Epiclastic volcanic debrites—evidence of flow transformations between avalanche and debris flow processes, Middle Ordovician, Baie Verte Peninsula, Newfoundland, Canada

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Abstract

The Balsum Bud Cove Formation of the Snooks Arm Group, eastern Baie Verte Peninsula, Newfoundland contains intervals of epiclastic mafic volcanic debrites characterized by textures indicative of gravity flow evolution in a submarine setting. These proximal to distal and aggradational deposits record a downslope change from debris avalanche to cohesionless debris flow processes. This change involves the mechanical formation of small cobble to granular matrix due to apparent crushing and grinding of large, angular basalt clasts during downslope movement. This flow evolution has been studied in two measured sections in the Upper Debrite Member of the Balsum Bud Cove Formation along Snooks Arm. Avalanche and proto-debris flow deposits have been studied in the stratigraphically lower and more proximal section at Haggis Point. An upper and more distal section, Devil’s Splitting Table (≈ 20–30 m above Haggis Point), contains mostly channelized basalt-clast debris flow deposits which are chaotic or crudely inversely graded and amalgamated with the underlying flow units. Some inversely graded, cohesionless, debris flows observed at Devil’s Splitting Table contain basaltic clasts, 20–100 cm in diameter, supported at or near their tops. In an effort to better understand the flow dynamics of the debrites observed at Haggis Point and Devil’s Splitting Table, individual flow units in both sections were analysed to determine original flow thickness at initiation, slope angle at flow initiation, and flow velocity. Using equations from Takahashi (1978) (Mechanical characteristics of debris flow, J. Hydraul. Div. Am. Soc. Civ. Eng., 104 (HYB 8), 1153–1159) and Takahashi (1981) (Debris flow, Ann. Rev. Fluid Mech., 13, 57–77), which are applicable to both to subaerial and submarine debris flows, flow velocities ranging from 6.22 to 7.78 m/s were calculated for proto- and cohesionless debris flows at Haggis Point. Initiation slopes range from 12.3 to 16.7°. An avalanche deposit at Haggis Point attained a velocity of 28.87 m/s. Cohesionless debris flows at Devil’s Splitting Table had a range of flow velocities of 5.86–12.32 m/s at calculated slopes of 4.8–18.8°. With the exception of the avalanche velocity these examples are consistent with velocities observed or calculated for other high slope submarine debris flow deposits. The calculated initiation slopes and velocities indicate 5–11 km of potential avalanche/debris flow run-out in the Upper Debrite. The epiclastic volcanic apron observed in the Upper Debrite outcrops along Snooks Arm is progradational. It consists of a proximal apron dominated by avalanche and proto-debris flow deposits and a distal apron dominated by highly channelized cohesionless debris flows and sandy turbidites. © 2000 Elsevier Science B.V. All rights reserved.
1. Introduction

The Middle Ordovician Balsum Bud Cove Formation of the Snooks Arm Group, eastern Baie Verte Peninsula, Newfoundland contains a series of epiclastic mafic volcanic debrites characterized by textures indicative of complex gravity flow evolution. Specifically, these are proximal to distal, aggradational, deposits recording a downslope change from avalanche to debris flow deposition in a submarine setting. This change occurs, both as the result of, and due to, the apparent mechanical formation of matrix due to clast crushing and grinding of angular basaltic boulders during downslope avalanche movement.

We measured two sections in the Upper Debrite Member of the Balsum Bud Cove Formation along Snook’s Arm (Figs. 1 and 2). Haggis Point, the stratigraphically lower section contains mostly avalanche and proto-debris flow deposits, where clast grinding and crushing with primitive matrix development appears to be a major mechanical process. The upper section, Devil’s Splitting Table, is ≈20–30 m higher and contains mostly channelized basaltic clast debris flow deposits with fine-to-medium-grained basaltic matrix. These flows are chaotic or crudely inversely graded and are often amalgamated with underlying flows in what appear to be individual channel fills. We infer that these flows can support (20–100 cm in diameter) large clasts at their tops. The aim of this investigation is a better understanding of gravity current flow transformations in a transition from avalanche to debris flow processes. To this end, clast distribution patterns and recognizable flow units are compared between the two sections in an effort to construct a scenario for the progradation of an epiclastic submarine debrite sequence. Using equations from Takahashi (1978, 1981) and assumptions about clast and fluid concentrations, initiation slope angles of debris flows and initial flow velocities were calculated. These calculations, which are adjusted to submarine transport conditions, suggest debris flow run-out distances in the excess of 5 km and may be useful in texturally demarcating the boundary between proto-debris flows and avalanches.

The presence of angular, apparently crushed, clasts (the material for early matrix creation) in avalanche and proto-debris flow deposits, and of a strong, clast support capability in debris flows, suggest that other processes such as granular flow may occur in this depositional setting. Similar processes are thought to occur in subaerial debris flows in the Triassic/Jurassic of the Newark Basin, where Takahashi’s equations yielded similar results (to those obtained for the Upper Debrite) in initiation slope angle and flow velocity (Kessler and Manspeizer, 1994).

The epiclastic debrite in the Upper Debrite Member of the Balsum Bud Cove Formation may be a useful analogue for similar deposits in the Archean. Both the Ordovician and the Archean are characterized by intense arc-related volcanism and high relative sea level (Cousineau and Bédard, 2000). Such a setting allows ample opportunity for eruptive events and major faulting in back arc basins and the channeling of lava to the forearc along major faults, as occurs in the modern southern Mariana arc, a well documented example with strong similarities to the Balsum Bud Cove Formation (Fryer et al., 1998). Such events create a source for epiclastic debrite and sufficient topography for its downslope movement as avalanches and debris flows in a submarine environment. The added presence of paleogeographic information (water depth, salinity, etc) from fossil occurrences in Ordovician and younger epiclastic debrite sequences makes their comparison to lithogically and texturally similar, but unfossiliferous, Archean examples potentially useful for the accurate determination of depositional setting.
Fig. 1. Location of Betts Cove Ophiolite and associated cover rocks. Baie Verte Peninsula is shown in inset map. Balsum Bud Cove Formation across study area is indicated by widely spaced dots. Letter A represents Haggis Point measured section in Upper Debrite Member, Balsum Bud Cove Formation. Letter B represents Devil's Splitting Table section, also in the Upper Debrite Member.
Fig. 2. Stratigraphy of the Betts Cove Ophiolite Complex, Upper Snooks Arm Group, and Cape St John Group. The Balsum Bud Cove Formation is an approximately 800 m thick interval near the top of The Upper Snooks Arm Group. Though not fully measured, the Upper Debrite Member is approximately 150 + m thick.

2. Terminology

Avalanches are characterized as large dislodged rock mass flows which move rapidly ($\approx 10–100$ m/s) down generally high slopes ($10^\circ +$). Cas and Wright (1987), p. 302) view an avalanche as "...a mobile, fluidal, close packing of blocks and fragments which jostle, bump, push, collide, and fragment each other in transit." Finer-grained interstitial material or matrix has little effect on avalanche movement and is largely abraded during flow. Avalanches do not have pervasive internal deformation and are thus not coherent flows. Flow momentum and mobility are maintained by grain-to-grain collisions with progressive momentum transfer through the avalanching mass (Cas and Wright, 1987). Avalanche deposits are generally very poorly sorted with a mixture of megablocks (tens of meters + in diameter), boulder and cobble-size fragments, gravel, sand, and mud. Due to collisional breaking during transport, individual clasts are generally very angular and often form a jigsaw fit breccia.

Debris flows are defined by Costa and Williams (1984) as "...a rapid mass movement of granular solids (such as sand, gravel, cobbles, and boulders), water, and air as a single phase system." This gravitational downslope movement involves clast, fluid, and matrix interaction to the extent that coarser particles such as gravel, cobbles, and boulders can be supported in the body of the flow. The clast-support property requires that debris flows have a yield strength, which must be exceeded for movement (deformation) to begin. Movement begins in a basal zone of maximum shear stress where laminar flow, sliding, and rolling of clasts occurs. Further up in the flow, in a zone of lower shear stresses, the rest of the material is rafted along as a semi-rigid plug. Clast-support mechanisms and their rheology vary in debris flows. Many debris flows are supported mostly by the strength of their interstitial matrix, which contains varying amounts of clay. In addition, such cohesive debris flows are also supported by the buoyancy of the clasts as exerted by the matrix. However, the main support mechanism in debris flows with a sandy and/or gravelly matrix appears to be inertial grain interaction, and they act as inertial slurries or granular fluids (Kim et al., 1995). In such cohesionless debris flows with large clast concentrations, inverse grading with the largest clasts supported at or near the top of the flow is observed (Shultz, 1984). Normal grading and/or chaotic distribution of larger clasts is also observed in both cohesive and cohesionless debris flows and depends on turbulence, degree of grain interlocking, amount of matrix and location along the debris flow's path (Fig. 3). Shultz (1984) equates debrite grading style, texture, and volume of matrix to the relative importance of cohesion, clast interaction or dispersive pressure, and fluid behavior.

We propose the new term, proto-debris flow, to facilitate the discussion of debrite matrix creation in flows which appear to be transitional between avalanches and debris flows. A proto-debris flow represents the first stage of matrix formation by apparent clast crushing and grinding during avalanche flow. Proto-debris flows that are observed in two parts of the Haggis Point section consist of small cobble and gravel size clasts as matrix between angular boulder-size basaltic fragments. Further downslope movement of proto-de-
bris flows leads to formation of finer grained matrix and fully developed cohesionless debris flows.

3. Geological setting

The Balsum Bud Cove Formation of the Snooks Arm Group in the eastern Baie Verte Peninsula, Newfoundland was deposited as part of the cover rocks of the Betts Cove Ophiolite which was one of a collage (temporally fourth of five) of oceanic terranes (the Dunnage Zone) accreted to the Laurentian continental margin (the Humber Zone) during the Taconic Orogeny (Williams, 1979; Hibbard, 1983; Williams et al., 1988). Humber and Dunnage zone rocks are separated by the Baie Verte-Brompton Line (BBL) which formed as a suture where the oceanic Dunnage terranes overthrust the Humber zone (Fig. 1). The Betts Cove Ophiolite (a relic of Ordovician oceanic crust) and its associated cover rocks provide a record of marginal basin evolution and terrain accretion at this time (Dunning and Krogh, 1985; Bédard et al., 1999, 2000). The volcano-sedimentary conformable cover of the Betts Cove Ophiolite is the 4300-m thick Upper Snooks Arm Group (Hibbard, 1983) which contains the 800-m thick Balsum Bud Cove Formation near its top (Fig. 1). The Betts Cove Ophiolite is overlain by the basaltic lavas of the Venams Bight Formation which is, in turn, overlain by the Balsum Bud Cove Formation (Fig. 2). The Balsum Bud Cove Formation is overlain by the basaltic lavas of the Round Harbour Formation.

The Balsum Bud Cove Formation is divided into two members. The lower member consists of pelagites, volcanioclastic turbidites, tuffaceous sandstones, and basaltic lava. The pelagites are interbedded with volcanioclastic sandstones. Above this, interbedded felsic tuffs (some massive and up to 4 m thick) and black shale are observed with succeeding units of thin tuff beds. The black shale interbeds of the lower member contain a graptolite fauna from the Didymograptus bifidus zone, indicative of an early Llanvirn age (≈ 477 Ma) (Williams, 1992).

The base of the Upper Debrite Member of the Balsum Bud Cove Formation is defined at the first thick mass flow and, as will be discussed below, is related to the development of a volcanioclastic apron with both proximal and distal parts (Bédard et al., 1999). Two detailed sections measured on the northeast shore of Snooks Arm at Haggis Point (HP on Fig. 1) and Devils Splitting Table (DSP on Fig. 1) are the basis for this study.

In the Snook’s Arm section of the Upper Debrite, the lower part of the member is exposed at Haggis Point and consists of 45 m of mass-flow deposits which contain large fragments (up to 20 m in diameter) of massive and pillow ed basalt, leucoxene-rich diabase, basalt breccia, polymictic breccia, and felsic tuff (Fig. 4). The larger basaltic clasts (> 10 × 30 m) are pillow ed and grade out through a monomict basaltic breccia to a polymict conglomerate. Lava clasts are cut by thin (1–2 cm) pebbly sandstone dykes. This basal debrite interval is overlain by ≈ 50 m of amalgamated, coarse, channelized conglomerates or debrites with individual beds or flow units ranging from 0.4 to 5.0 m thick. Debris flow conglomerates have a matrix which contains clinopyroxene fragments (1–2 mm), saussuritized plagioclase (< 1–2 mm), and occasional sand-size basalt fragments in fine-grained, turbid chlorite + epidote matrix. Most clasts are basaltic or andesitic. At-
Devil’s Splitting Table, 24 m of this section was described. At the top of the Devil’s Splitting Table Section, a set of planar- and cross-stratified sandstones appear, followed by thin-bedded turbidite sandstones and pelagic mudstones. Above the Devil’s Splitting Table section, a further 100 + m section of channelized debris flow deposits in a distal volcaniclastic apron is observed. These debrites are interbedded with basin-plain turbidites and pelagites near their tops.

4. Descriptions of measured sections

Two accessible measured sections in the Upper Debrite Member of the Balsum Bud Cove Member, Haggis Point and Devils Splitting Table, were initially described (1:50 scale) along the northeast shore of Snooks Arm (Fig. 1). These sections, which are the main data base for this study, illustrate the main proximal to distal variations in debrite texture.

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**Fig. 4. Haggis Point measured section showing depositional processes and mechanically analysed debris flows. Letter A on section log indicates amalgamation surfaces between individual debris flow units.**
Fig. 5. Haggis Point (A) polymictic conglomerate/breccia from 7.8 to 8.3 m. Clasts are polymictic with chaotic distribution and fine grained to granular basaltic material as matrix. Diameter of tape measure is 17 cm. (B) Top of monomict breccia at 22.8–23.2 m, large clasts (outlined in black) supported at top of flow with crude clast ordering below. This is part of a proto-debris flow with a granular matrix. Length of pen is 13 cm. (C) Top of monomict breccia (1) with overlying muddy turbidity current deposit (2) which is, in turn, overlain by a basalt slab (3) shown in Fig. 5D. The three units are separated by black lines. The slab slid or was probably carried down slope by a proto-debris flow. The interval is from 22.8–23.5 m. Length of pencil is 16 cm. (D) Top of monomict breccia shown in Fig. 5C (1) with overlying basalt slab (3) (note pillows on viewer’s left). Basalt slab grades laterally and vertically into monomict breccia interval shown in Fig. 7A, B. Up is toward viewer’s left of picture. Length of hammer is 28 cm.

4.1. Haggis Point

Haggis Point (measured section, 42 m), is the stratigraphically lowermost measurable section in this study. Starting from the base, the lowest 15 m of the section is composed of five amalgamated flow units (1.5–4.0 m in thickness) of polymictic conglomerate containing cobble- and boulder-size clasts of leucoxene-rich diabase, basaltic breccia, and felsite tuff (Fig. 4). Clasts are mostly angular and range in diameter from 3.5 to 35.0 cm. with a generally coarse matrix material (coarse-grained, granule, even pebble size) between them. The angular shape of coarser clasts in the matrix suggests formation by grinding and crushing during continued downslope movement. The five amalgamated flow units observed in this interval are generally crudely stratified with chaotic bedding, poor sorting, or crude inverse grading (large clasts supported at their tops). Chaotic bedding with little size sorting of clasts is shown in the interval from 7.8 to 8.3 m (Fig. 5A), angular to sub-rounded clasts ranging in size from gravel to small boulders are scattered in a matrix of sand- to silt- size basaltic material. A discrete flow unit from 10.0 to 11.5 m appears to be
deposited in a shallow scour and has a $25 \times 60$ cm sub-rounded basaltic clast at its base whilst supporting a $25 \times 35$ cm clast at its top (Fig. 4). A thin mudstone unit at 14.9–15.1 m ends this episode of debrite deposition.

Beginning at 15.1 m, individual flow units of cobble and boulder debrites become more difficult to identify (Figs. 4 and 6). As shown on the detailed core log from 16.0 to 25.0 m, there are several zones where a group of boulders appear to be floating at the top of a flow unit, at 17.0, 18.0, 21.5, and 23.0 m, respectively (Fig. 6). Only the 17.0 and 18.0 m examples have clear bases and are recognizable as single, crudely inversely graded, debris flow units. The interval from 22.8 to 23.5 m is of major interest in understanding the mechanics of epiclastic debrite emplacement (Fig. 5B,C, Fig. 6). As Fig. 5B shows, the monomict breccia observed from 22.8 to 23.0 m consists of large ($15 \times 25$ and $20 \times 17$ cm) clasts supported at the top of a flow unit with crude clast ordering below. The small cobble-, gravel-, and granule-size clasts are very angular and appear to act as a matrix, which supports the larger clasts. Debrites

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Fig. 6. Haggis Point detailed measured section between 16.0 and 25.0 m. This interval illustrates the effects of deposition from proto- and cohesionless debris flows and the results of the down slope sliding of large basaltic slabs or blocks.
with these matrix characteristics are referred to as proto-debris flows in this study and are probably the product of clast grinding and crushing during downslope movement. The upper surface of this flow unit is irregular and shows some zones where granule and gravel-sized clasts show normal rather than inverse grading. This may indicate deposition from the main body of the flow rather than near the front or snout as suggested by the presence of the larger boulders (Fig. 5C). Two other features are visible in Fig. 5C. Just above the debrite material is a muddy unit \( \approx 10 \text{ cm} \) thick with planar and contorted vortex-like bedding and normal grading. Based on bedding characteristics, this probably represents a muddy turbidity current, between debrite emplacement events. Immediately above this muddy unit, are three basaltic slabs (one a pillow basalt) which lie on top of the debrite and muddy turbidite unit (Fig. 5C,D, Fig. 6). The base and main body of the pillow basalt is seen at the top of Fig. 5C and in Fig. 5D. These slabs (tens of meters in length) may have initially been carried down slope by debris avalanches and have advanced further by being carried by newly formed proto-debris flows. The pillow basalt slab shown in Fig. 5D grades laterally and vertically into the monomict breccia interval which is observed in Fig. 7A and B.

The interval from 25.0 to 34.0 m includes 6.0 m of mostly monomict, cobble to boulder, basaltic breccia which has sub-rounded to angular clasts with a large basaltic block (1.3 m in thickness) at its top (Fig. 8). Flow units are not easily recognizable though some differences are apparent higher in the section. The interval from 26.1 to 26.5 m consists of large clasts (10–20 cm diameter) with a matrix of smaller sub-angular to sub-rounded clasts (Fig. 7A Fig. 8). The lack of an ordered fabric in this flow unit indicates that clast size reduction is an ongoing process, and that grain support support mechanisms (whether through grain collision or a cohesive matrix) have only begun to develop.

In the section from 27.3 to 28.5 m the interval consists of angular basaltic clasts ranging in diameter from 2.0–25.0 cm and having the appearance of angular pieces in a jigsaw puzzle (Fig. 7B). Such features in subaerial avalanche deposits are referred to as ‘crackle or jigsaw breccia’ and are the result of in place, pervasive, fracturing of large rocks during down-slope avalanche movement and large clast collision (Yarnold, 1993). Since there is space observed between angular clasts in this interval, it probably represents a ‘jigsaw breccia’. The presence of numerous small angular basaltic clasts suggests that even more organization has occurred with the small clasts representing the beginning of matrix formation (Fig. 9). Though this matrix is not yet a true support mechanism, it may represent the earliest stages of proto-debris flow formation with clast crushing and grinding and lie between the first two stages of flow evolution shown in Fig. 9.

The remainder of the Haggis Point measured section from 31.0 to 42.0 m consists of sand matrix cohesionless debris flow deposits with matrix supported cobbles and boulders. Such cobble-dominated debris flows are generally disorganized as shown at 38.5 to 40.0 m (Fig. 7C). In addition, several parts of this interval contain massive and normally graded sandstone scour fills with occasional planar and cross bedding. Such a feature is shown at 34.8 to 35.6 m where massive and planar bedded, coarse-grained sandstone fill a scour (Fig. 7D). The sandy, more organized, upper part of the Haggis Point section probably represents deposition in the distal part of a submarine volcanioclastic (epiclastic) apron.

4.2. Devil’s Splitting Table

The Devil’s Splitting Table measured section is \( \approx 30 \text{ m} \) stratigraphically above the top of the Haggis Point section. The lower 9.0 m at Devil’s Splitting Table contains 12 separate flow units, either sandy or bouldery scour fills or amalgamated debris flows (Figs. 10 and 11). The conglomeratic flow unit from 0.2 to 0.8 m has inversely graded basalt clasts with diameters ranging from 2.0–4.0 cm at the base to 25 cm at the top (Fig. 12A). The matrix is generally medium-fine grained basaltic sand. This flow unit could be best described as a cohesionless debris flow with grain interactions supplying the principal support mechanism. This debris flow may be filling a scour in the top of the underlying flow and could
be, in part, channelized. It is amalgamated with the overlying flow. At 3.6–4.0 m a scour downslope into massive sandy (basaltic) material is observed (Figs. 11 and 12B). This scour is filled with granular basaltic material and appears to be part of a complex anastomosing channel system on the distal part of the volcaniclastic debris apron surface.

In contrast to the inversely graded cohesionless debris examined at 0.2–0.8 m, a highly disordered flow unit is observed from 5.5 to 7.3 m (Fig. 12C). This flow unit consists of boulder and cobble size basaltic clasts in a sandy and silty matrix with virtually no discernible pattern of size sorting. This totally disordered interval contains elongate boulders standing on end and complete scattering of clast sizes throughout. This indicates turbulent flow conditions in this cohesionless debris flow.

The upper part of the section (9.0–12.7 m) contains six inversely graded flow units with very large basaltic clasts at their tops and a sandy/silty matrix (Fig. 13). The largest of these clasts is $116 \times 42$ cm and is in a debris flow unit from 10.4 to 11.4 m (Fig. 12D). Considering the size and
apparent weight of this basaltic clast, the support mechanism of this debris flow must be in part cohesive, since inertial grain interaction may not be sufficient for the task. The remainder of the Devil's Splitting Table section from 12.0 to 17.65 m consists of scour fills with massive and tractive bedding deposited by high concentration sandy turbidity currents (Fig. 13). This turbidite deposition is punctuated by isolated, channelized, basaltic conglomerates that are the product of cohesionless debris flows. Of particular note, is a channelized debris flow deposit at 16.6–17.4 m which has inverse grading to disordered clast distribution upward of fairly large (up to 25 cm diameter) basaltic clasts (Fig. 14). Above this debris flow the section is dominated by sandy turbidity current deposits.

Debritate deposition at Devil’s Splitting Table appears to be largely the result of cohesionless debris flows, which depending on clast size, matrix strength and nature, and various flow parameters may be inversely graded or highly disordered. Rare normal grading is also observed.

Fig. 8. Haggis Point detailed measured section between 25.0 and 34.0 m. The transformation from debris avalanche to proto-debris flow processes with the formation of primitive matrix is observed in this interval.
5. Depositional mechanics

In an effort to understand flow transformations and dynamics of the debrite deposits observed in the Balsum Bud Cove Formation better measurements, estimates, and calculations of various flow parameters have been made. The ultimate aim of this quantitative analysis is calculation of reliable values for such properties as debris flow initiation ($\theta$) and depositional ($\gamma$) slopes, initiation ($U$) and depositional ($U_1$) flow velocities, and flow yield strength ($k$). These calculations allow us to predict debris flow run-out potential and better understand facies distribution on the epiclastic debrite apron. In addition, the results of these calculations allow us to better recognize flow transformations between debris avalanche and cohesionless debris flow processes and deposition (Fig. 9).

Following the lead of Kessler and Moorhouse (1984) and Hiscott and James (1985), who made calculations of such properties as yield strength, slope, and flow velocity, measurements and estimations of parameters like outcrop flow unit thickness, maximum and 16% ile large clast diameters ($d$), and flow initiation ($h$) and depositional ($h_1$) thicknesses were made. Values for overall debris flow density ($\nu_0$) and initiation/depositional flow thicknesses were derived from estimated values of clast and matrix concentrations ($C$ and $C_{du}$) and an assumption of an at rest flow unit porosity ($\phi$) of 0.30 (Beard and Weyl, 1973). Since virtually all the clasts in the studied flow units are basaltic, a clast density ($\sigma$) of 2.70 was used. Deposition under marine conditions was accounted for by a fluid density ($\rho_f$) of 1.03 (Table 1).

Equations for debris flow initiation/depositional slopes and flow velocities developed by Takahashi (1978, 1981) were used in our study (Table 2). These equations were chosen for their apparent general applicability to both cohesive and cohesionless debris flows (Chen, 1987). Most other velocity equations either apply only to muddy matrix debris flows or do not consider flow density or clast concentration variability (Chen, 1987). The Takahashi (1978, 1981) equations for slope and velocity are based on ideas by
Bagnold (1954) of dispersive pressure resulting from the momentum exchange between grains in neighboring layers and through collisions and near misses. This momentum transfer also involves intergranular fluid in the flow. This mechanism, which was the result of experimental work by Bagnold (1954), is in contrast to cohesive debris flow models where the main grain support is from the plastic strength of an interstitial clay slurry.

More complex debris flow support mechanisms define flow competence by equating the weight of the largest supported clast with the sum of buoyancy and cohesive strength in the flow (Johnson, 1970). Such a mechanism is more likely to support clasts in a clay/water slurry. Hampton (1975, 1979) states that dispersive pressure created by grain collisions in debris flows makes a major contribution to grain support in addition to the dominance of cohesive strength and buoyancy.

Fig. 10. Devil’s Splitting Table measured section showing depositional processes and mechanically analysed debris flows. Letter A on section log indicates amalgamation surfaces between individual debris flows.
Pierson (1981) adds a further support mechanism to plastic strength, buoyancy, and dispersive pressure. He believes that excess pore pressure contained between clasts and in matrix in a debris flow unit is necessary to support large boulders. Pierson states that up to 67% of debris flow yield strength, where large clasts are supported is accounted for by buoyancy resulting from excess pore pressure. Preservation of pore pressure to the extent of making this mechanism dominant does not seem likely in a cohesionless submarine debris flow.

5.1. Application of Takahashi’s equations

The Takahashi (1978, 1981) equations for debris-flow slope and flow velocity are given in Table 2. Solutions of the debris flow initiation (θ) and depositional (γ) slope equations require values for clast density (σ), fluid density (ρ), grain concentration (C_w), equilibrium concentration (C_{eq}), angle of internal friction (φ), and flow initiation thickness (h) (Tables 1 and 2). The value of the debris flow initiation slope angle (θ) is used as the slope where maximum flow velocity is
attained. The depositional slope angle ($\gamma$) represents the highest slope at which the flow will freeze and deposit. Solution of the Takahashi (1978, 1981) equation for debris flow initiation velocity ($U$) requires values for clast diameter (16%ile; $d$), acceleration of gravity ($g = 981$ cm/s$^2$), constant ($a = 0.042$), angle of internal friction ($\phi$), grain concentration ($C_g$), equilibrium concentration ($C_{du}$), fluid density ($\rho$), clast density ($\sigma$), flow initiation thickness ($h$), and initiation slope angle ($\theta$) (Tables 1 and 2). The value of the debris flow initiation flow velocity is used as the maximum velocity achieved by the flow. The depositional flow velocity ($U_1$), which represents the lowest velocity which will sustain the flow, is calculated by substituting the depositional flow thickness ($h_1$) for $h$ and the depositional slope angle ($\gamma$) for $\theta$ in the velocity equation (Table 2).

As stated, some of the parameters used for solution of the Takahashi (1978, 1981) equations must be estimated and the assumption for these estimations should be reviewed. The most impor-
tant assumption is that of an at rest flow unit porosity ($\phi$) of 0.30. This value is based on an average porosity for moderately to poorly sorted, medium to coarse-grained, mixed, wet, sand as determined by Beard and Weyl (1973). This paper is often used as a basis for porosity and permeability estimates in shallow marine sands and supplies the closest available analogy to pre-initiation, submarine gravity flows responsible for the Upper Debrite. Using a porosity value of 0.30, a baseline grain concentration by volume ($C_o$) of 0.70 is calculated ($1.0 - 0.3$) for a flow unit with an equal distribution of clasts and matrix. Using this baseline, $C_o$ was visually estimated for the eight flow units analyzed in this study with a range of 0.68–0.85 (Tables 3 and 4). Low values ($\approx 0.70$) indicated nearly equal amounts of clasts and matrix while higher values (0.80+) indicate a dominance of clasts. Values of $C_{du}$, the equilibrium concentration or grain concentration by volume once the flow is moving are normally in the range of 0.70–0.75 again based on relative clast/matrix concentrations (Takahashi, 1998). Values of $C_{du}$ range from 0.50 to 0.61 (Tables 3

Fig. 13. Devils Splitting Table detailed measured section between 9.0 and 17.65 m. This interval contains debris flow units with boulders supported at or near their tops.
and 4). $C_w$ is used as the proportion of basaltic material in calculating flow density ($\rho$) and depositional thickness ($h_1$). The value of $1.0 - C_{du}$ is used as the proportion of basaltic material in computing flow initiation thickness ($h$). The angle of internal friction (\(\gamma\)) is assumed to be 25° for the use of the Takahashi equations in this study. Since the angle of internal friction is not readily measurable in ancient deposits, this assumption is based on what material scientists think would be accurate for very coarse poorly supported debris (Takahashi and Barree, 1998). The 16% ile clast size diameter is used instead of the median clast size (Takahashi, 1981) in order to account for a small amount of cohesive support of very large outside clasts in some flow units.

In order to evaluate whether the computed initiation and depositional flow velocities from selected flow units in the Upper Debrite are realistic, the densiometric Froude number (Fr%) was calculated for each velocity. This dimensionless number is the ratio between inertial forces (velocity) and gravitational forces operating in a flow and is adjusted for a submarine setting. A value < 1.0 for Fr% indicates that gravitational forces dominate in the flow and it is said to be sub-critical. Such conditions in a debris flow indicate laminar flow with little turbulence and internal disruption within the flow. A densiometric Froude number > 1.0 indicates that inertial forces (velocity) forces dominate in the flow which is described as supercritical. Supercritical flows have surface waves, internal disturbances, and can develop full-

![Fig. 14. Debris flow unit at 16.6–17.4 m (between arrows and black lines, up is to reader’s right) containing angular to sub-rounded basaltic clasts (10–30 cm diameter) with crude inverse grading to disordered class distribution. Larger clasts are supported at the top of the flow. Hammer is 28 cm long.](image-url)
scale turbulence. A densiometric Froude number > 2.0 indicates highly turbulent conditions where debris flow deposits would have little or no clast organization.

5.2. Haggis Point — proto-debris flows and debris avalanches

Three flow units at Haggis Point were selected for calculation of flow thickness, slope, and velocity at flow initiation and deposition (Fig. 4, Table 3). Flow unit 1 from 17.0 to 18.0 m in the measured section is amalgamated with flows immediately above and below it and supports a 45 × 20 cm clast at its top (Figs. 4 and 6). This flow which is crudely inversely graded is interpreted as a primitive cohesionless debris flow with granular to small cobble matrix between cobble to small boulder clasts. This flow unit was calculated to have a flow density of 2.28 and a flow thickness

Table 3
Calculated debris flow properties — Haggis Point

<table>
<thead>
<tr>
<th></th>
<th>Flow 1</th>
<th>Flow 2</th>
<th>Flow 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section level (m)</td>
<td>17.0–18.0</td>
<td>21.5–23.5</td>
<td>26.5–29.8</td>
</tr>
<tr>
<td>Grain concentration (vol.) C_d</td>
<td>0.75</td>
<td>0.80</td>
<td>0.85</td>
</tr>
<tr>
<td>Equilibrium concentration C_{du}</td>
<td>0.55</td>
<td>0.58</td>
<td>0.61</td>
</tr>
<tr>
<td>Grain diameter (16% ile) d (m)</td>
<td>0.09</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td>Initiation thickness h (m)</td>
<td>1.45</td>
<td>2.52</td>
<td>4.50</td>
</tr>
<tr>
<td>Deposition thickness h_1 (m)</td>
<td>1.25</td>
<td>2.16</td>
<td>3.80</td>
</tr>
<tr>
<td>Flow density ρ</td>
<td>2.32</td>
<td>2.36</td>
<td>2.45</td>
</tr>
<tr>
<td>Initiation slope θ</td>
<td>12.3–13.3°</td>
<td>12.8–16.7°</td>
<td>13.1–18.4°</td>
</tr>
<tr>
<td>Deposition slope γ</td>
<td>0.9°</td>
<td>0.6°</td>
<td>0.4°</td>
</tr>
<tr>
<td>Flow velocity (initiation) U (m/s)</td>
<td>7.78</td>
<td>6.22</td>
<td>28.87</td>
</tr>
<tr>
<td>Flow velocity (deposition) U_1 (m/s)</td>
<td>2.11</td>
<td>2.87</td>
<td>7.90</td>
</tr>
<tr>
<td>Yield strength (dynes/cm²) k</td>
<td>3.78 × 10⁴</td>
<td>5.18 × 10⁴</td>
<td>5.98 × 10⁴</td>
</tr>
<tr>
<td>Froude number (density — initiation) Fr</td>
<td>1.87</td>
<td>0.95</td>
<td>3.17</td>
</tr>
<tr>
<td>Froude number (density — deposition) Fr'</td>
<td>0.51</td>
<td>0.45</td>
<td>0.90</td>
</tr>
</tbody>
</table>

a Proto-debris flow.
b Debris avalanche.

Table 4
Calculated debris flow properties — Devil’s Splitting Table

<table>
<thead>
<tr>
<th></th>
<th>Flow 1</th>
<th>Flow 2</th>
<th>Flow 3</th>
<th>Flow 4</th>
<th>Flow 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section level (m)</td>
<td>0.2–0.8</td>
<td>4.7–5.6</td>
<td>5.5–7.3</td>
<td>10.48–11.35</td>
<td>16.6–17.4</td>
</tr>
<tr>
<td>Grain concentration (vol.) C_d</td>
<td>0.67</td>
<td>0.75</td>
<td>0.72</td>
<td>0.68</td>
<td>0.70</td>
</tr>
<tr>
<td>Equilibrium concentration C_{du}</td>
<td>0.50</td>
<td>0.56</td>
<td>0.54</td>
<td>0.51</td>
<td>0.53</td>
</tr>
<tr>
<td>Grain diameter (16% ile) d (m)</td>
<td>0.11</td>
<td>0.15</td>
<td>0.13</td>
<td>0.18</td>
<td>0.13</td>
</tr>
<tr>
<td>Initiation thickness h (m)</td>
<td>1.03</td>
<td>1.15</td>
<td>2.48</td>
<td>1.34</td>
<td>1.18</td>
</tr>
<tr>
<td>Deposition thickness h_1 (m)</td>
<td>0.80</td>
<td>1.00</td>
<td>2.18</td>
<td>1.19</td>
<td>1.04</td>
</tr>
<tr>
<td>Flow density ρ</td>
<td>2.15</td>
<td>2.28</td>
<td>2.23</td>
<td>2.16</td>
<td>2.20</td>
</tr>
<tr>
<td>Initiation slope θ</td>
<td>9.8–11.8°</td>
<td>6.3–12.5°</td>
<td>4.8–12.3°</td>
<td>10.4–18.8°</td>
<td>6.7–12.1°</td>
</tr>
<tr>
<td>Depositional slope γ</td>
<td>1.1°</td>
<td>0.9°</td>
<td>0.4°</td>
<td>1.2°</td>
<td>0.6°</td>
</tr>
<tr>
<td>Flow velocity (initiation) U (m/s)</td>
<td>5.86</td>
<td>9.31</td>
<td>12.32</td>
<td>8.71</td>
<td>11.25</td>
</tr>
<tr>
<td>Flow velocity (deposition) U_1 (m/s)</td>
<td>1.33</td>
<td>1.01</td>
<td>2.11</td>
<td>2.90</td>
<td>2.98</td>
</tr>
<tr>
<td>Yield strength (dynes/cm²) k</td>
<td>1.05 × 10⁴</td>
<td>1.59 × 10⁴</td>
<td>2.96 × 10⁴</td>
<td>6.98 × 10⁴</td>
<td>1.23 × 10⁴</td>
</tr>
<tr>
<td>Froude number (density — initiation) Fr</td>
<td>1.63</td>
<td>2.28</td>
<td>2.08</td>
<td>1.87</td>
<td>1.98</td>
</tr>
<tr>
<td>Froude number (density — deposition) Fr'</td>
<td>0.37</td>
<td>0.30</td>
<td>0.70</td>
<td>0.48</td>
<td>0.52</td>
</tr>
</tbody>
</table>
of 1.45 m at initiation and 1.25 m at deposition. Flow was initially down a slope of 12.3–13.3° with flow termination at 0.9° (Table 3). Flow initiation velocity was calculated as 7.78 m/s (Table 3). The maximum flow velocity for flow dissipation was calculated to be 2.11 m/s. Using the equations of Johnson (1970) (Table 2), the yield strength \( k \) was calculated to be \( 1.78 \times 10^4 \) dynes/cm² (Table 3). This yield strength is consistent with cohesionless debris flows of similar thicknesses studied by Kessler and Moorhouse (1984). The densiometric Froude number for the initiation flow velocity of 7.78 m/s was 1.87, which indicates supercritical, semi-turbulent conditions at flow commencement. A densiometric Froude number of 0.51 was computed for the depositional flow velocity 2.11 m/s suggests laminar flow at this time. Such conditions are consistent with the formation of crude inverse grading in cohesionless debris flows, just before or at deposition.

Flow unit 2 from 21.5 to 23.3 m in the measured section has an amalgamation surface at its base and carries large basaltic slabs (tens of meters in length) at its top. As mentioned, these slabs were initially carried downslope by debris avalanches and advanced further either by sliding over or being carried by newly formed proto-debris flows (Fig. 5C,D, Fig. 6). For purposes of flow property calculations, it is assumed that these slabs were carried by flow unit 2. Below these slabs, the main body of flow unit 2 is interpreted as a proto-debris flow with crude inverse grading and 20 + cm thick clasts supported at its top. The matrix between cobble and boulder clasts in this flow consists of small cobble, gravel, and granular size basaltic material. A flow density of 2.36 was calculated with initiation and depositional thicknesses of 2.52 and 2.16 m, respectively (Table 3). Flow movement initiated down a slope of 12.8–16.7° with deposition commencing on a maximum slope of 0.6°. Flow initiation velocity was calculated at 6.22 m/s with initial deposition being possible at 2.87 m/s (Table 3). Debris flow yield strength was 5.18 \( \times 10^4 \) dynes/cm², approximately three times that of flow unit 1. The densiometric Froude number for the initiation flow velocity in flow unit 2 was 0.95 indicating non-turbulent, generally laminar flow conditions. Such conditions should be common in proto-debris flows where a very coarse matrix separates large clasts, and continued downslope movement is as a granular flow with clast (especially matrix) grinding and crushing leading to size reduction (Savage, 1979).

Flow unit 3 from 26.5 to 29.8 m is a complex flow unit consisting of monomict basalt breccia with rare zones of basaltic matrix (Figs. 4 and 8). At its base flow unit 3 is amalgamated with a primitive proto-debris flow (Fig. 7A, Fig. 8). It is overlain by a large basaltic slab that was either carried downslope on top of flow 3 or slid over it (Fig. 8). The flow unit is dominantly composed of angular boulders and cobbles ranging in diameter from 2.0 to 25.0 cm and having the appearance of angular jigsaw fit pieces (Fig. 7B). Based on clast size and appearance with a lack of matrix, the flow unit is interpreted as a debris avalanche deposit. Flow unit 3 has a flow density of 2.45 with an initiation thickness of 4.50 m (Table 3). At the beginning of deposition flow thickness was 3.80 m. Flow initiated on a slope ranging from 13.1 to 18.4° with deposition beginning on a slope of 0.4°. Flow initiation velocity was calculated at 28.87 m/s with initial deposition being possible when the flows slows to 7.90 m/s on a lower slope (Table 3). Flow yield strength was calculated as 5.98 \( \times 10^4 \) dynes/cm², but is not be applicable if flow unit 3 is not a debris flow with a clast support mechanism. The densiometric Froude number was calculated to be 3.17 for the initiation flow velocity and 0.90 for the depositional flow velocity. These high velocities and densiometric Froude numbers suggest highly turbulent flow conditions well beyond those expected for either proto- or cohesionless debris flows in a submarine setting. Comparable submarine velocities (20 m/s) have been measured from cable breaks and modeled by various workers for debris slides/avalanches which appear to evolve downslope into debris flows and turbidity currents (Heezen and Ewing, 1952; Kuenen, 1952; Piper et al., 1985; Kirwin et al., 1986). Of particular note, is the debris slide/avalanche event off the end of the extended runway at Nice airport on to the Var Submarine Fan in 1979. Analysis of cable break
information and modeling by Mulder (1994) and Mulder et al. (1997) indicate initial velocities ranging from 36 to 43 m/s for slide, avalanche, and debris flow movement in the Var Canyon. The debris flow movement described here is probably similar to our debris avalanche movement. Depending on assumptions about flow viscosity, slide/avalanche initiation velocity may have been as high as 65 m/s (Mulder et al., 1997). The high slide/avalanche velocities mentioned above in the Var example are the result of supercritical flow down steep slopes ranging from 12 to 17°, not unlike the 13.1–18.4° computed for flow unit 3. The high calculated value for initiation velocity obtained for flow unit 3 by using Takahashi’s equations would suggest that this method applies to both debris flows and avalanches and is capable of yielding the high velocities and Froude numbers expected in the latter. Study of further examples from the Upper Debrite and other similar sequences in the future may help define a velocity and Froude number range between avalanches and debris flows.

5.3. Devil’s Splitting Table — cohesionless debris flows

Five flow units in the Devil’s Splitting Table measured section were selected for calculation of flow thickness, slope, and velocity at flow initiation and deposition (Figs. 10, 11, and 13, Table 4). These flows (numbered 1–5 in Table 4) are all cohesionless debris flows carrying cobble and boulder clasts with a well-developed matrix of medium to fine grained sand with rare muddy zones. With the exception of flow unit 3 (Figs. 11 and 12C) which has a chaotic clast distribution, these deposited cohesionless debris flows all show some degree of inverse grading. Flow unit 1 from 0.2 to 0.8 m in the measured section is inversely graded with basaltic clasts up to 25 cm diameter at its top (Fig. 12A). At its base the flow unit fills a scour in an underlying cross-bedded flow. Flow 1 had a calculated flow density of 2.15 with a flow thickness of 1.03 m at initiation and 0.80 m at deposition. Flow was initially down a slope of 9.8–11.8° with flow termination at 1.1° (Table 4). Flow initiation velocity was calculated at 5.86 m/s with initial deposition being possible at 1.33 m/s (Table 4). Debris flow yield strength was 1.05 × 10⁴ dynes/cm². The densiometric Froude number for the initiation flow velocity in flow unit 1 was 1.63 which indicates supercritical, but not necessarily turbulent flow conditions. Fr for depositional flow conditions was 0.37 which indicates subcritical laminar flow conditions. These conditions are consistent with the well developed inverse grading observed in the outcrop. With the exception of a much higher initiation flow velocity (9.31 m/s) and densiometric Froude number (2.28) flow unit 2, an inversely graded cohesionless debris flow with larger clasts near its top, has similar flow properties to flow unit 1 (Fig. 11, Table 4).

Flow unit 3 from 5.5 to 7.3 m in the measured section has a highly disordered and chaotic, cobble and boulder, clast distribution in a sandy and silty matrix (Figs. 11 and 12C). The flow unit has a density of 2.23 with a flow thickness of 2.48 m at initiation and 2.18 m at deposition (Table 4). Flow initiated at a slope of 4.8–12.3° with deposition commencing at 0.4°. The velocity at flow initiation was calculated as 12.32 m/s with a densiometric Froude number of 2.08 (Table 4). The high velocity and densiometric Froude number indicate that this cohesionless debris flow was supercritical and likely turbulent at initiation. Despite a velocity of 2.11 m/s at the beginning of deposition and a densiometric Froude number of 0.70, both indicating laminar flow conditions, there is little clast ordering upon the deposition of flow unit 3. Debris flow yield strength was 2.96 × 10⁴ dynes/cm².

Flow unit 4 (10.48–11.35 m in the measured section) is a cohesionless debris flow with a very large clast (116 × 42 cm) supported at its top (Fig. 12D, Fig. 13). Calculated values for thickness, slope, and velocities are similar to those obtained for flow units 1 and 2 and little difference between the flows is apparent (Table 4). However, the yield strength for flow unit 4 is 6.98 × 10⁴ dynes/cm², the highest observed in this study (Tables 3 and 4). The high yield strength value suggests that more than inertial grain interaction is probably supporting the large clast at the top of the flow. Though not readily visible, the matrix may contain mud or silt and thus have some cohesive
strength. In addition, other support mechanisms such as pore pressure and various buoyancy phenomena may effect this flow.

Flow unit 5 from 16.6 to 17.4 m in the measured section is a channelized cohesionless debris flow which is inversely graded with a disordered distribution of basaltic clasts at its top (Figs. 13 and 14). This flow, which has an initiation velocity of 11.25 m/s and a densiometric Froude number of 1.98, occurs near the end of this cycle of Upper Debrite deposition and may represent some sort of partially turbulent surge event.

The cohesionless debris flows observed at Devil’s Splitting Table appear to be largely channelized as shown by the down-cutting erosional surfaces between some debris flow units (Figs. 11 and 12A,B). Though in part turbulent on initiation, most of the cohesionless debris flows observed here show at least some clast organization on deposition. These channelized flows are the distal facies equivalent of upslope debris avalanches and proto-debris flows similar to those observed at Haggis Point. The matrix and rounded clasts in these flows have evolved from upslope debris avalanches and proto-debris flows through clast shattering, crushing, and grinding during downslope movement.

5.4. Another application of Takahashi’s equations

Kessler and Manspeizer (1994) examined two channelized, subaerial, cobble-boulder, medium grained sand to granular matrix, debris flows which crop out in the Upper Triassic/Lower Jurassic Passaic Formation along the western border fault of the Newark Basin of SE New York State. These flows, which were mapped along their 12-km run-out, were analysed using the Takahashi (1978, 1981) equations for debris flow initiation and depositional slopes and velocities. Initiation slopes ranged from 10 to 12°. This high slope is no surprise, since provenance studies (boulders from the Rosetown dyke swarm to the north) show that the debris flows originated from a rift accommodation zone between the Newark and Hartford Basins (Ratcliffe, 1980). Depositional slopes ranged from 1 to 2°. Calculated initiation velocities from near the sediment source ranged from 9 to 12 m/s with depositional velocities of 2–4 m/s. Froude numbers ranged from 1.15 to 1.78 suggesting the possibility of moderate turbulence at flow initiation. Generally laminar flow conditions are indicated at deposition by Froude numbers of 0.61–0.79 and the presence of inverse grading with large boulders at the top of each flow unit. The matrix of these two debris flow units contains angular quartzite and carbonate granules which were crushed and ground into finer material during downslope transport. Though these debris flows were subaerial, solutions to the Takahashi (1978, 1981) equations suggest that similar types of downslope movement and deposition occurred in both the Upper Debrite and Newark Basin examples.

5.5. Implications of depositional mechanics

Measurements, estimates, and calculations of such flow parameters as flow density; flow initiation and depositional thicknesses, slopes, and velocities; flow yield strengths; and densiometric Froude numbers have helped us better understand downslope flow evolution in an ancient epiclastic (volcaniclastic) debrite apron. After first identifying debris avalanche, proto-debris flow, and cohesionless debris flow deposits from clast size and textural changes in outcrops of the Upper Debrite Member of the Balsum Bud Cove Formation, these parameters were useful in illustrating some of the differences between the processes responsible for such flows. As Tables 3 and 4 show, the debris avalanche example from Haggis Point has a very high flow density, yield strength, and initiation/depositional velocities with an associated high densiometric Froude number. These values are consistent with those from other proximal submarine slides and debrite avalanches and much larger than those obtained from the debris flow examples. Such results strongly suggest that flow movement and deposition is governed by factors other than grain interaction or cohesive strength, as in a debris flow. The differences between proto- and cohesionless debris flows as illustrated by the flow parameters is more subtle. At Haggis Point a proto-debris flow (flow unit 2) and very primitive cohesionless debris flow (flow
unit 1) have flow densities of 2.36 and 2.32, respectively, with similarly high yield strengths and depositional slopes (Table 3). However, flow unit 2 (the proto-debris flow) has a densiometric Froude number of 0.95, which indicates subcritical, non-turbulent, generally laminar flow conditions. Such conditions are consistent with proto-debris flow movement where coarse matrix separates large clasts and continued downslope transport involves granular flow with clastic and matrix grinding and crushing. The cohesionless debris flows, which were analysed at Devil’s Splitting Table, generally had lower initiation slopes which on the low end ranged from 4.8 to 10.4° (Table 4). These lower initiation slopes indicated a distal setting for these channelized cohesionless debris flows (Fig. 15). Other flow parameters vary greatly for the cohesionless debris flows. Velocities and yield strengths vary greatly depending on flow thickness, slope, maximum sizes of large supported clasts, and amount of cohesive support (Table 4).

6. Facies distribution in a volcaniclastic apron

The Upper Debreite Member as observed at Haggis Point and Devil’s Splitting Table was deposited as epiclastic debris probably generated initially by avalanches on the submarine flanks of a shield volcano. This depositional setting is indicated from the lithologic descriptions of
Cousineau and Bédard (2000) who observe thick (200+ m) sequences of pillow lavas and sheet flows with associated feeder sills in the Balsum Bud Cove Formation. These sequences are, in turn, overlain by the thick epiclastic debris avalanche and debris flow deposits examined in our study. These debris flows are almost certainly derived from the underlying volcanics. Such a depositional site is consistent with flow initiation slope angles ranging from 12.3 to 18.4° which were calculated for debris avalanche, proto-debris flow, and primary cohesionless debris flow deposits at Haggis Point (Table 3). As is illustrated by Fig. 15, the debris avalanche material moves downslope with large clasts and blocks being crushed and fragmented during this non-coherent flow movement. Beginning further downslope where Haggis Point (HP) is shown in Fig. 15, flow units look more organized than the more proximal debris avalanche deposits. Here proto-debris flows with crude inverse grading and gravel to small cobble matrix between cobbles and boulders begin to form after possible clast crushing and grinding during earlier debris avalanche movement (Fig. 9). Proto-debris flows were probably deposited either in swales or crude scours on the edges of debris avalanche material. Further downslope where Devil’s Splitting Table (DSP) is shown in Fig. 15, channelized cohesionless debris flows are observed. Cohesionless debris flows consist of either inversely graded or chaotically bedded basaltic clasts with a matrix of fine to medium grained basaltic sand with varying amounts of silt. Within channels debris flows are either amalgamated or scour into each other. Some channels in this lobate part of the epiclastic debris apron contain massive bedded sandy turbidites with cross-bedded intervals of varying thickness. Thin sheets of basin plain turbidites and mudstone, which immediately overlie the debrisites at Devil’s Splitting Table, are apparently distal to this channelized and lobate zone (Figs. 10 and 15).

From the base of the measured section at Haggis Point to the top of the section at Devil’s Splitting Table, the depositional setting becomes more distal (Figs. 4 and 10). Debris avalanche and proto-debris flow deposits grade upward into channelized cohesionless debris flows and thin basin plain turbidites. These vertical changes reflect changes in the location of debris avalanche origin, slope, and topography as deposition continues. As time progresses, the source of basaltic clasts is exhausted and the debris apron is abandoned. This change is indicated at the boundary with basin plain turbidites at the top of the Devil’s Splitting Table section.

A volcanic sedimentary fan on the submarine part of the La Fournaise volcano, Réunion Island, SW Indian Ocean has some similarities to the Upper Debrite deposits at Snooks Arm (Ollier et al., 1998). Sonar studies and coring show that the proximal fan contains sedimentary slides and debris avalanche deposits from 500 down to 2000-m water depth. Reworked finer sedimentary lobes are seen to be just distal to the debris avalanches. Since there seem to be some similarities to the Upper Debrite, at least in facies distribution, the 1500 m of slide/avalanche change in water depth can be used to roughly estimate potential flow run-out of the analysed flows at Haggis Point and Devil’s Splitting Table. Using the sine of computed flow initiation angles for the debris avalanche, proto-debris flow, and primitive cohesionless debris flow studied at Haggis Point, a range of flow run-out distances from 4753 to 7042 m was calculated. At Devil’s Splitting Table flow run-out distances for cohesionless debris flows were further, ranging from 6205 to 11 750 m using this method. These larger values resulted from lower flow initiation angles, inclusion of the channelized lobate part of the apron system, and possibly greater flow efficiency of cohesionless debris flows. The values for flow run-out in the Upper Debrite are essentially estimates, but seem reasonably consistent with the La Fournaise example and smaller landslides with debris flow characteristics studied by Iverson (1997).

7. Summary and conclusions

The epiclastic mafic volcanic debrites which we have studied in the Upper Debrite Member of the Balsum Bud Cove Formation, Baie Verte Peninsula, Newfoundland have been useful in helping us to understand gravity flows from debris
avalanche to cohesionless debris flow processes in a submarine setting (Fig. 9). The mostly monomict basaltic rocks studied here represent a rare opportunity to study a system where clast and matrix material densities are always the same, allowing for easy and accurate calculation of flow parameters such as flow density, initiation slope, velocity, and yield strength. In addition, this study helps the volcanic worker better understand the dynamics and results of the marine sedimentary processes which alter now cooled eruptives.

Conclusions about the deposits observed are as follows:

1. Cycles of submarine debrite emplacement show a complex downslope evolution from highly fractured and disordered clasts of debris avalanche origin to clast and matrix supported debris flows.

2. Downslope debris avalanche deposits evolve into proto-debris flows where cobble and boulder size clasts are carried in a gravel to small cobble matrix. Proto-debris flows are crudely inversely graded and represent the first stage of matrix formation due to clast crushing and grinding under granular flow conditions (Haggis Point).

3. Basalt slabs (tens of meters in length) may slide over (causing clast shattering, bed distortion, Neptunian dykes) or be supported and ride downslope on debris avalanches or proto-debris flows (Haggis Point).

4. Debris avalanche and proto-debris flow deposits as observed at Haggis Point indicate deposition in the proximal part of a debrite apron, perhaps in an upslope feeder valley.

5. Overlying channelized debris flows are either crudely inversely graded or have a disorganized clast distribution with a medium to fine grained basaltic sand size matrix. The principal support mechanism in debris flows of this sort is thought to be inertial grain interaction. Such flows are referred to as cohesionless debris flows and can support large outsize clasts (Devil’s Splitting Table).

6. Scour surfaces between individual and amalgamated cohesive debris flows in the Devil’s Splitting Table section suggest their deposition in channels in the lobate distal part of a debrite apron. Associated tractive sand and sandy turbidite channel fills are also observed in this part of the apron (Devil’s Splitting Table).

7. Since the both the Ordovician and Archean are characterized by intense arc-related volcanism and high relative sea level, the epiclastic basaltic debrite sequence in the Balsum Bud Cove may be a useful analogue (especially in a paleogeographic context) to similar deposits in the Archean.

The second part of this study involved the measurement, estimation, and calculation of such flow parameters as flow density, flow initiation and depositional thicknesses, slopes, and velocities; flow yield strengths, and densiometric Froude numbers in an effort to better understand flow evolution. Equations from Takahashi (1978, 1981) were used for slope and velocity calculations with the results being realistic for avalanches and debris flows and consistent with other analyses. Conclusions from these results included:

8. High initiation flow velocity and densiometric Froude number (28.87 m/s and 3.17, respectively) for a debris avalanche flow unit at Haggis Point suggest highly turbulent flow conditions, unlikely with debris flow movement. This velocity is similar to initiation flow velocities for other submarine debris slides/avalanches.

9. Based on a sub-critical densiometric Froude number, laminar, generally non-turbulent flow conditions are suggested for a proto-debris flow at Haggis Point. Such conditions are consistent with flow movement where coarse matrix separates large clasts and further downslope transport involves granular flow with continued clast and matrix grinding and crushing.

10. Five analyzed cohesionless debris flows at Devil’s Splitting Table had a range of initiation slopes which varied from 4.8 to 18.8° with initiation velocities which ranged from 5.86 to 12.32 m/s. Such variability is typical of cohesionless debris flows and dependent
on other factors like flow density, flow thickness, maximum size of large supported clasts, and amount of cohesive support.

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