. However, if the rhyodacites and rhyolites of the second volcanic cycle (Balsam Bud Cove Formation) are considered to represent evolved equivalents of the Bobby Cove magmas, then this implies that the calc-alkaline volcano probably continued to fractionate as a closed system. This further implies that little or no basalt was being fed into the calc-alkaline volcano’s magma chamber, even though this was a period when there was voluminous tholeiitic volcanism (Venam’s Bight). This dichotomy of behaviour between the two systems (calc-alkaline and tholeiitic) supports the notion that the calc-alkaline and tholeiitic suites of the Snooks Arm Group had distinct plumbing systems and were not fed by the same parental magmas. A possible modern analogue for the Betts Cove-Snooks Arm Group is the southern Mariana arc, where arc tholeiites and dacite of the active arc erupt through an older boninitic basement which is being split by an active back-arc spreading center (the Mariana Trough) which erupts back-arc basin basalts (Fryer et al., 1998).

6. Conclusions

The Snooks Arm Group consists of alternating volcanic flow- and sediment-rich cycles. The Bobby Cove Formation represents one of the sediment-rich phases, with a lower member that formed largely by mafic pyroclastic activity. The upper member reflects epiclastic sedimentation related to weathering and erosion of a mature arc. The Snooks Arm Group conformably overlies the supra-subduction zone Betts Cove ophiolite. The shift towards a more explosive style of eruption relates to changes in lava chemistry from boninite (Betts Cove ophiolite), to arc tholeiite (Mt. Misery Formation, basal Snooks Arm Group), to back-arc basalts (Scrape Point Formation), and finally to calc-alkaline basalts and andesites (Bobby Cove Formation). The change in chemistry also relates to a change in tectonic setting from an expanding fore-arc oceanic crust to a progressively more mature magmatic arc/back-arc system. The abundance of pillowed flows and graptolite-bearing mudstones in bounding formations imply a persistent deep-water environment.

All facies in the Bobby Cove Formation result from mass-flow sedimentation, but can be subdivided into: (1) monogenic pyroclast-rich, and polygenic pyroclast-poor facies; and (2) mudstone-rich, and mudstone-poor facies. Lack of exposure of more proximal and more distal facies
of the Bobby Cove Formation, especially the critical near-vent facies, limits discussion of the exact mechanism that led to the formation of the various facies. Pyroclast-rich and mudstone-poor mass-flow deposits (tuff-turbidite, lapilli tuff-breccia and lapilli tuff facies) are intimately interfingered and were probably deposited from a rapid succession of high density flows with limited turbulence, and less commonly from lower density, more turbulent flows. They were possibly emplaced from subaqueous Surtseyen-type eruptions. What cannot be ascertained is whether the flows issued: (1) directly from pyroclastic flows or pyroclastic falls, modified or not by flow transformation; or (2) from remobilization of pyroclast-rich deposits formed from contemporaneous or near-contemporaneous eruptions. The tuffaceous conglomerate facies contains no mudstone interbeds, and interfingers with the pyroclast-rich facies. It is grouped with the pyroclast-poor facies because of its more polygenic, often locally variable, clast compositions and is interpreted to have resulted from rapid sedimentation contemporaneous with volcanism, but the debris was probably derived from previously deposited, near-vent volcanlastic deposits. Resedimentation may have been triggered by earthquakes associated with eruptions.

The uppermost facies of the lower member still contain a few pyroclasts, as well as the characteristic greenish color of the coarser facies of the lower member, but also contain maroon to purple mudstones, as well as sandy deposits resembling turbidites. The transition from lower to upper members of the Bobby Cove Formation is characterized by a progressive shift toward facies deposited from flows resembling classic turbidites, in conjunction with greater proportions of mudstone interbeds and more polygenic clast populations. The upper member is composed of only one facies, which is the most heterolithic in composition and the most mudstone-rich of all the Bobby Cove facies. The abundance of mudstone interbeds reflects extensive periods of quiescence, allowing for background pelagic sedimentation to occur. The more polygenic composition of this pyroclast-poor facies relates possibly to a greater diversity of source terranes as the calc-alkaline material is eroded away. Thus, in the Bobby Cove Formation, a combination of heterolithic composition and mudstone interbeds favors an epiclastic mechanism of deposition, while monogenic, pyroclast-rich compositions and the paucity of mudstone interbeds favor a more primary (pyroclastic) origin of deposits.

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