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“Bottomsets” of the lava-fed delta of James Ross Island Volcanic Group, Ulu Peninsula, James Ross Island, Antarctica

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Abstract: Sedimentological study of the three geographically separated outcrops of bottomsets of a single lava-fed delta (Pliocene) in the James Ross Island (Antarctica) allows recognition of six lithofacies. Deposits of traction currents, deposits of volcaniclastic debris flows and products of such flows transformations (both low- and high-density turbidity currents) and glacigenic deposits (subaqueous debris flows and traction/turbidity currents) were all recognised. Existence of submarine proglacial environment formed prior to formation of volcaniclastic deposits partly covering the subaqueous slopes of volcano is supposed. The principal role of mass flow processes was recognised and explained by relative steep slopes of the lava-fed delta. The distribution of lithofacies significantly differs in the individual outcrops. These variations in sedimentary succession and also in thickness of volcaniclastic deposits of “bottomsets” of the single lava fed delta suggest principal role of local conditions and paleogeography for development and preservation of this part of delta depositional system. Moreover proximal and distal setting can be followed and direct vs. more distant relation to over-riding lava-fed delta supposed. The sedimentary succession terminated by foresets of hyaloclastite breccia.

Key words: Antarctica, James Ross Island, lava-fed delta, lithofacies, Pliocene.

Introduction

Lava flows from land into the body of standing water become fragmented and may produce deltaic bodies with external morphology and internal stratigraphy analogous to that of alluvial Gilbert-type deltas (Nemec 1990a; Porębski and Gradziński 1990; Smellie 1999, 2006; Skilling 2002).

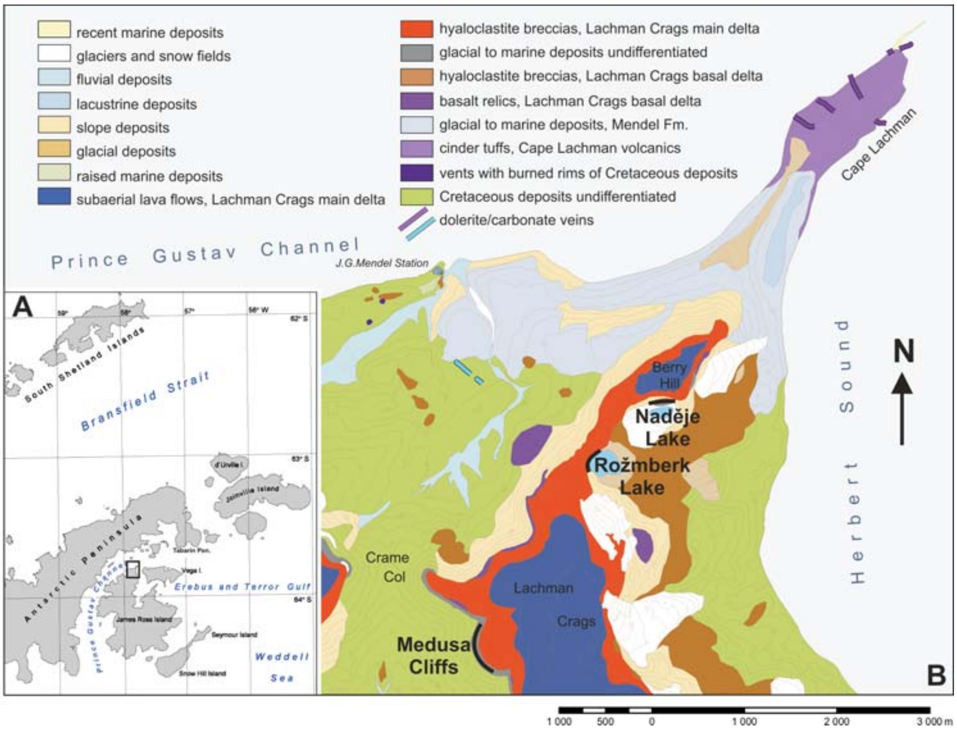


Fig. 1. **A**. Geographical sketch of location of the studied area. **B**. Sketch geological map of northern part of Ulu Peninsula, James Ross Island with studied sections indicated by thick black lines. Geology adopted from Nývlt *et al.* (2011) and Mlčoch (2013).

Gilbert-type deltas (Gilbert 1885) typically exhibit tripartite depositional system of sub-horizontal topsets (subaerial part), dipping foresets and sub-horizontal bottomsets (subaqueous parts; see Ethridge and Wescott 1984; Hwang and Chough 1990). The subaerial part is dominated by fluvial traction, mass debris flows and/or marine reworking (transitional part – Wescott and Ethridge 1980). The subaqueous parts (foresets and proximal bottomsets/toesets) are characterized by various sediment gravity flows such as rock falls, slides, slumps, debris flows and turbidity currents (Postma and Roep 1985; Nemec 1990a; Falk and Dorsey 1998). Suspension setting may be an important depositional process for distal bottomsets (Ford *et al.* 2007).

The descriptions of lava-fed (hydroclastic) deltas are much less common in the geological literature than the studies of alluvial deltas. Moreover foresets and topsets of hydroclastic (hyaloclastic) deltas attracted significantly more attention (Nelson 1975; Pirrie and Sykes 1987; Sykes 1988; Porębski and Gradziński 1990; Skilling 1994; Smellie and Skilling 1994; Behncke 2004; Smellie 2006; Smellie *et al.* 2008) than bottomsets (Hambrey *et al.* 2008; Nelson *et al.* 2009).

Spectacular outcrops of lava-fed deltas represent one of the most striking morphological features of the James Ross Island (Nelson 1975; Davies *et al.* 2013). This paper demonstrates results of a study of deposits recognised in the bottomset position (*i.e.* directly below foresets of hyaloclastite breccia) observed in the area of the Ulu Peninsula, James Ross Island during the 2013 field season. Location of the studied area is presented in Fig. 1A and lava-fed deltas in Fig. 2A. The main intention of the paper is to emphasize the important role of mass-gravity processes, paleogeography and local conditions for formation of these volcaniclastic deposits.

Geological setting

Over 5 km thick succession of deposits of the James Ross Basin (back-arc basin) of Aptian to Eocene/Oligocene clastic sedimentary rocks represents the oldest rocks cropping on the James Ross Island (Ineson *et al.* 1986; Crame *et al.* 1991; Pirrie *et al.* 1997; Francis *et al.* 2006).

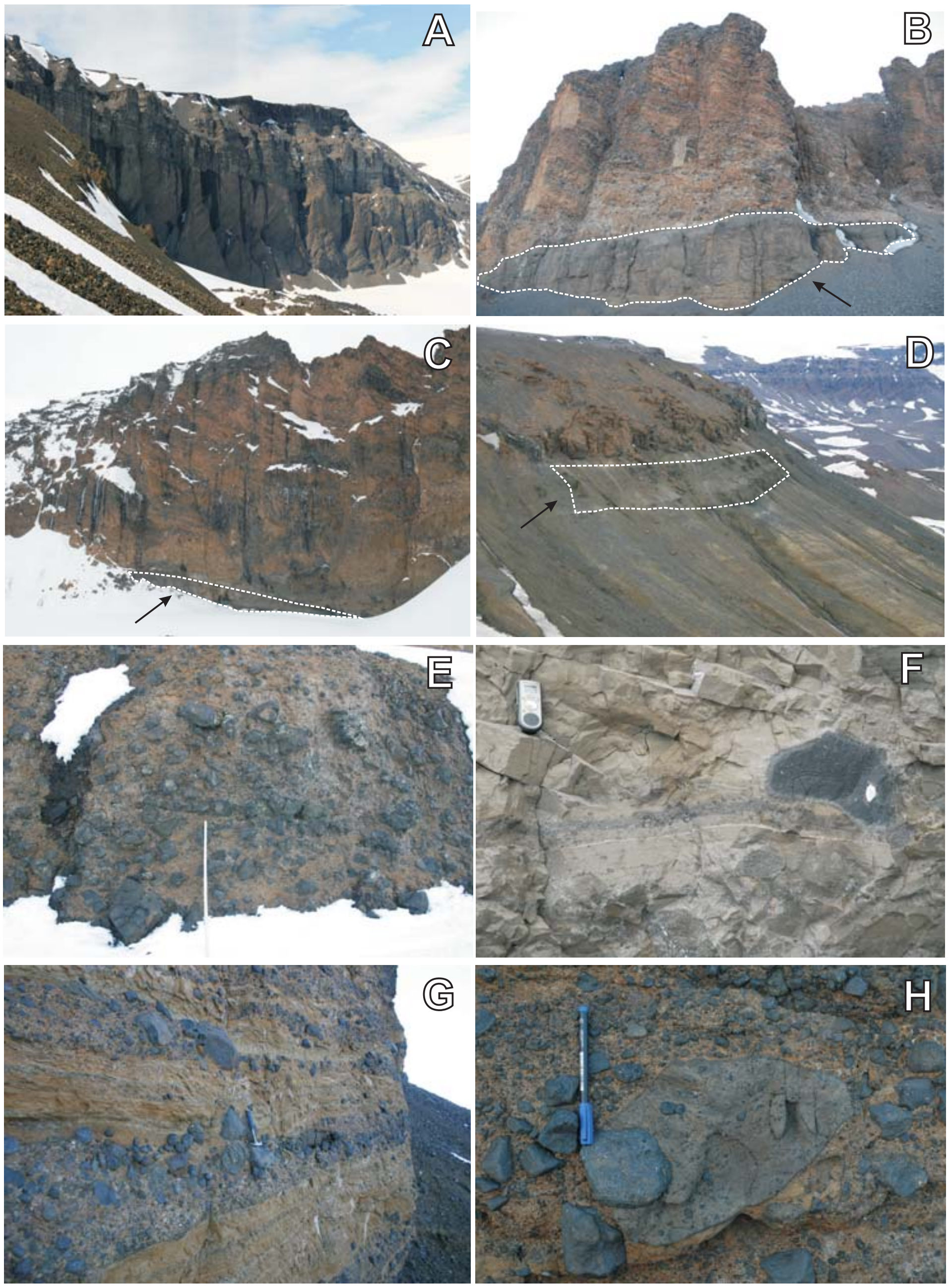
Several hundred meters thick succession of basaltic hyaloclastite breccias, alkali basalt lavas, and tuffs of the James Ross Island Volcanic Group (Late Miocene-Holocene) rest unconformably on the Cretaceous strata (Nelson 1975; Smellie 1999; Skilling 2002; Smellie *et al.* 2008, 2013; Hambrey *et al.* 2008; Košler *et al.* 2009). The James Ross Island Volcanic Group (JRIVG) is a large (c. 6000 km^2) basaltic volcanic field situated in northern Antarctic Peninsula (Nelson 1975; Smellie 1999; Smellie *et al.* 2008, 2013) dominating by the Mount Haddington stratovolcano. Persistence of volcanism over the last >6 million years resulting in at least 50 mainly effusive eruptions that are preserved predominantly as lava-fed deltas and a small number of tuff cones. Most of the eruptions took place during glacial periods (Smellie *et al.* 2008, 2013) and thus under glacier cover. Lava-fed deltas are represented by basalt lava''topset beds'' overlying much thicker steep-dipping homoclinal hyaloclastite breccia "foreset beds" (Nelson 1975; Skilling 1994, 2002; Smellie and Skilling 1994; Smellie 2006).

Thin, discontinuous but complex associations of coarse clastic sediments, described as "tuffaceous conglomerates", "marine tuffs" and "diamictites" (Bibby 1966; Nelson 1975; Hambrey *et al.* 2008; Nelson *et al.* 2009; Nývlt *et al.* 2011), are located between the Upper Cretaceous sediments and the volcanic strata, or between individual phases of volcanic rocks. They were originally described as the Hobbs Glacier Formation by Pirrie *et al.* (1997). However, further formations of clastic sediments below and within the JRIVG have subsequently been defined in this area (Jonkers 1998; Lirio *et al.* 2003; Smellie *et al.* 2006; Nývlt *et al.* 2011; Pirrie *et al.* 2011). The sequences are typically just a few metres thick, some of them could reach up to >100 m (Smellie *et al.* 2006; Nelson *et al.* 2009; Nývlt *et al.* 2011). The deposits comprise poorly sorted matrix-supported polymict conglomerate to pebbly mudstone diamictite with very poorly preserved marine fossils, and laminated volcanic sandstone or siltstone (Pirrie *et al.* 1997; Hambrey and Smellie 2006; Smellie *et al.* 2006; Hambrey *et al.* 2008; Nelson *et al.* 2009; Nývlt *et al.* 2011).

Description and interpretation of three previously unstudied outcrops of these deposits along the Lachman Crags volcanic mesa, northern part of the Ulu Peninsula (Fig. 1A) are presented in this study. Lachman Crags Mesa is the product of a monogenetic satellite centre located at its southern margin (Smellie *et al.* 2008) and three lava-fed deltas have been recognised here (Smellie *et al.* 2008, 2013). The formerly defined Lachman Crags basal, main and upper deltas (Smellie *et al.* 2008) have recently been renamed Cape Lachman, Johnson Mesa and Lachman Crags Formations by Smellie *et al.* (2013). The relics of Lachman Crags basal delta could be found around the northern part of Lachman Crags and Berry Hill Mesa (Fig. 1B; Mlčoch 2013; Smellie *et al.* 2013) and Lachman Crags upper delta is preserved only in the southern part of the mesa (Smellie *et al.* 2013). The Johnson Mesa Formation (*i.e.* the Lachman Crags main delta) represents one of the longest monogenetic volcaniclastic accumulations in James Ross Island. Deposits at Medusa Cliffs (Figs 1B, 2D) rest unconformably on the Cretaceous sediments of Santa Marta Formation, although the direct contact is covered by scree and are covered by the Lachman Crags main delta foresets, *i.e.* the Johnson Mesa Formation (Smellie *et al.* 2013). Outcrops at Naděje and Rožmberk Lakes (Figs 1B, 2B, C) crop out between the Lachman Crags basal and main deltas, *i.e.* the Cape Lachman and Johnson Mesa Formations (Smellie *et al.* 2013). The basal contact with hyaloclastite matrix-supported breccia of the Cape Lachman basal delta, was observed in the outcrop at Naděje Lake, but is not directly cropping at Rožmberk Lake site. Underlying breccia of Lachman Crags basal delta was dated at 5.32 Ma, which however differs from the age of the Cape Lachman volcanic island (5.85 Ma) given by Nývlt *et al.* (2011) and represents a different volcanic phase (and thus also a different formation) separated stratigraphically from Cape Lachman volcanic rocks by the Mendel Formation (Nývlt *et al.* 2011). The foresets of Johnson Mesa Formation lies in the direct superposition of the studied sediments at these two sites. The Lachman Crags main delta (the Johnson Mesa Formation) was dated at 5.04–5.08 Ma (Smellie *et al.* 2008). The studied sediments therefore occur at the same stratigraphic position, *i.e.* at the base of the Johnson Mesa Formation and their depositional age must be in the range 5.32–5.08 Ma, which means they developed during the earliest Pliocene.

Studied bottomsets are not completely flat, with bedding inclined between 7° to 15°. However such an inclination is much lower than the one of the overlying foresets (30° to 35°).

Fig. 2. Characteristics of the outcrop and structural features of the studied outcrops. **A**. Spectacular outcrops of lava-fed deltas represent one of the most striking morphological features of the James Ross Island. **B**. The studied outcrop at Naděje Lake, where foresets of Lachman Crags Main Delta directly cover bottomset deposits. **C**. The outcrop at Rožmberk Lake during the season 2013. **D**. Bottomset deposits at Medusa Cliffs are unconformably resting on the Cretaceous sediments of Santa Marta Formation and covered by the foresets of Lachman Crags Main Delta. **E**. Hyaloclastite matrix-supported breccia below studied bottomset deposits (outcrop at Naděje Lake). **F**. Light grey, brownish volcaniclastic laminated mudstone of lithofacies Ml with discontinuous interlaminas of →



volcaniclastic sandstone and scattered outsized clasts of dark basalts and vesicular glassy lapilli (Rožmberk Lake). **G**. Alternation of beds of lithofacies Svl (light brown yellow to reddish-brown laminated volcaniclastic sandstone) and lithofacies Cvm (matrix to clast supported structureless conglomerate with crude coarse-tail inverse grading) – Naděje Lake. **H**. Rip-ups of diamictites of lithofacies Dm were recognised within the beds of lithofacies Cvm. Clasts of dark basalts (the JRIVG provenance) strongly dominate.

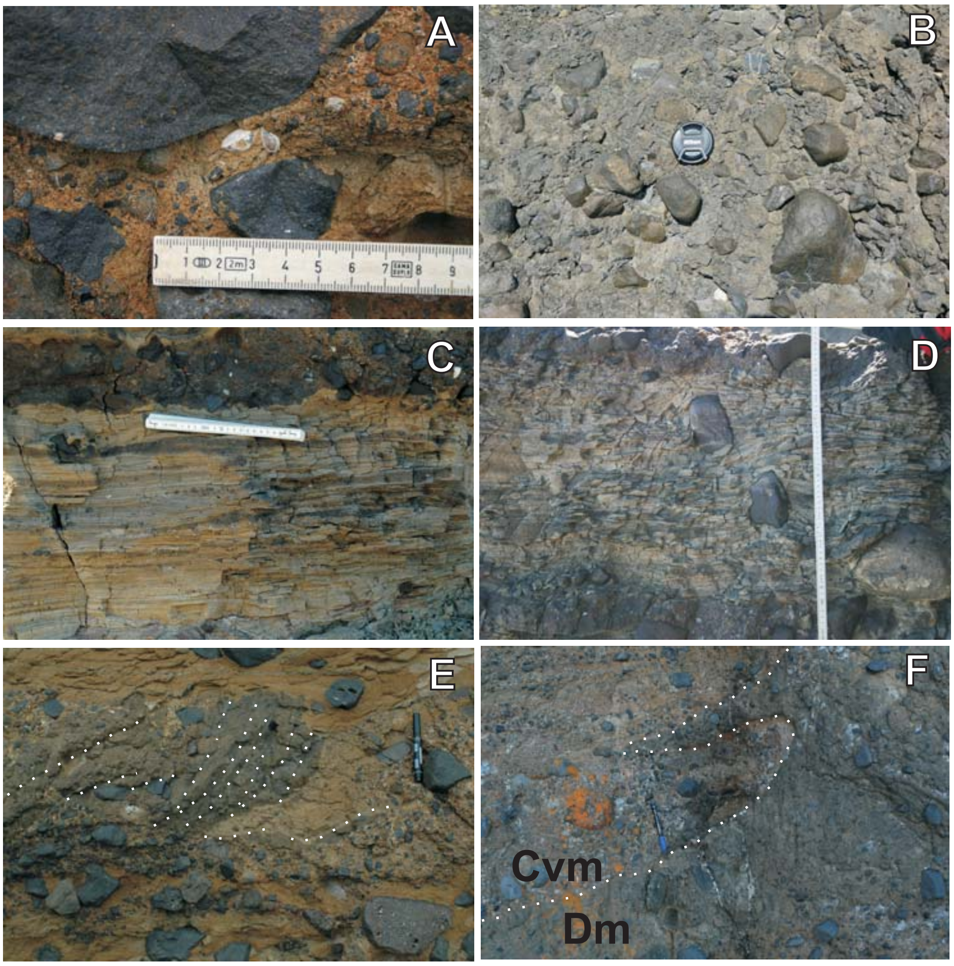


Fig. 3. Characteristics of the outcrop and structural features of the studied outcrops. **A**. Relatively well-preserved shells of brachiopods (*Terebratulida* gen et sp. indet.) were exceptionally documented within studied volcaniclastic (Naděje Lake). **B**. Pebbly mudstone diamictite of lithofacies Dm. Clasts of dark basalts of JRIVG predominate, whereas TPG phyllite or Cretaceous sediment are rare (outcrop at Medusa Cliffs). **C**. Laminated fine-grained sandstone to siltstone with interbeds/ interlaminas to thin lenses of gravelly sandstone represents lithofacies L. **D**. Rounded to subrounded lonestones (JRIVG provenance – dark basalts) within beds of lithofacies L. These outsized isolated clasts show penetration into underlying silty material, whereas upper contacts preserve a combination of onlap and compactional folding (Medusa Cliffs). **E**. Shearing deformations along the contacts of diamictites of lithofacies Dm and volcaniclastics (lithofacies Svl, Cvm) – (Naděje Lake). **F**. Plastic deformations along contact of volcaniclastic lithofacies Cvm and diamictite of lithofacies Dm (Naděje Lake).

Methods

Sedimentary lithofacies were estimated visually and documented in measured sections according to sedimentary textures and structures. The lithofacies subdivision and palaeocurrent estimation were following Tucker (2004) and Walker and James (1992). Thin sections were used for a more detailed description of some lithofacies. Relation between maximum particle size and bed thickness were followed in beds with outsized clasts in the finer matrix (Nemec and Steel 1984).

Sediment provenance was determined visually from clast lithologies. Division into four main clast and matrix lithologies previously recognised in the study area (Pirrie *et al.* 1997; Smellie *et al.* 2008; Hambrey *et al.* 2008; Nývlt *et al.* 2011): (A) Plutonic rocks (Antarctic Peninsula plutonic group – APPG); (B) Permo-Triassic Trinity Peninsula Group metasediments, phyllites and schists (TPG); (C) Late Neogene volcanic rocks (JRIVG); (D) Cretaceous back-arc marine sediments, was followed.

Results

Sedimentary lithofacies

Six lithofacies were recognised and their examples are demonstrated in Figs 2 and 3, whereas their distribution within the sedimentary profiles is presented in the Figs 4A, B, 5 and 6. The principal characteristics and a brief interpretation of lithofacies are presented in Table 1. The occurrence of individual lithofacies sig-

Table 1

The principal characteristics and a brief interpretation of recognised lithofacies.

Facies symbol	Description	Interpretation
Ml	Light grey, brownish to buff coloured volcaniclastic mudstone, mostly planar laminated, rarely were observed undulated or convolute laminations or normal grading. Discontinuous interlaminas of fine or very fine volcaniclastic sandstone.	Products of traction currents and/or low density turbidity currents
Cvm	Matrix to clast supported conglomerate, masive/structureless, crude coarse-tail inverse grading. Clast size varies between granule and cobble size. Pebbles and cobbles are commonly rounded to subrounded.	Products of volcaniclastic mass flows - volcaniclastic cohesive debris flow
Svl	Light brown yellow, orange to reddish-brown fine- to medium-, rarely coarse-grained volcaniclastic sandstone, plane-parallel laminated. Scattered pebbles or cobbles are relatively common.	Products of volcaniclastic mass flows – deposition from turbulent sandy suspension
Cvg	Very coarse volcaniclastic sandstone to granule conglomerate with coarse tail normal grading. Scattered pebbles exceptionally cobbles (up to 15cm in a-axis) were recognised along the base of the beds.	Products of volcaniclastic mass flows – deposits of high-density turbidity currents
Dm	Light brown, greenish grey, yellowish brown or brownish green very fine to fine muddy sandstone with scattered pebbles or pebbly mudstone, structureless/massive.	Glacigenic deposits - glacigenic subaqueous debris flows
L	Laminated fine-grained sandstone to siltstone. Subfacies L_1 is represented by light to whitish yellow laminated medium to fine sandstone, rarely muddy sandstone with interbeds of gravelly sandstone. Subfacies L_2 is formed by greyish fine laminated sandy mudstone, siltstone to muddy sandstone.	Deposits of relatively low velocity traction currents to turbidity currents

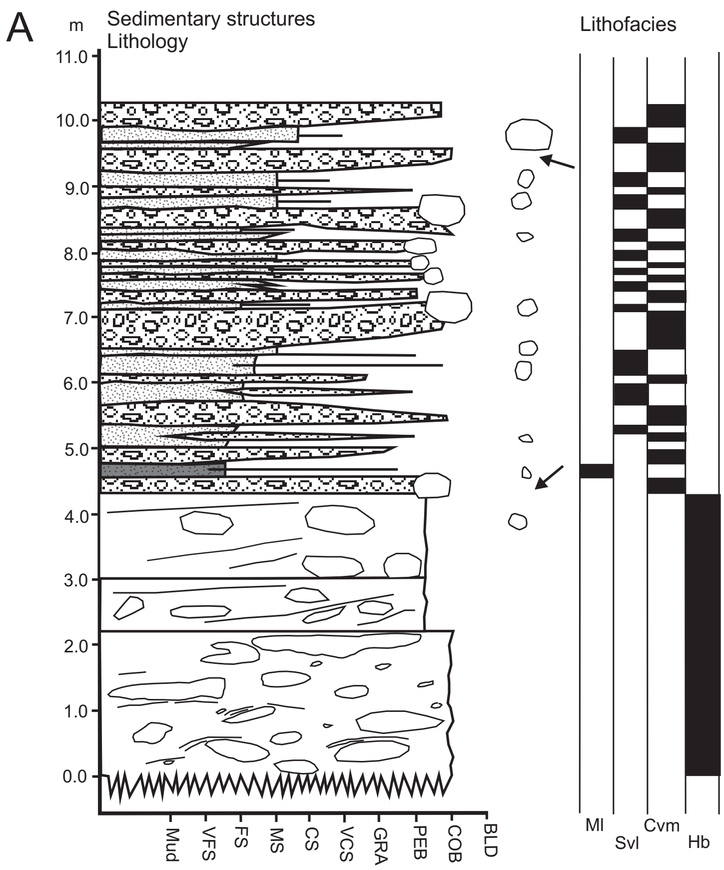
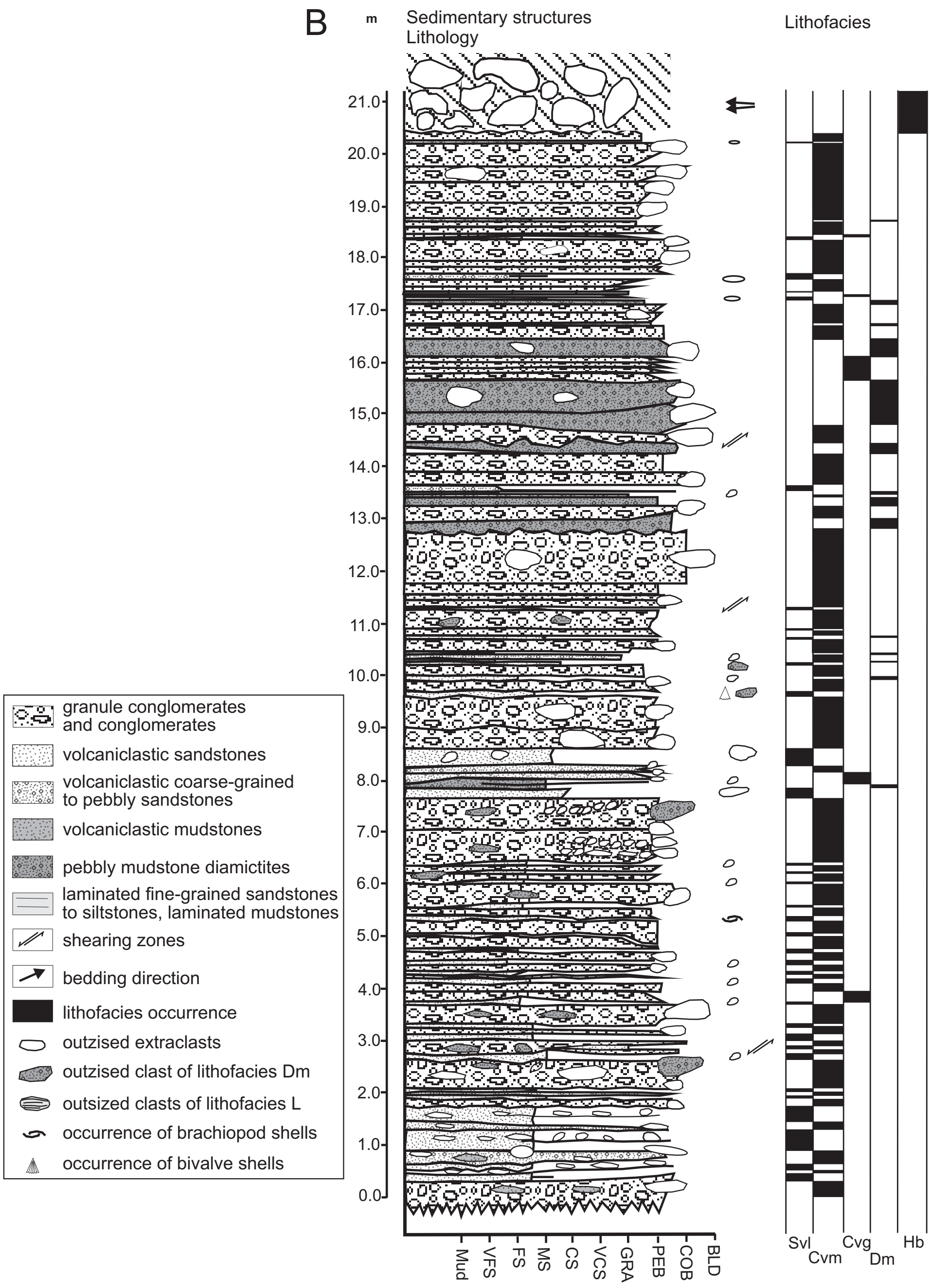


Fig. 4. Schematised sedimentary logs with distribution both of lithofacies and lithofacies associations for Naděje Lake locality. **A**. Eastern part of the outcrop/contact with basal contact with hyaloclastite breccia of Lachman Crags Basal Delta. **B**. Central and western part of the outcrop/composed profile.

nificantly differs in individual outcrops. Hyaloclastite matrix-supported breccia (Fig. 2E) underlying, cropping or exceptionally interbedded with the bottomset beds are assigned as further seven facies Hb (see Fig. 4A, B).

Lithofacies Ml is formed by light grey, brownish to buff coloured volcaniclastic mudstone (Fig. 2F). Mudstone is mostly planar laminated, rarely were observed undulated or convolute laminations. Normal grading was observed locally. Discontinuous (on the outcrop scale) interlaminas of fine or very fine volcaniclastic sandstone were also present. Variations in relative thickness of mudstone beds and abundance of sandstone interlaminas are common.

Lithofacies Ml strongly dominates (90% of the succession) at the Rožmberk Lake locality, where subrounded to subangular pebbles, cobbles and even boulders (more than 1 m in diameter) mostly of dark basalt (JRIVG provenance) have been documented within the lithofacies Ml. Outsized clasts of vesicular glassy lapilli are significantly smaller (several centimetres in diameter). Clasts are scattered without



preferred orientation or position. Soft sediment deformations of the hosted mudstone below the outsized clasts are present. The interbeds of lithofacies Cvm and also palagonite breccia (facies Hb) with thickness between 3 and 20 cm were commonly associated with lithofacies Ml at Rožmberk Lake locality. Maximum ob-

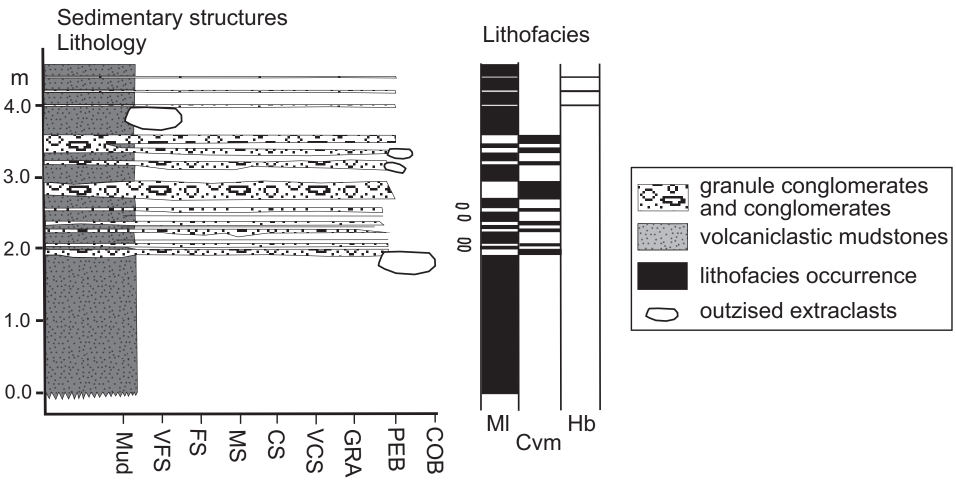


Fig. 5. Schematised sedimentary logs with distribution both of lithofacies and lithofacies associations for the Rožmberk Lake locality.

served bed thickness was over 1 m, but it usually reaches only several cm. Beds of lithofacies Ml have generally irregularly tabular shape, affected by subsequent erosion. The bases are sharp and irregular, because of the protruding irregularities from the top of underlying bed. The tops are also sharp and both erosive and non-erosive.

Isolated subrounded pebbles, max. 3 cm in diameter, were observed within the lithofacies Ml at the Naděje Lake locality, where the occurrence of lithofacies Ml is exceptional (forming only 0.1% of the succession). This lithofacies was not observed at Medusa Cliffs.

Interpretation: Planar lamination with variations in grains size of individual laminae points to layer-by-layer deposition of lithofacies Ml from traction currents and/or can be related to low density turbidity currents. Interbeds of lithofacies Cvm and Hb, together with similar petrography (nonvesicular basalt pebbles, ash to lapilli matrix) suggest their cogenetic relationship. Outsized basalt boulders with bedding sags are interpreted as debris fall and/or dropstones from icebergs. Pirrie *et al.* (1997) interpreted similar deposits as traction current deposits laid down at a delta front in a non-ice-contact proglacial setting. Similar deposits were described also by Hambrey *et al.* (2008) as reworked by traction currents.

Lithofacies Cvm is formed by matrix to clast supported conglomerate, structureless, commonly with crude coarse-tail inverse grading (Fig. 2G). Matrix supported domains prevail, although broadly lensoidal clast-supported domains are relatively common. Matrix is formed by coarse to very coarse volcaniclastic sandstone and granules. Clast size varies between granule and cobble size, probably with a dominance of medium to coarse pebbles, although outsized boulders (up to 0.65–1.2 m) are not exceptional. Pebbles and cobbles are commonly rounded to subrounded. Oc-

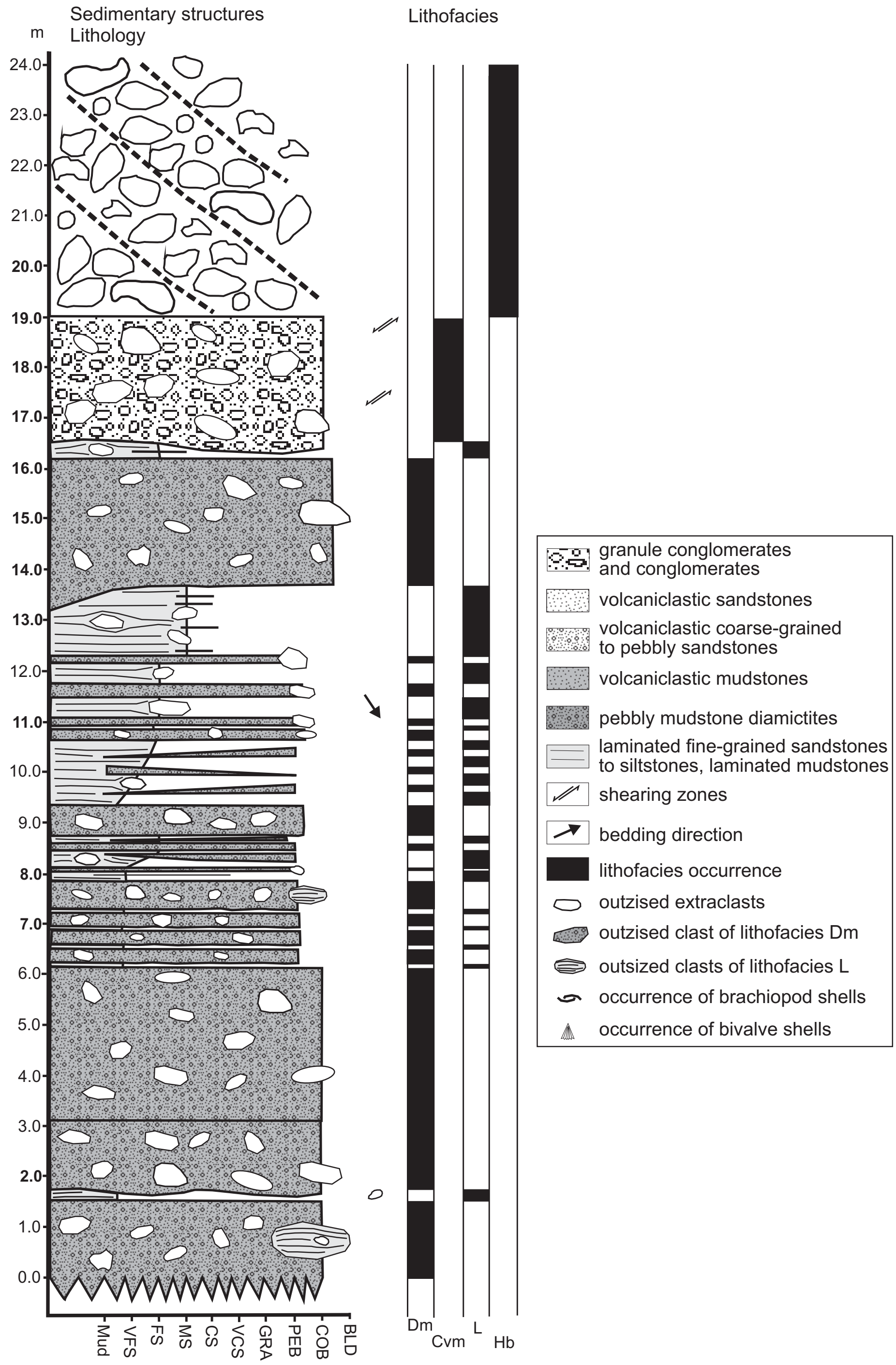


Fig. 6. Schematised sedimentary logs with distribution both of lithofacies and lithofacies associations for the Medusa Cliffs locality.

currence of outsized clasts is usually relatively higher along top or base of the beds, sometimes forming pebble clusters. Clasts are sometimes oriented sub-parallel with bedding (A p), but chaotic orientation generally prevails. The JRIVG provenance of clasts (dark basalts strongly dominates, hyaloclasts are rare) was mostly recognised. Basalts look fresh, unaltered. APPG-derived clasts (quartz conglomerate) and TPG-derived clasts (phyllites, metasediments) were observed very exceptionally. Rip-ups of diamictites of lithofacies Dm (up to boulder size) were common (Fig. 2H). They often reveal shearing deformations (irregular subhorizontal planes reflecting layer by layer shearing deformation). Bed thickness of lithofacies Cvm varied between 10 and 50 cm, amalgamated bedsets are common. Bases are irregularly flat or broadly concave, both erosive and non-erosive. Tops are irregular, commonly broadly convex up. Beds are lensoidal to wedge shaped; they laterally often terminated by discontinuous horizon of isolated large pebbles or cobbles. Shearing zones were recognised in some beds (Fig. 3E). Beds of lithofacies Cvm often erodes beds of lithofacies Svl or less commonly of lithofacies Dm. Lithofacies Cvm forms 69.6% of the succession at Naděje Lake locality; 16.7% at Medusa Cliffs and about 10% at Rožmberk Lake site. Relatively well-preserved shells of bivalves (Pectenidae sp.?) and brachiopods (Terebratulida gen. et sp. indet.) were exceptionally documented (Fig. 3A) at Naděje Lake locality.

Interpretation: Lithofacies Cvm represents deposits of volcaniclastic debris flow (Johnson 1984; Nemec and Steel 1984; Shultz 1984). Because the matrix is composed of coarse to very coarse sandstone and granules non-cohesive debris flows can be supposed as depositional phenomenon. However the relation between thickness of a conglomerate bed (BTh) and the bed's maximum particle size (MPS) (Nemec and Steel 1984) presented in Fig. 7 suits more to the cohesive debris flow *i.e.* subaqueous deposition of cohesive debris flows. To explain this situation we could speculate about small content of mud in the flow, which changed the flow behaviour. The origin of such mud could be (partly?) connected with a reworking and incorporation of glacigenic diamictites (see lithofacies Dm) into the mass flow. The experiments showed that relatively small amounts of cohesive mud changed the flow behaviour dramatically (Baas *et al.* 2011; Talling *et al.* 2012). These deposits are basically non-turbulent, with pervasive pseudo-laminar shear. Coarse clasts are supported by the strength and/or high viscosity of the sand size matrix, but may collide. Lateral transitions in sorting, grading style and internal structure are observed within individual beds, suggesting heterogeneity within flows. The high value of the positive correlation coefficient for lithofacies Cvm points to a consistency in the physical behaviour of individual debris flows.

Lateral variations/trends in distribution of matrix- and clast-supported domains and downslope coarsening, reflect differences in concentration, flow regime and momentum transfer (Nemec 1990a; Sohn *et al.* 1997; Blikra and Nemec 1998). A(p) fabric probably reflects clast shearing in the last flow stages, as the still mobile dispersion acquires a high concentration. Frontal clast stringers are

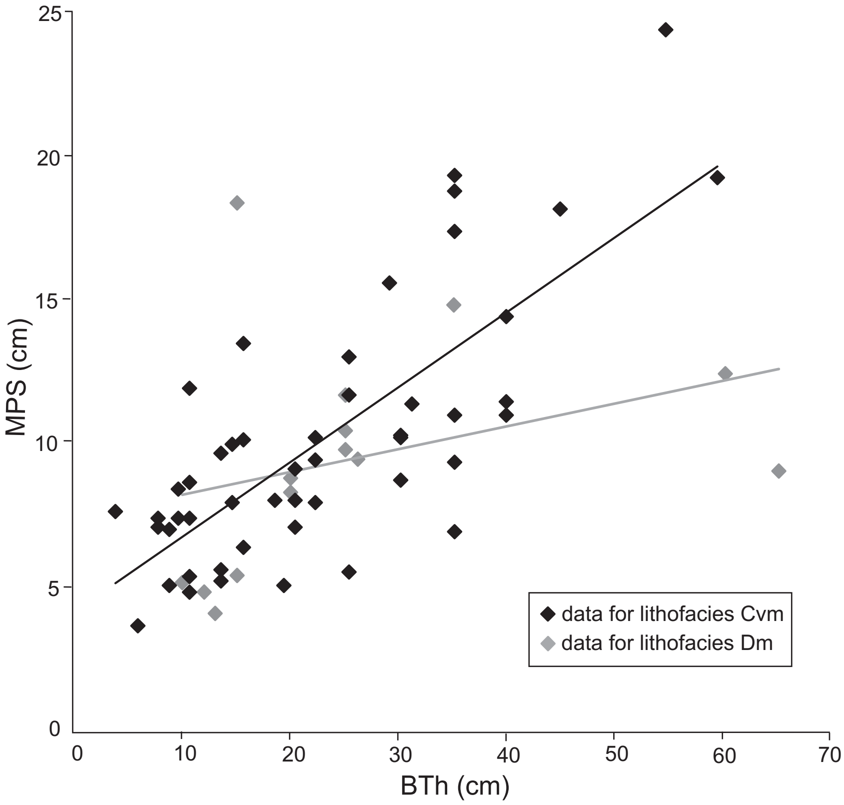


Fig. 7. The diagrams of the thickness of a bed (BTh) and the bed’s maximum particle size (MPS) (according to Nemec and Steel 1984) for studied deposits of gravity mass flows. Evidence of the cohesive strength factor (*i.e.* possible termination of the regression line within the MPS axis) was used for the classification of the debris flows. The regression line gradient was used as an evaluation of further clast supporting factors in flows (other factors than cohesive strength) and flow competence.

produced as outsized clasts roll ahead due to their high inertia (Kim *et al.* 1995). Basal scours indicate mobilization of unstable debris by descending flows.

The rounded and subrounded pebbles of basalt, together with the presence of rock varnish on clasts surfaces suggest redeposition of this material from older deposits. The content of distant (*i.e.* non-JRIVG or Cretaceous provenance) clasts was very low. They might be derived from local diamictite substratum and incorporated into the overriding gravity flows (Porębski and Gradziński 1990; Walker and Plint 1992; Sohn *et al.* 2008). We found no evidences of marine reworking. Occurrence of marine shells material demonstrates capability of submarine erosion and efficient vertical mixing occurred as the flow moved along the floor.

Debris flow deposits are subject to rapid flow transformation (Nemec 1990b; Falk and Dorsey 1998; Sohn 2000).

Lithofacies Svl is represented by light brown yellow, orange to reddish-brown fine- to medium-, rarely coarse-grained volcaniclastic sandstone, plane-parallel (sometime broadly undulated) laminated (resembles spaced/stepped bedding – Talling *et al.* 2012). Laminated appearance is defined by alternations of different grain sizes and segregation of layers with different colour (Fig. 2G). Laminas reveal thickness differences on mm scale. Discontinuous horizons of granules (lapilli) were followed. Scattered pebbles or cobbles (25 cm in diameter) are relatively common. Discontinuous pebble strings or pebble clusters were rare. Orientation of the a-axis of the outsized clasts was commonly parallel with stratification. Pebbles and cobbles are mostly subrounded, but subangular to rounded ones were also present. Basalts of JRIVG provenance predominate.

Beds of lithofacies Svl are broadly tabular, often discontinuous mostly due to erosion by superimposed lithofacies Cvm. The thickness of beds of lithofacies Svl varies from a few cm to 30 cm in amalgamated bedset. The bases of Svl lithofacies beds are sharp, flat, irregular or broadly undulated. Lithofacies forms 18.1% of the succession at Naděje Lake and was not recognised at Rožmberk Lake and Medusa Cliffs.

Interpretation: Lithofacies Svl often alternates with lithofacies Cvm. The thickness of the lithofacies Svl reaches commonly only few centimetres, which is many times less than the thickness of neighbouring lithofacies Cvm. The thin-bedded laminated deposits record chiefly a traction deposition from turbulent sandy suspension. Vertically segregated bipartite flows producing denser lower part (lithofacies Cvm) and diluted upper part (lithofacies Svl) are commonly described as results of flow transformation (Postma *et al.* 1988; Sohn 2000).

The planar stratification reflects variations in discharge and discontinuities in the accretion of the beds (Nemec and Steel 1984). Successive debris flows (lithofacies Cvm) typically eroded (at least partly) the preceding deposits of lithofacies Svl.

Lithofacies Cvg is formed by very coarse volcaniclastic sandstone to granule conglomerate with coarse tail normal grading. Scattered pebbles exceptionally cobbles (up to 15 cm in a-axis) were described along the base of the beds. Pebbles are mostly subrounded to rounded basalts. Inverse grading part (several cm thick) above the base of the bed followed by normal grading part (dominant portion of the bed) was exceptional. Beds reveal tabular, irregularly lensoidal to wedge shape. Beds are mostly about 10 cm thick, the thickest one reveals 35 cm. Base is sharp and subhorizontal, whereas tops are either erosive (if it is overlain by lithofacies Cvm) or flat to slightly convex up (if it is overlain by lithofacies Dm). This lithofacies forms 1.3% of the succession at Naděje Lake locality. Lithofacies was not recognised at Rožmberk Lake and Medusa Cliffs.

Interpretation: Lithofacies Cvg was rarely recognised comparing to lithofacies Svl. Deposits of lithofacies Cvg are interpreted to have been deposited by high-density turbidity currents. Outsized clasts along the base are partial product of protruding from reworked upper surface of the overlying beds of lithofacies Cvm. The lack of other sedimentary structures related to turbulent deposition may be due to the generation of the current from the precursor, higher sediment concentration debris flows (Lowe 1982; Falk and Dorsey 1998).

Lithofacies Cvm, Svl and Cvg represent product of volcaniclastic mass flows (sensu Nemec 1998). Mass flows are relatively heavy and tend to be redirected by local topography. Absence of gas-escape structures and perlitic or matrix vesicles (Cole and DeCelles 1991; Trofimovs *et al.* 2008) shows that flows were water-driven mass flows not gas-driven ones. Absence of hydrothermal alteration also points to indirect relation to eruptive activity. Nelson *et al.* (2009) interpreted similar deposits as deposits of hyperconcentrated or concentrated density flows". The geometry of such deposits varies with the local bedrock configuration (Nelson *et al.* 2009). Hambrey *et al.* (2008) wrote about subaqueous gravity flows.

Lithofacies Dm consists of pebbly mudstone diamictite. Lithofacies is represented by light brown, greenish grey, yellowish brown or brownish green very fine to fine muddy sandstone with scattered pebbles or pebbly mudstone, structureless/massive (Fig. 3B). Lithofacies contain up to 20% of clasts, mainly pebble-sized (usually up to 5 cm), but outsized cobbles (up to 21 cm) were also rarely recognised (typically in thicker beds). Clasts of dark basalts of JRIVG predominate, whereas hyaloclastites are exceptional. TPG phyllite or Cretaceous sediment clasts have also been found, but their presence is rather irregular and they might be missing in some diamictite beds. Basalts look fresh, unaltered, spherical in shape, mostly subrounded, without preferred orientation. Clast abrasion (including striations and faceting) was not recognised. Penetrations of volcaniclastic lithofacies (Svl, Cvm) and diamictite of lithofacies Dm was often recognised with common ductile/plastic deformations along contact (Fig. 3F). Beds of lithofacies Dm are commonly only erosional relics, laterally discontinuous on the distance of several meters. The thickness of the beds varies from several up to 60 cm. Both bases and tops of the beds are uneven. Lithofacies Dm forms 58.7% of the succession at Medusa Cliffs; 11.0% at Naděje Lake and was not recognised at Rožmberk Lake.

Large rip-ups of lithofacies Dm were often recognised within the lithofacies Cvm. These "intra-clasts" are mostly recognised in the lower part of the succession, whereas more continuous beds of lithofacies Dm are typical for the upper part of the succession at Naděje Lake.

Interpretation: Non erosional conformable basal contacts, missing subglacial or ice-thrust deformation features, relative lateral conformity of lithofacies Dm with surrounding volcaniclastic lithofacies, abundant deformed diamictite rafts within the beds of lithofacies Cvm, all point to subsequent subaqueous emplacement (Eyles *et al.* 1985; Lønne 1995). Nelson *et al.* (2009) interpreted similar deposits as glacigenic subaqueous debris flows. The results of relation of the thickness of a conglomerate bed (BTh) and the bed's maximum particle size (MPS) (Fig. 7) confirm cohesive strength of matrix in the clast-support mechanism for lithofacies Dm. The steeper slope of the MPS/BTh regression line for lithofacies Cvm comparing to lithofacies Dm refers to a higher role of further clast supporting factors in flows of lithofacies Cvm (probably mainly dispersive pressure) and lower competence of lithofacies Dm. Lithofacies Dm represents glacigenic deposits accumulated probably near the margin of ice masses. Nelson et al. (2009) interpreted similar deposits as glacigenic debris flow and Hambrey et al. (2008) as glacigenic subaqueous debris flows.

The strong dominance of local (JRIVG) clast lithologies, important admixture of erratic clasts (TPG and APPG, especially at Medusa Cliffs) and the evidence of erosion and incorporation of rafted blocks into lithofacies Cvm point to a relation of glacigenic deposits and volcaniclastic mass flows.

Occurrence of isolated outsized boulders is typical for all gravity flows lithofacies. Outsized particles affected the MPS/BTh plots, which is also evident by the low value of linear regression coefficient ($R = 0.32$ for data from Dm lithofacies, whereas $R = 0.76$ for data from Cvm).

The lithofacies L is formed by laminated fine-grained sandstone to siltstone and was further subdivided into two sublithofacies. Strongly predominant sublithofacies L_1 is represented by light to whitish yellow medium to fine sandstone, rarely muddy sandstone, fine laminated, relatively well sorted (Fig. 3C). Interbeds/interlaminas to thin lenses (up to 5 cm thick) of gravelly sandstone are common. Granules, rarely pebbles up to 3 cm in diameter, dominate in the gravelly fraction. Moreover, scattered large pebbles and cobbles up to 18 cm large are rare. Lonestones are mostly rounded to subrounded with dominance of clast of JRIVG provenance (dark basalts), but also APPG granites and TPG phyllites and schists were observed in low shares, with some of them being striated. Although lamination is dominantly flat, soft-sediment deformation, resembling convolute folding and load casts, were present locally especially around the larger clasts. These outsized isolated clasts show penetration into underlying silty material, whereas upper contacts preserve a combination of onlap and compactional folding (Fig. 3D). Beds of sublithofacies L_1 have sharp, mostly erosive top and sharp slightly uneven bases. Bed thickness varies from 7 cm to 1 m. Sublithofacies is commonly preserved only as erosional relic within lithofacies Dm. Rafted blocks of sublithofacies L_1 were often observed within beds of lithofacies Dm and Cvm.

Subordinate sublithofacies L_2 is formed by greyish fine laminated sandy mudstone, siltstone to muddy sandstone. The thickness of beds of sublithofacies L_2 was only 8 to 15 cm. Tops were erosive, whereas bases were generally flat. Lithofacies L was recognised only at Medusa Cliffs locality, where it forms 24.6%.

Interpretation: Lithofacies L is spatially related to diamictites of lithofacies Dm. The penetrative lower contact and the onlaping upper contacts of isolated outsized clasts in the laminated layers are clear evidence of dropstones (Thomas and Connel 1985; Jones and Fielding 2008) from floating ice. Deposition in subaqueous setting *i.e.* marine proglacial environment is supposed. Fine-grained laminated sandstones indicate a role of traction and deposition from relatively low velocity traction currents to turbidity currents in relative quiet environment. The close vertical and lateral associations of diamictites and laminated mudstones are therefore also consistent with a subaqueous debris flow origin for the diamictites. Processes connected with transformation of subaqueous sediment gravity flows could be responsible for the formation of the lithofacies L. The presence of closely associated deformed sediments of lithofacies L and undeformed sediments of lithofacies Dm, as well as the erosional upper contact suggest that deformation occurred as these sediments were deposited or shortly after. Mixing of Cretaceous marine sediment and JRIVG hyaloclastite material points also to an important role of reworking of older weathered material.

Provenance study

Clast lithological analyses undertaken in different units of lithofacies Dm, L_1 and Cvg shows on a predominance of clasts of local JRIVG basalts, they always compose >90% of the clasts at Medusa Cliffs, but nearly 100% at Rožmberk and Naděje Lakes. The most common further lithology, clasts of which have been found in different diamictite and laminite units of Medusa Cliffs, are TPG phyllites and metasediments, less common are Cretaceous sandstone and APPG granite clasts.

Discussion

Although the studied deposits are spatially related to the foresets of the lava-fed delta system, not all recognised lithofacies are necessary related to them genetically. Bottomsets were defined by Gilbert (1885) as gently inclined (# 10°) fine grained sediments and represent the down-dip terminations of foresets, where the lithofacies association is transitional, deposited by both gravitational flow and suspension fall-out processes (Colella 1988; Massari and Parea 1990; Nemec 1990b; Chough and Hwang 1997; Ford *et al.* 2007; Backert *et al.* 2010). Significant variations in the lithofacies development, especially in the role of glacigenic *vs*. volcaniclastic deposits in the studied outcrops, point to different depositional processes and paleogeography before the onset of the lava-fed (hydroclastic) foresets of the same delta.

Relative coarse grain character of deposits of volcanogenic gravity flows (lithofacies Cvg, Cvm), their co-occurence with glacigenic deposits (lithofacies Dm and L), common occurrences of reworked volcaniclastics recognised in the outcrops at Naděje Lake and Medusa Cliffs point to different depositional environment and conditions comparing to the situation at Rožmberk Lake, where glacigenic deposits are missing.

However differences in the proportion of glacigenic and volcaniclastic deposits were recognised also between outcrops at Naděje Lake and at Medusa Cliffs, together with various occurrences of individual lithofacies (see Figs 5 and 6).

Whereas volcaniclastic sediments strongly dominate over glacigenic ones at Naděje Lake (89% : 11%), the situation is directly inverse at Medusa Cliffs (16.7% : 83.3%). Differences between these two outcrops can be followed also in provenance. Strong dominance of local source from JRIVG material and common preservation of relative fragile intraclasts confirm relative short transport distances. Occurrence of some APPG-derived erratics within diamictites points to larger areal extent of glaciers (possibly extending across the Prince Gustav Channel – Nelson *et al.* 2009). A very low role of the APPG derrived erratics within the deposits at Naděje Lake and their slight increase in the deposits at Medusa Cliffs support role of local sources and reworking of several spatially "independent"/separated glacigenic deposits. We can speculate about the role of morphology affecting the paths, existence of several glaciers with different lateral extent and/or about their formation during different events.

The common rafts of glacigenic diamictites/laminites in volcanoclastic debris flows, and superposition of volcanogenic deposits over the glacigenic ones suggest that glacigenic deposits might be a precursor sediment that was locally overridden by the lava fed delta.

Model of depositional environment and processes is presented in Fig. 8. The transition from distal to proximal settings can be followed in the succession from Naděje Lake. The distal part of the system (succession in Fig. 4A and lower part of the succession in Fig. 4B) is typical by thin beds of debris flow deposits of lithofacies Cvm which alternates with interbeds of lithofacies Svl, Ml and Cvg (*i.e.* deposits of more "diluted /transformed" flows). The glacigenic facies are missing here, however they might underwent complete disintegration after incorporation into the gravity flows and only the results of debris flow behaviour, could point to this processes. The occurrence of thicker beds of lithofacies Cvm together with interbeds of glacigenic diamictite higher in the succession (see upper part of the Fig. 4B) represents more proximal parts of the system, where glacigenic deposits were incorporated into the debris flows as rafts.

The succession at Medusa Cliffs reflects probably the proximal and also "peripheral" settings, where volcaniclastic debris flows propagated into the environment formerly covered by glacigenic deposits. The thickness of volcaniclastic debris flows is significantly lower than at Naděje Lake, which could point to peripheral position concerning the progradation of the lava fed delta.

Depositional environments of the studied deposits in outcrops at Medusa Cliffs and Naděje Lake are interpreted as located on subaqueous slopes of volcano. Jonkers *et al.* (2002), Hambrey *et al.* (2008), Smellie *et al.* (2008) and Nelson *et al.* (2009) presented a model for JRIVG volcanism that depicts eruptions of Mt. Haddington beneath relatively thick ice which produce a sequence of glacigenic sediments and lava-fed deltas. However according to Smellie *et al.* (2008) the Lachman Crags delta is an independent satellite delta and their possible source vent is the small plug at S end of Lachman Crags.

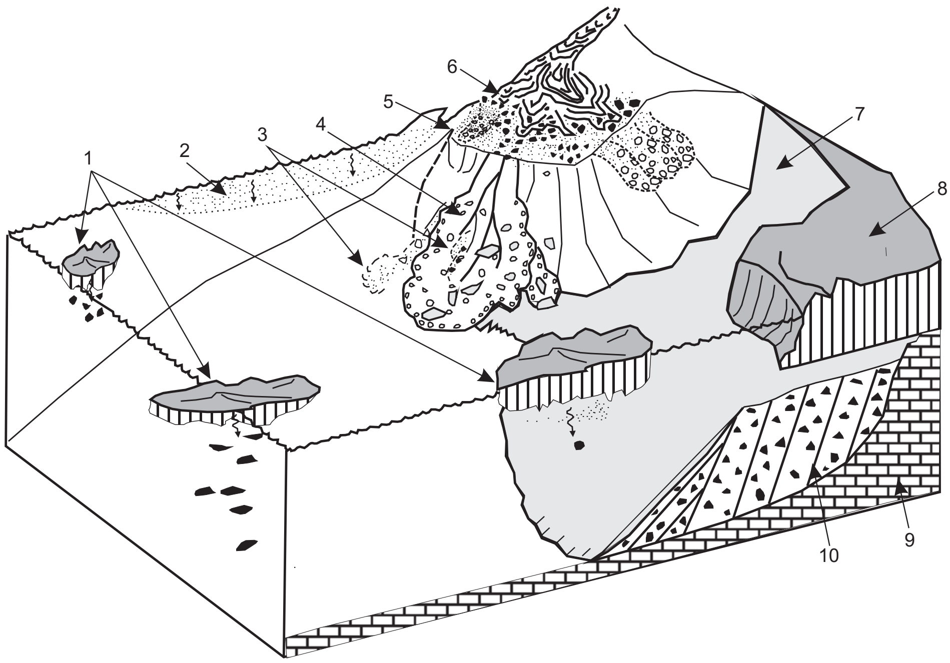


Fig. 8. Depositional model for studied deposits: 1, small icebergs (production of dropstones – outsized clasts); 2, hypopycnal flows – low density flows (redistribution of fine tuff); 3, formation and transformation of subaquatic volcaniclastic mass flows (deposits of lithofacies Svl and Cvg, partly also Cvm); 4, formation of debris flows on a submarine slopes of volcano (deposits of lithofacies Cvm); 5, proximal depositional setting (dominance of lithofacies Ml, thin interbeds of facies Cvm and Hb, direct relation to lava flows); 6, capping lava-fed delta (hyaloclastite – possible formation of foresets/topsets); 7, glacigenic deposits (facies Dm and L) deposited prior to onset of volcaniclastic deposits; 8, glaciers in the adjacent areas partly covering the landscape; 9, basement formed by the Upper Cretaceous sediments; 10, foresets of the older lava-fed deltas.

The dominant lithofacies Ml in deposits at Rožmberk Lake are interpreted as produced by tractional currents. The thin interbeds of lithofacies Cvm and palagonite breccia connected with foresets of adjacent hydroclastic delta, are interpreted as proximal bottomset, close to the source of hydroclastic material. Deposition occurred in non-ice-contact settings, however icebergs on the sea, responsible for production of dropstones highly probably existed. Rapid deposition, only JRIVG provenance and occurrence of fragile palagonite are characteristic for this situation.

The differences in sedimentary succession and thickness of volcaniclastic deposits of “bottomsets” of the single lava fed delta suggest principal role of local conditions for development and preservation of this Gilbert delta depositional system.

An absence of palagonite breccia interbeds at Naděje Lake and Medusa Cliffs successions points to missing direct continuity of processes on lava delta foresets and bottomsets (contrary to the situation at Rožmberk Lake). Hambrey *et al.* (2008) described loaded and mixed contacts between glacigenic diamictites and volcanogenic deposits on different outcrops of JRVIG, which points to complex spatial and temporal but coeval relations of these two systems. However, the contact of the bottomset deposits with overlaying foresets is sharp with angular disconformity (“downlapping”) in the studied outcrops. Such contact may reflect break in the activity of the volcanic feeder system and time break in deposition. The studied deposits were noticeably affected along this contact, where yellowish orange horizon several dm thick is developed.

The differences in lithofacies succession of “bottomset” deposits can be explained by differences in paleogeography and local conditions. The principal role of mass flow processes was recognised and explained by significantly steep slopes of the lava-fed deltas. The foresets dip under the angle of more than 30° and such angle was followed also directly above studied bottomsets withouth gradual formation of less steep “sigmoidal” toe-sets.

Conclusions

Bottomsets of the lava-fed deltas represent rarely investigated target of the sedimentological studies. These deposits, recognised directly below foresets of hyaloclastite breccia of the Lachman Crags main delta (Pliocene), have been studied in the three outcrops in the area of the Ulu Peninsula of James Ross Island (Antarctica).

Six lithofacies were recognised and their distribution significantly differs in the individual outcrops. Dominance of lithofacies Ml with interbeds of lithofacies Cvm, produced by volcaniclastic debris flow, and palagonite breccia connected with the foresets of adjacent hydroclastic delta is characteristic for the outcrop at Rožmberk Lake. Such situation points to proximal setting and direct relations to superimposed lava-fed delta.

Both glacigenic and volcaniclastic deposits were recognised in next outcrops. Deposits of volcaniclastic mass flows dominate in the outcrop of Naděje Lake over glacigenic ones. The most common lithofacies Cvm was deposited by volcaniclastic debris flows. Formation of significantly less common deposits of lithofacies Svl (product of low-density turbidity currents) and lithofacies Cvg (product of high-density turbidity currents) is explained by rapid flow transformation of debris flows. Glacigenic deposits are in this outcrop subordinate and represented by lithofacies Dm.

Glacigenic deposits formed by lithofacies Dm (product of glacigenic subaqueous debris flows) and lithofacies L (low velocity traction/turbidity currents in marine proglacial environment) prevail in the outcrop at Medusa Cliffs over deposits of volcaniclastic mass flows (lithofacies Cvm).

Depositional environments in the outcrops at Medusa Cliffs and Naděje Lake are interpreted as located on subaqueous/submarine slopes of volcano, where succession from distal to proximal settling can be followed. eruptions beneath relatively thick ice produced a sequence of volcaniclastic and glacigenic mass flow deposits.

The superimposition of and volcaniclastic debris flows over glacigenic diamictites/laminites suggests that glacigenic deposits might be precursor sediment that was locally overridden by the lava fed delta. Although the studied deposits are spatially related to the foresets of the lava-fed delta system, not all recognised lithofacies are related to them genetically.

The variations in lithofacies succession of the "bottomset" deposits on the individual studied outcrops are explained by differences in paleogeography and local conditions. The principal role of mass flow processes was recognised in all studied cases.

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