Deposits of pyroclastic mass flows at Bibby Hill (Pliocene, James Ross Island, Antarctica)

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Abstract

Sedimentological study of the southern slopes of Bibby Hill (relic of a Pliocene tuff cone) allows recognition of twelve lithofacies and three facies associations. Deposits of pyroclastic currents (both low- and high density pyroclastic currents) dominate over the deposits of pyroclastic flows. Products of suabaerial resedimented pyroclastic deposits play minor role. Vertical distribution of facies associations within the studied succession is not uniform. These differences in the distribution of facies associations are interpreted as response to variations in the intensity and type (Surtseyan, Taalian) of phreatomagmatic eruptions, water availability and morphology of the cone.

Key words: pyroclastic currents, pyroclastic flows, resedimented pyroclastic deposits

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Introduction

Tuff cones are relative small volcanoes with steeply dipping rim beds, produced by hydrovolcanic or phreatomagmatic activity due to explosive interactions of magma and ground or surface water, commonly in shallow marine environments and terrestrial lowlands (Sohn et al. 2008). Tuff cones are mostly local and short-lived, but they can deliver significant amount of volcaniclastic sediments to nearby terrestrial or marine environments (Sohn et al. 2002). This debris is provided either directly by aerial fallout from eruption columns, pyroclastic flows, debris flows or by rivers,

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wind and glacial processes during interruption periods. These make tuff cones important for the sedimentological study in addition to volcanological investigation, which provides a key to understanding the nature of volcanosedimentary processes and environments (Cas et Wright 1987, Sohn et al. 2008, Smith 1991).

Bibby Hill, the most striking morphological feature of the northeastern coast of the Ulu peninsula, represents relic of a tuff cone (Smellie 1999, Smellie et al. 2008, 2013), and several further tuff cones were recognised within the James Ross Island Volcanic Group.

During the field season in February 2013, the authors had an opportunity to observe the part of the southeastern slope of the Bibby Hill (Fig. 1). The presented paper describes the results of the facies analyses and suggests, that the studied part of the tuff cone is formed dominantly by the deposits of several types of mass flows.

Geological settings

The James Ross Island Volcanic Group (JRIVG) is resting unconformably on top of the Cretaceous strata and crops out within an area of aprox. 6000 km^2 situated in northern Antarctic Peninsula (James Ross Island, Vega Island and several smaller islands nearby in Prince Gustav Channel and Antarctic Sound, southern Dundee Island and Paulet Island, Tabarin Peninsula and Cain and Abel nunataks) (Nelson 1975, Smellie 1999, Smellie et al. 2006). The JRIVG represents volcanic production of the back-arc basin and consists of voluminous intrusions of lavas and other volcanics corresponding in composition to tholeiites, alkali basalts, hawaiites and rarely also to basanites and mugearites (Smellie 1989, Smellie 1999). Volcanics are enriched by the mantle component to a MORB-like depleted mantle with no significant contribution of sedimentary material from the subducted oceanic lithosphere of the Antarctic plate, which is explained by regional extension linked to the roll-back of the subducted slab of Antarctic plate (Košler et al. 2009).

The Bibby Hill tuff cone is younger than 5.04 Ma (the age of an older lava-fed delta of the Johnson Formation cropping out on its east flank; Smellie et al. 2008, 2013). The dykes associated with the Bibby Hill tuff cone cropping on its northern slope reveal an ^{40}Ar/^{39}Ar age of 3.34 ± 0.15 Ma (unpublished data of B. Mlčoch and D. Nývlt, Czech Geological Survey), giving the Bibby Hill tuff cone a Late Pliocene age.

The tuff cones of the JRIVG are composed principally of ragged, highly vesicular vitriclasts (Smellie 2001). Explosions occurred at a high structural level, essentially in the upper vent area and the situation is compared with volcanoes of Surtseyan type, with vents flooded either by lake (glacial or non-glacial) or by sea. The presence of rare marine fossils in some strata and laterally continuous beds indicate eruption in a marine environment (Smellie et al. 2006, Williams et al. 2006).

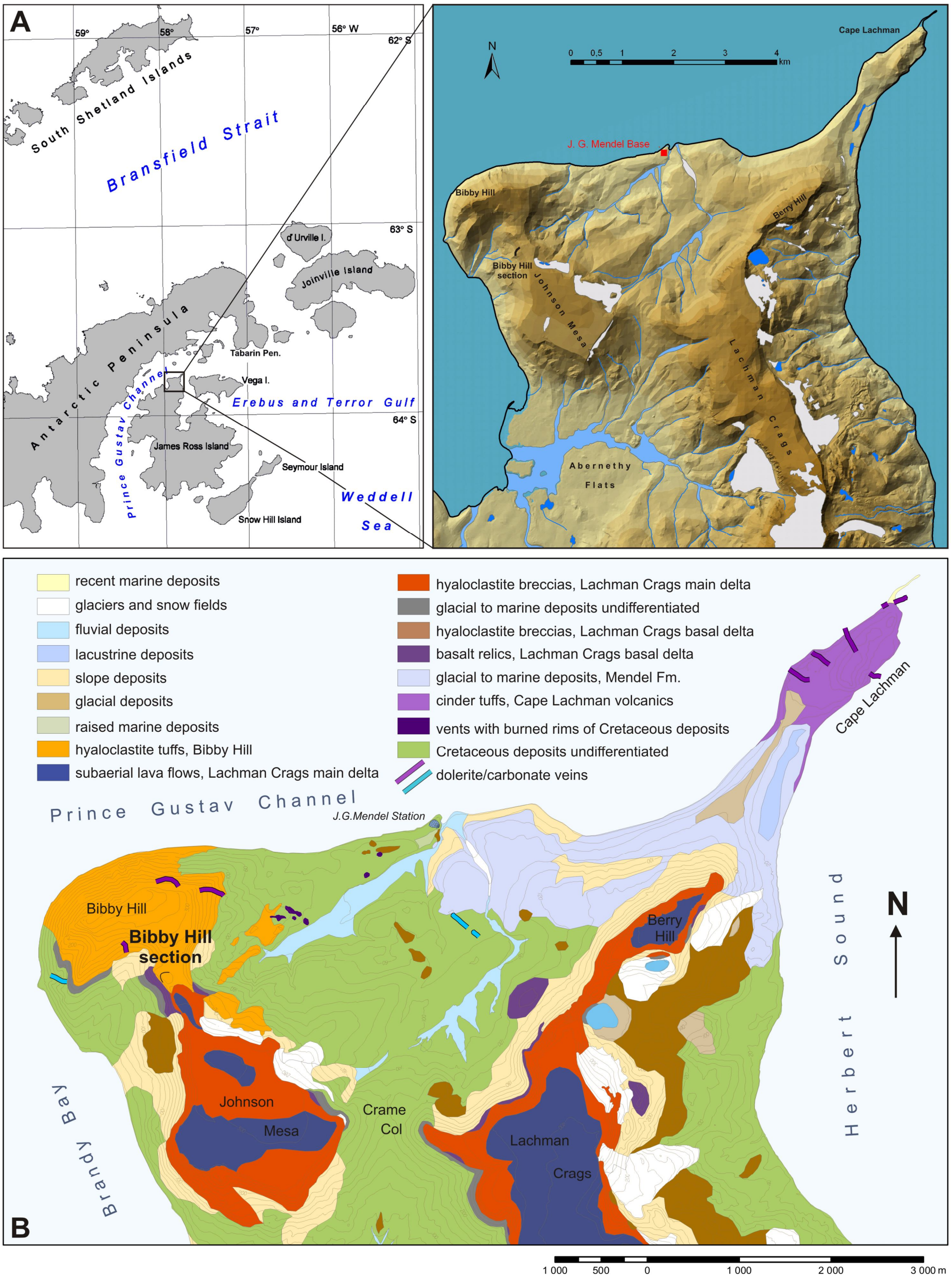

Fig. 1. A) Northern area of Antarctic Peninsula with an ice-free area of James Ross Island indicated by a rectangle and a geographical sketch of location of the studied successions. **B)** Sketch geological map of northern part of Ulu Peninsula, James Ross Island with studied section indicated by a thick black line. Geology adopted from Nývlt et al. (2011) and Mlčoch (2013).

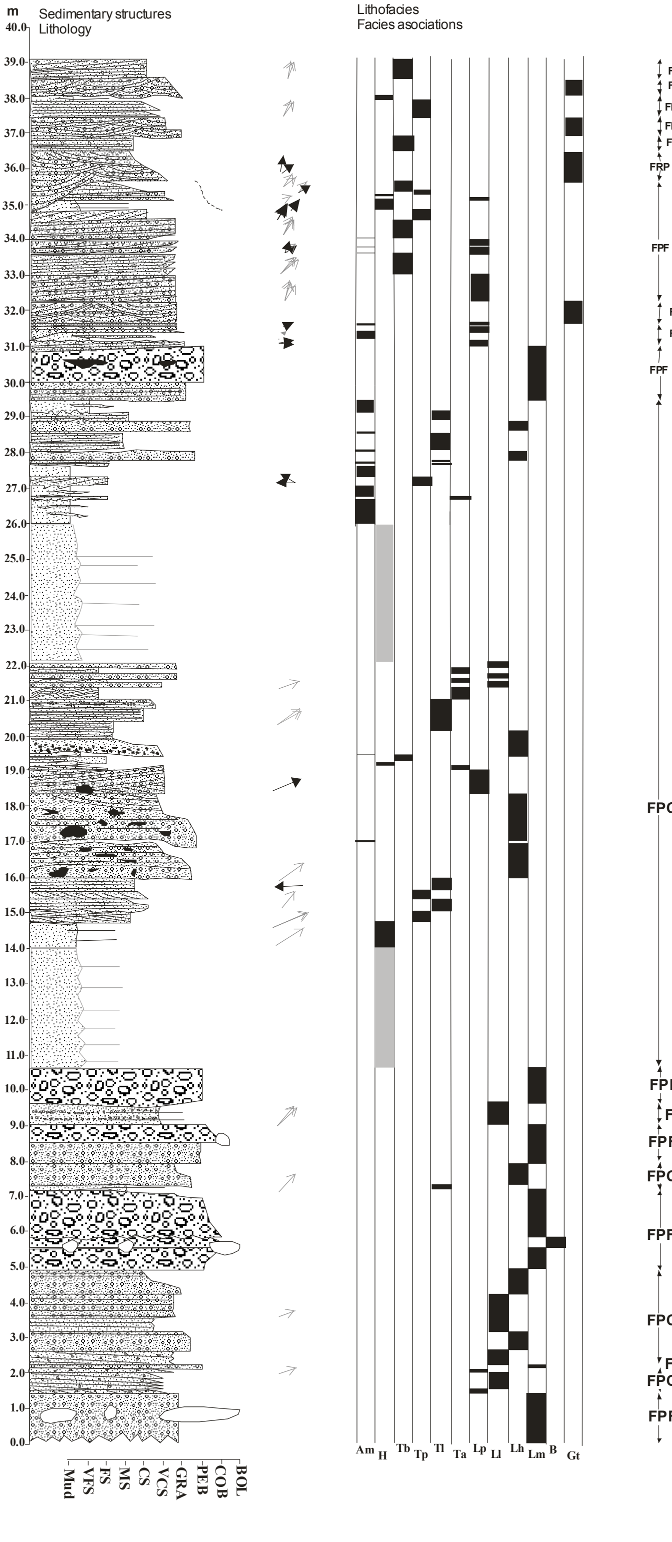
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Fig. 2A

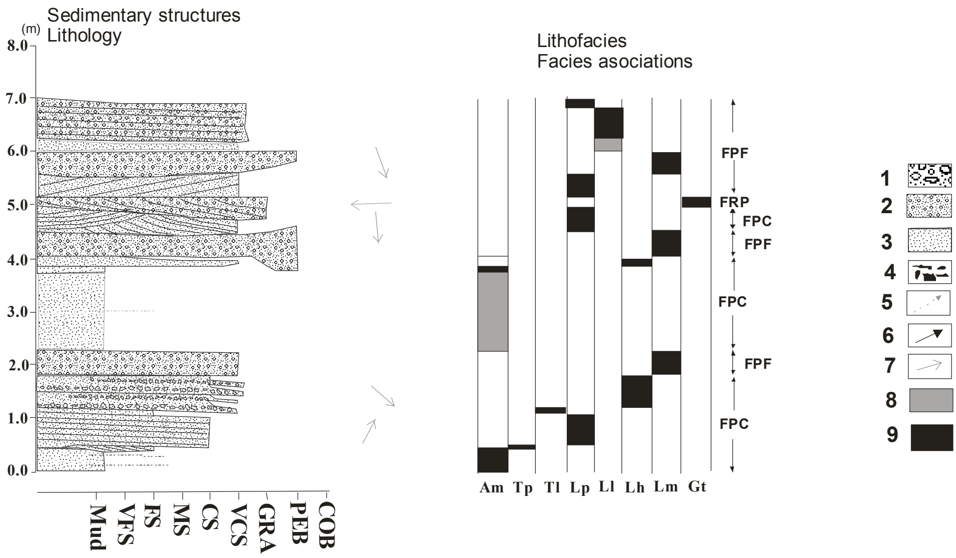

Fig. 2B

Fig. 2. **A**) Schematized sedimentary log with distribution both of lithofacies and facies associations. **B**) Suplementary log for the upper part of the profile. Explanation: 1) lapilli, 2) coarse ash, 3) fine ash, 4) rip ups of facies Am, 5) direction of channel axis, 6) direction of cross stratification, 7) bedding direction, 8) poorly exposed part of the section, 9) well exposed part of the section.

Methods and terminology

Logged sections represent two profiles more than 45 m long. The produced logs are presented in **Fig. 2A, B.** Climatic conditions (snow cover), very steep relief and talus cover did not allow to study the longitudinal section and the depositional architecture.

The identification of lithofacies is based on grain size, sorting, and primary sedimentary structures. The facies subdivision and palaeocurrent estimation were following Tucker (2004) and Walker et James (1992). Lithofacies have been combined, based on their spatial grouping and depositional processes into facies associations. Relation between maximum particle size and bed thickness were followed in beds with outsized clasts in the finer matrix (Nemec et Steel 1984).

The nomenclature used for bed thickness and grain size of the pyroclastic deposits follows Sohn et Chough (1989) and Sulpizio et al. (2007). The volcanological terminology for pyroclastic mass flows is very rich and numerous terms have different meaning to different authors. The terms pyroclastic flow and pyroclastic current are used in the sense of Nemec et al. (1998).

Results

Lithofacies

Twelve lithofacies were recognised and their distribution within the profile is presented in the **Fig. 2A, B** and the examples of lithofacies in the **Fig. 3**. The principal characteristics and a brief interpretation of lithofacies are presented in Table 1. Study of thin sections reveal, that pale-coloured fine lapillistones and lapilli tuffs are formed of variably vesicular cuspate to blocky glass fragments that are pervasively palagonite altered. The variable vesicularity, grain shapes and alteration of the abundant glass fragments are characteristic of magma interaction with surface or groundwater and indicate that the rocks formed during explosive phreatomagmatic eruptions (similarly White 1991, Smellie 2001).

Lithofacies Am is formed by dark grey to black fine tuff with massive appearance or with poorly defined planar lamination. Coherent appearance of the tuff prevents better definition of primary structures. Lateral transition to brownish grey planar laminated fine ash was observed locally. Grain size analyses of ash reveal strong dominance (over 75%) of grain size fraction below 0.063 mm. Deposits are mostly well sorted without obvious occurrence of larger clasts. Tuff is nonvesicular with coherent appearance and is dominantly formed by argilitized volcanic glass with isotropic plagioclase microlites.

Thin (max. cm thick) discontinuous (on the distance of first meters) laminas to lensoidal interbeds (thickness up to 2 cm) of very fine lapillistone with sharp planar bases were observed rarely within these dark grey to black tuffs. Soft-sediment deformations are common along the base of these lapillistones.

Lithofacies Am was recognised either as thick monotonous beds or as thin (several cm thick) interbeds within coarser facies. Tops are sharp and commonly erosive. The bottoms are both flat and irregular. Typical is tabular shape of beds, exceptional is an infill of the broad (3-4 m wide) shallow (30 cm deep) depression. In this case admixture of coarse lapilli and blocks (mostly basalts, exceptionally cobbles of Cretaceous sandstones up to 10 cm in diameter) was recognised. Facies Am represents 11.6% of the studied succession.

***Interpretation*:** Planar lamination points to layer-by layer deposition and origin from pyroclastic current with fluid turbulence as support mechanism (Talling et al. 2012). Deposition from en masse consolidation from low-concentration pyroclastic current and co-current fall (suspension ash cloud) is supposed (Sohn et Chough 1992, Nemec et al. 1998). The considerable thickness and uniform character of lithofacies suggest pseudo-steady flow conditions and/or relative rapid deposition. Laterally persistent bedding with variations in bed thickness across topographic irregularities could support some role of ash cloud/ash plume (Fisher et Schmincke 1984).

Ash-cloud can accompany pyroclastic current or could be emplaced by the lofting and entrapment of fine ash produced during the passage of such a current at a break in slope (Charbonier et Gerstisser 2012). An absence of erosional truncations points to low energy currents. Thin interbeds of very fine lapilli reflect deposition from pyroclastic currents and role of traction. The formation of the depression with infill of lithofacies Am is explained by prior reworking of the surface/slope by stream flows during the period of relative volcanic quiescence, or by scouring action of the pyroclastic current's strongly turbulent, ash-rich head. Depression was filled subsequently by deposits of current´s tail. The cobble sized material in the deepest part of depression represents the lag.

Thin interbeds of lithofacies Am within significantly coarser tuffs and lapillistones are connected with the dilute turbulent suspension of the waning current and/or the current tail. A dilute volcanic ash input could be relative long lasting (McCave 1984, Scheiber et Southard 2009).

Formation of ash clouds and also formation of low-density pyroclastic currents could be connected with rapid chilling and mechanical disintegration of molten lava during quenching (Moore et al. 1973, Freundt 2003).

Lithofacies H is represented by heterolitic deposit, where dominant dark grey to black fine tuff, structureles/masive, nonvesicular, alternates with continuous tabular (2-4 cm thick) beds or lenses (up to 5 cm thick, 20 cm long) of fine to medium-grained tuff, planar laminated or wavy to ripple stratified. The contacts are sharp, commonly with loading structures. Lithofacies H is thinly to medium bedded (6-23 cm). Beds have broadly tabular or wedge shape and are often discontinuous on the outcrop scale. They have sharp bases and commonly erosive tops. Lithofacies H represents 9.9% of the studied succession.

Interpretation: Pinching-out of coarser layers suggests tractional and saltating movement of coarse grains, whereas the relatively continuous fine-grained layers suggest settling of fines from suspension. Abrupt changes in grain size across a sharp surface and ripple cross-lamination are indicators of dilute, fine-grained and fully turbulent pyroclastic current. Although dominant deposition was from suspension a subordinate horizontal movement was able to induce traction. The generally well-defined alternations of coarser- and fine-grained layers suggest deposition from dry pyroclastic currents and alternation of deposition from suspension and traction point to their dilute and pulsating character (Sohn et al. 2008).

Lithofacies Tb is formed by yellow coarse- rarely medium-grained tuff**,** with plane parallel lamination, low-angle inclined or undulated stratification. Scattered fine-grained lapilli (up to 5 mm) and flasers to thin interbeds (max. 2 cm) of dark massive fine tuff were rarely observed. Coarsing upwards trend was described commonly, whereas fining upward one was rare. Lithofacies Tb is medium to thickly bedded (20-60 cm). Beds have usually wedge shape with inclined tops, sharp convex down bases and common erosive tops. Lithofacies Tb forms 2.6% of the studied succession.

***Interpretation*:** The well-stratified tuffs are interpreted to have been emplaced by both suspension and traction sedimentation from turbulent pyroclastic currents with varying degrees of suspended-load fallout rate, traction and sorting (Sohn et al. 2008). The generally well-defined alternations of coarse-grained and fine-grained layers suggest deposition from dry pyroclastic currents (Sohn et al. 2008).

Lithofacies Tp is represented by yellowish medium grained tuff, planar cross stratified. Occurrences of both scattered fine to medium grained lapilli (pumice up to 5 mm) and very irregular intraclasts of facies Am (max. 3 cm in diameter) were rare. No preferred position of outsized clasts was identified. Lithofacies is thinly to medium bedded (max. thickness 28 cm). Beds are discontinuous and have wedge shape with inclined top. Two types of bases were recognised. Uneven base with loading structures was observed only when lithofacies Tp was superimposed to lithofacies Am. Flat sharp base was recognised in all other cases. Lithofacies Tp forms 4.4% of the studied succession.

***Interpretation*:** The well-stratified (lapilli) tuffs are interpreted to have been emplaced by both suspension and traction sedimentation from turbulent pyroclastic current (Sohn et al. 2008). The dune bedforms can be attributed to subcritical flow-regime and indicate tractional transport beneath turbulent, relatively low-concentration currents. Outsized pebbles represent lag, mostly along erosive bases. Intraformational clasts or rafts were derived from underlying or upslope beds.

Lithofacies Tl is formed by yellowish medium- to coarse-grained tuff, plane parallel stratified, sometime with low angle of inclination (up to 6°). Lithofacies is thinly to thickly bedded (6-40 cm). Discontinuous laminas of fine-grained lapilli or scattered lapilli were common. Flasers of black fine tuff oriented parallel to lamination were recognised rarely. Lithofacies forms 6.2% of the studied succession.

Interpretation: The planar stratification implies tractional deposition from super-critical flow. Formation via low-amplitude bedwaves (Best et Bridge 1992) beneath low-density pyroclastic current or via repeated collapse of traction carpets below high-density pyroclastic current (Sohn et al. 2008, Talling et al. 2012) is supposed. Flasers of black tuffs were recognised only in situation when lithofacies Tl is deformed and material from adjacent beds is incorporated into convolute folds (soft-sediment deformation).

Lithofacies Ta is formed by yellowish medium-grained tuff, relatively well-sorted, with climbing ripples and antidunes. Thin (max. 1 cm thick) flasers of dark grey fine ash were recognised rarely. Lithofacies is thinly to medium bedded (6-30 cm). Beds have generally tabular shape. Base is sharp and slightly uneven. Top is slightly undulated. Lithofacies Ta forms 2.0% of the studied succession.

Interpretation: Strata pattern indicates simple vertical accretion ('standing-wave' antidune structure) turning into an asymmetrical accretion with or without truncations and are connected with relatively rapid sediment deposition (Baas 2000, Kane et Hodgson 2010, Jobe et al. 2012) from dilute, rather fine-grained and fully turbulent flow (Baas et al. 2011). The bedforms can be attributed to fluctuations between supercritical and subcritical flow-regime, due to transient hydraulic jumps caused by internal waves within pyroclastic current (Schmincke et al. 1973, Valentine 1987, Fisher 1990, Cole 1991, Nemec et al. 1998).

Lithofacies Lp is represented by coarse-grained tuff to fine-grained lapillistone, planar cross stratified (tangential and sigmoidal contact of foresets to the base). Stratification is commonly connected with alternation of laminas with higher and lower content of lapilli. Relative low angle of cross-stratification (mostly up to 10°, rarely up to 15°) is typical. Lithofacies is medium to thickly bedded (up to 80 cm) and individual sets are 7 to 16 cm thick. Beds have wedge or tabular shape, sharp erosive base and top. Fining upward trend was recognised in some cases. Flasers of black fine tuff, scattered fine grained lapilli (pumice, angular basalt clasts up to 6 mm in diameter) were all rarely recognised along the lower part of the foresets. Lithofacies forms 11.4% of the studied succession.

Interpretation: Planar cross-stratification indicates tractional transport, dune formation and grain by grain deposition form a turbulent, relatively low-density pyroclastic currents, in which suspension and traction were the main transport mechanisms (Sulzipio et al. 2007). Low angle bedforms have been interpreted by Sohn et Chough (1989) to form beneath dilute surges, which have lost their coarse bedload, but are still capable of exerting high shear stress on the bed. Alternating fine- and coarse-grained layers suggest emplacement by pulsating currents that fluctuated in velocity. Outsized pebbles along erosive bases represent lag. Intraformational clasts were derived from underlying or upslope beds.

Lithofacies Ll is formed by alternation of laminas of yellowish coarse-grained ash and fine-grained lapillistone with plane parallel lamination, slightly inclined. Beds are medium to thickly bedded. Beds have sharp base and slightly undulated top. Lithofacies forms 9.2% of the studied succession.

***Interpretation*:** The well-stratified lapilli tuffs are interpreted as a product of turbulent pyroclastic currents (Sohn et al. 2008). The planar stratification implies tractional deposition from supercritical flow. Formation via low-amplitude bedwaves (Best et Bridge 1992) beneath low-density turbidity currents or via repeated collapse of traction carpets below high-density turbidity currents (Talling et al. 2012) is supposed. Alternating fine- and coarse-grained laminas suggest pulsating currents that fluctuated in velocity. Lapilli records the basal, coarse grained part of each pulse, while stratified coarse ash record the passage of the uppermost, more diluted part of the current that accompanies each pulse (Sulpizio et al. 2007).

Lithofacies Lh is bipartite. Lower part of the bed is formed by coarse- to fine-grained (clasts mostly about 1 cm, max. 2 cm in diameter) lapillistone, massive, matrix to clast supported, rarely with inverse to normal grading (coarse tail type). Lapilli are mostly represented by angular to subangular pumice or dark basalt clasts. Matrix is formed by yellowish fine to coarse grained ash. Upper part of the bed constitutes coarse-grained tuff with plane parallel or undulated lamination and fining upward trend. Lamination sometimes reveal low angle of inclination. Antidunes or climbing ripples were recognised very rarely within the upper part. Lithofacies is thickly bedded (56 cm up to 1 m). Tops of the beds are only slightly irregular. Bases are sharp and often erosive. Very irregular rip ups of the lithofacies Am (up to 40 cm in diameter, mostly subhorizontally oriented) were commonly observed along the base, if lithofacies Lh is superimposed to lithofacies Am. Lithofacies Lh forms 16.6% of the studied succession.

***Interpretation*:** Lithofacies Lh is interpreted as deposits of high-density pyroclastic current (Nemec et al. 1998). The lower part shows evidence of flow turbulence, but will lack evidence of tractional deposition, which is evident in the upper part. It indicates rapid dumping of sediment directly from a ‘thickening’ turbulent suspension (Lowe 1988, Nemec 2009).

Lithofacies Lm is formed by fine- to coarse-grained lapillistone, poorly sorted, structureless/massive, sometimes with coarse tail inverse grading. Lapilli are represented by angular to subangular pumice (up to 3 cm in diameter) and dark basalt clasts (up to 15 cm in diameter). Matrix support prevails, clast supported domains are less common. Matrix is formed by yellowish fine-grained lapilli to coarse-grained ash. Some beds contain intraformational clasts of facies Am along their bases. Outsized lapilli were sometime recognised in depressions along the base of the beds. Lithofacies Lm is medium to thickly bedded (24 cm - 1 m). Sharp very uneven base and concave up top are typical. Lithofacies form 14.3% of the studied succession.

***Interpretation*:** Massive beds with scoured base, poorly sorted muddy matrix and presence of intraformational clasts are characteristic for pyroclastic debris flow deposits. The results of the thickness of a conglomerate bed (BTh) and the bed´s maximum particle size (MPS) (**Fig. 4)** confirm cohesive strength of matrix as important clast-support mechanism and indicate subaerial deposition of flows. Dispersive pressure was probably an additional clast supporting factor. There are several possible mechanisms of formation of pyroclastic debris flows. The occurrence of intraformational clasts suggests that some flows resulted from failure of oversteepened crater rim deposits. Some flows may also have originated from slumping of water-saturated tephra or from sediment-laden stream flows by infiltration of water into an unsaturated substrate (Shultz 1984), or from water-rich collapsed eruption clouds (Sohn et Chough 1992).

Lithofacies B is formed by pyroclastic breccia to coarse grained lapillistone, massive. No preferred grain fabric is observed. Angular to subangular blocks (max. 35 cm in diameter) and also the coarse lapilli (8-14 cm in diameter) are mostly formed by dark basalt. Matrix is represented by medium lapilli to coarse ash, unstratified/massive. The layers of breccia are mostly one block thick, rarely more than a few grains thick, and are laterally discontinuous, pinching out within only few metres. Base is very uneven and sometime poorly distinctive due to blocks protrusions. Top is undulated. Facies form 0.8% of the studied succession.

***Interpretation*:** Large blocks were probably produced as ballistic fall during volcanic eruptions (Sohn et Chough 1989) and subsequently further transported by gravity on the slopes of tuff cone, because missing bedding sags. Such situation could represent short periods of vent-clearing or vent-widening explosions (Cas et al. 1989). Matrix infiltrated into the open space between the blocks during the subsequent depositional processes. The blocks are clearly inadequate to the competence of surrounding bed produced by massflow, as expressed in the diagram of the thickness of a conglomerate bed (BTh) and the bed´s maximum particle size (MPS) (Nemec et Steel 1984) - *see* **Fig. 4**.

Lithofacies Gt is represented by very coarse volcaniclastic sandstone to volcaniclastic conglomerate (reworked lapilli) trough cross stratified, with rare scattered cobbles (up to 9 cm in diameter) mostly along the base of the beds. Outsized clasts are commonly subrounded, mostly of volcanic origin (pumice, dark basalts), but also pebbles of Cretaceous sandstones were rarely identified. Rare very irregular and angular to subangular rip ups of facies Am (20 cm in diameter) were recognised. Individual sets are 6 to 30 cm thick, cosets are 55-60 cm thick. Fining and thinning upward trend was observed in cosets, coarsening upward trend was less common. Laminas of dark fine ash were sometime recognised along the lower parts of the foresets. Beds have irregular or wedge shape. Bases are uneven and erosive, whereas tops are inclined and flat. Lithofacies forms 7.0% of the studied succession.

Interpretation: The sedimentary structures indicate reworking of primary pyroclastic material and filling or erosive scours. Cross-stratification and channel scours at the base are all consistent with channel infill by water flow (Miall 1978). Trough cross-stratification indicates infilling of a channel by bedload in the form of migrating bedforms (Miall 1985). Fining- and thinning-upward trend resulted from the lateral migration of streams or a deceleration in flow velocity due to a decrease in channel activity. Intraformational clasts or rafts were derived from underlying or upslope beds (Sohn et Chough 1993). Channel reactivation was not observed, which point to occasional formation of the scours/rills. The situation could be connected with saturation of the substrate with water and surface runoff by water flows (Sohn et Chough 1992). Pebble-sized to cobble-sized clasts on erosional surfaces were deposited as a lag deposit on a channel floor. The occurrence of the substrate clasts (Cretaceous sandstones) in such high position could be explained by their redeposition from possible basement outcrop along the path of the flow or the clasts were derived from the relatively unconsolidated Cretaceous strata that the tuff cone vent traversed. We can also speculate about the transport of sandstone pebbles by littoral drift along the slopes of tuff cone, however the role of wave action or marine processes was not recognised in the studied succession. Ash layers on top of this lithofacies point to very low flow energies after relocation of the scour (Lenhardt et al. 2011).

The paleotransport data results are based on measurements of orientation of bedding, foresets of cross-stratification and channel axis. The tilt of the beds is supposed to represent the orientation of the paleosurface. The orentation of the absolute majority of the paleotransport data (*see* Fig. 2) is towards NNE–NE.

Lithofacies symbol	Description	Interpretation
Am	Dark grey to black fine tuff with massive appearance or with poorly defined planar lamination, mostly well sorted.	Deposits of low-concentration pyroclastic currents and co-current falls.
H	Heterolithic deposit, dominant dark grey to black fine tuff, structureles/masive, nonvesicular and subordinate fine- to medium-grained tuff, planar laminated or wavy to ripple stratified.	Deposits of dilute, fine-grained and fully turbulent pyroclastic currents with dilute and pulsating character.
Tb	Yellow coarse- rarely medium-grained tuff, with plane parallel lamination, low-angle inclined or undulated stratification. Scattered fine-grained lapilli and flasers to thin interbeds of dark massive fine tuff.	Products of turbulent dry pyro-clastic currents.
Tp	Yellowish medium-grained tuff, planar cross stratified. Rare occurence of fine- to medium-grained lapilli and irregular intraclasts of facies Am.	Deposits of turbulent pyroclastic current.
Tl	Yellowish medium- to coarse-grained tuff, plane parallel stratified.	Deposits of pyroclastic current.
Ta	Yellowish medium-grained tuff, relatively well-sorted, climbing ripples and antidunes.	Deposits of pyroclastic currents.
Lp	Coarse-grained tuff to fine-grained lapillistone, planar cross stratified.	Deposits of low-density pyroclastic currents.
Ll	Alternation of laminas of yellowish coarse-grained ash and fine-grained lapillistone with plane parallel lamination.	Deposits of turbulent pyroclastic currents.
Lh	Bipartite beds with lower part formed by coarse- to fine-grained lapillistone, massive, matrix to clast supported, rarely with inverse to normal grading (coarse tail type) and upper part formed by coarse-grained tuff with plane parallel or undulated lamination.	Deposits of high-density pyroclastic currents.
Lm	Fine- to coarse-grained lapillistone, poorly sorted, structureless/massive, sometimes with coarse tail inverse grading, mostly matrix supported.	Deposits of pyroclastic debris flows.
B	Pyroclastic breccia to coarse-grained lapillistone, massive.	Ballistic fall during volcanic eruptions, resedimented by gravity.
Gt	Very coarse volcaniclastic sandstone to volcaniclastic conglomerate, trough cross stratified, rare scattered cobbles.	Channel infill by water stream flow

Table 1. List of identified lithofacies with their brief description and interpretation.

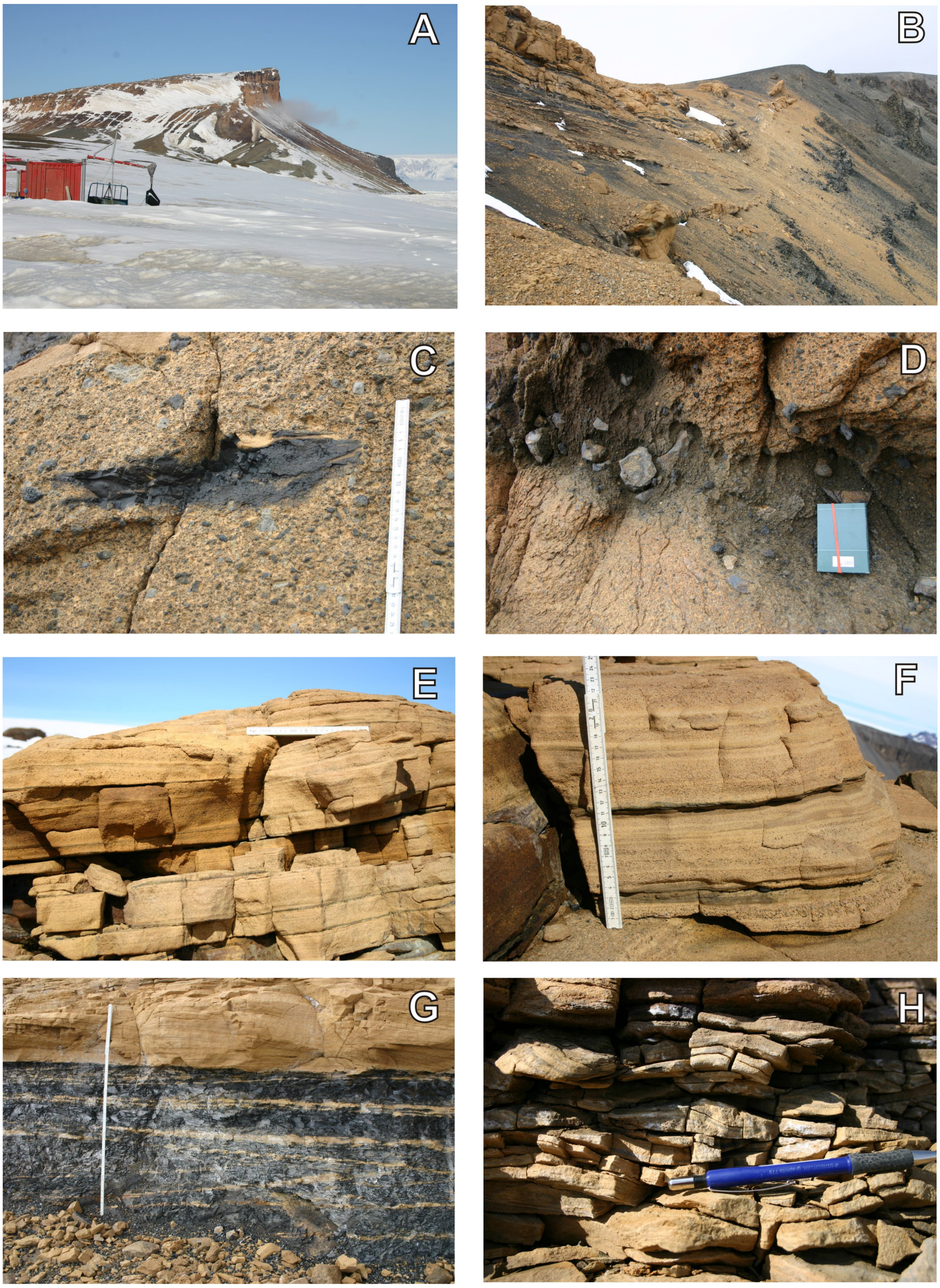

Fig. 3. Characteristics of the outcrop and structural features of the studied deposits at Bibby Hill. A) The tuff cone of Bibby Hill, B) Southern slopes of Bibby Hill, C) Facies Lm with rip ups of facies Am, D) Facies B and Lm, E) Facies Lp and Ll, F) Facies Lh, G) Facies Am and Tp, H) Facies Ta.

Facies associations

Three facies associations were recognised based on spatial grouping of facies and depositional processes forming the facies. The distribution of facies associations in the profile is presented in Fig. 2.

Facies association of pyroclastic currents (FPC) represent the volumetrically prevalent association forming 78.6% of the logged succession. Two sub-associations can be recognised, *i.e.* the low-density pyroclastic current, which is the dominant one (forming 62%) and the minor high-density pyroclastic current one (forming 16.6%).

The sub-association of low-density pyroclastic currents consists of well-stratified tuffs and lapilli tuffs of facies Ta, Tb, Tp, Tl, Ll, Lp, Am and H, which have been emplaced by both suspension and traction sedimentation from turbulent pyroclastic currents with varying flow competence and capacity (Sohn et Chough 1989, Chough et Sohn 1990). The variations in stratification are interpreted as the expressions of diverse bedforms (Schmincke et al. 1973, Sohn et Chough 1989, Chough et Sohn 1990). An upward facies transition reflects variations in the fallout rates and flow density, like an upward transition from Tl to Tp probably records a decrease in sediment fallout rates and transition to more dilute flow. Mantling layers of facies Am represent the very dilute turbulent suspension of the waning current. The sub-association of high-density pyroclastic current consists of facies Lh. It can be generated by turbulent inflation of pyroclastic flow or deceleration of low-density pyroclastic currents.

The deposits of the pyroclastic currents are interpreted to have been deposited almost wholly in a subaerial setting because low-density pyroclastic currents (pyroclastic surges) are not thought to be able to enter water (Moore et al. 1966, Waters et Fisher 1971, Carey et al. 1996).

Facies association of pyroclastic flows (FPF) represent the 11.4% of the logged succession and is formed by facies Lm and B, although facies Lm strongly predominates. The thick-bedded, massive poorly sorted, matrix (ash) supported deposits are often interpreted as been emplaced by debris flows that were generated by generally wet phreatomagmatic eruptions of Surtseyan-type (Kokelaar 1983, Ross 1986, Leat et Thompson 1988), remobilization of steep rim deposits by slope failure (Cas et al. 1989, Sohn et Chough 1992) and rapid collapse of voluminous and water laden eruption columns (Kano 1998).

The deposits of facies B, although originated by ballistic fall, were recognised surrounded by beds of the facies Lm.

Facies association of subaerialy resedimented pyroclastic deposits (FRP) is formed by only one facies Gt and represents 7% of the studied succession. Several sedimentary characteristics (rounding of volcaniclasts, occurrence of substrate clasts, formations of irregular scours and rills, erosion surfaces) point to resedimentation and subaerial reworking processes by rill flows and overland flows (Bull et Cas 2000, Sohn et al. 2008). We can speculate about the formation of this association during „quiescent“ periods.

Distribution of facies associations within the succession is not regular. The FPF were recognised mostly in the lower part of succession, accompanied by FPC (both high and low-density ones). The middle part of the succession is formed only by FPC. The high-density pyroclastic currents play here important role. The upper part of the succession is the most variable one. The FPC prevails here and is almost dominantly formed by deposits of low-density pyroclastic currents. The FPF was also recognised in the upper part of succession, but its beds are thinner here comparing to the lower part. The FRP was recognised only in the upper part of the succession.

Interpretation

The predominance of deposits of pyroclastic currents and flows suggests that the studied succession represents the slope deposit of a tuff cone (Waters et Fisher 1971, Kokelaar 1986, Sohn 1996).

The pre-eruption surface was possibly locally exposed subaerially, because documented pebbles of Cretaceous sandstones within the scour infill (facies Gt and Am). Submergence of the surfaces below the water is improbable, because missing evidence of marine processes (wave action, cliff formation, *etc.*) contemporaneous with deposition in the logged part of the tuff cone. However the unstudied lower parts of the tuff cone might have formed underwater. The deposits are not necessary to be wholly subaerial, because many of the Surtseyan depositional processes can continue into subaqueous settings and result in 'primary' subaqueous deposition, even if generated by emergent Surtseyan activity (Thorarinsson et al. 1964, Kokelaar 1983, White 1996, Kano 1998, Nemeth et al. 2006).

Vertical distribution of facies associations allows interpretation of the eruptions evolution and paleogeography. Deposits of pyroclastic mass flows strongly predominate within the studied succession. The close relationship between the environments of eruption, depositional processes and the character of the deposits were multiply documented (Sohn et Chough 1989, 1992; Chough et Sohn 1990, Lajoie et al. 1992, Colella et Hiscott 1997).

Deposits of tuff cones are commonly interpreted as deposits of pyroclastic surges (Moore 1967, Fisher et Waters 1970, Waters et Fisher 1971). Individual surge deposits are typical by significant proximal to distal facies changes. They evolve downcurrent due to decelerating of the current, which experienced a downflow decrease in turbulence, particle concentration and suspended-load fall-out rate, and an increase in traction processes. Thinning of the surge deposits from the vent is accompanied by evolution of structures (Vessel et Davies 1981, Smith 1988, 1991, Chough et Sohn 1990, Colella et Hiscott 1997). The facies transitions are further related to topography as well as to the distance from the volcanic vent (de Rosa et Dellino 1999). These facies and structural changes reveal different behaviour of mass flow *i.e.* they can be classified as deposits of pyroclastic flow, deposits of high- and low-density pyroclastic currents (*see* Nemec et al. 1998). Statement that pyroclastic currents can comprise dense and dilute phases in a single overall event is common (Sparks 1976, Pierson et Scott 1985, Druitt 1992, Branney et Kokelaar 2002, Edmonds et Herd 2005, Talling et al. 2012).

According to above mentioned downflow variations in the facies distribution the lower part of the succession could be interpreted as the most proximal one and the middle part of the succession as the most distal one (to the vent). The deposition from the main body of pyroclastic currents alternated in the middle part of the succession with deposits from its tail (Nemec et al. 1998). The upper part of the succession reveals both deposition from the main body of the pyroclastic currents and also reworking of the depositional surface during intereruptive periods. However the observed succession represents only a very small part of the upper section of the cone, so such an interpretation (concerning the vent) is speculative. Pyroclastic mass flows may undergo various transformations, because of such factors as the deposition or entrainment of sediment, the dynamic response to a topographic relief, or passage through the air-water interface (Fisher 1983, Sohn et Chough 1989, Cas et Wright 1991, Levine et Kieffer 1991, Carey et al. 1996). Occurrences of both subaerially reworked pyroclastic deposits and pyroclastic flows in the upper part of the succession point to frequent disruption of volcanic activity and remobilization of the cone deposits. The studied succession probably reveals also variation in the activity/intensity of the volcanic source.

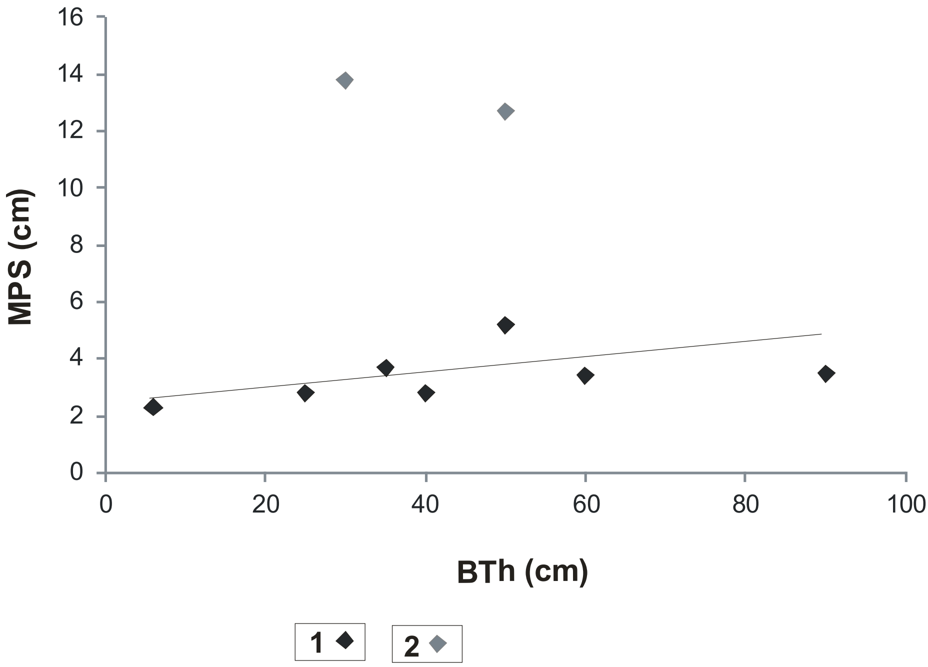

Fig. 4. The diagram of the thickness of a bed (BTh) and the bed´s maximum particle size (MPS) (according to Nemec et Steel 1984) for studied deposits of pyroclastic flows. 1) data for facies Lm, 2) data for facies B.

Discussion

The studied succession is interpreted as a tuff cone produced by subaerial phreatomagmatic eruptions. The deposits of pyroclastic flows can be connected with relatively wet tephra, frequent disruption and remobilization of the cone deposits. Although the pyroclastic deposits are mostly formed by cohesionless lapilli, which point to relative drier conditions (Sohn et Cough 1993), cohesive strength of the matrix in the clast-support mechanism was proved. This implies that external water was available and the eruption style was similar to a wet, Surtseyan-type tuff cone (Sohn et Chough 1992).

The eruptive conditions became drier and the eruption produced dry tephra in the middle part of the succession. Middle and also upper parts of the succession comprise relatively abundant, fine-grained deposits of facies Am or H compared to the lower part. This suggests that the efficiency of magma fragmentation increased due to an optimal mixing ratio of water to magma during this stage of tuff cone evolution (Wohletz et Sheridan 1983). Such deposits are typical of 'Taalian' explosivity (Kokelaar 1986) with numerous closely spaced phreatomagmatic explosions generating short-lived, highly energetic single-surge type pyroclastic density currents that wax and wane rapidly (*e.g.* Sohn 1996). Typically, the currents involve abundant fine-grained ash and form extensive dune fields proximally (Moore 1967).

The studied profile reveals variations in the intensity and type (Surtseyan, Taalian ones) of eruptions, water availability and possibly also morphology. But for the detailed model of pyroclastic deposition and evolution of the Bibby Hill tuff cone recognition of lateral facies relationships/ depositional architecture is necessary.

A short part of the succession was folded and contorted. This part grades laterally into undisturbed strata of massive, homogenized lapilli tuff of facies Lm or Lh generally towards SE direction, whereas towards NW it grades into into dark grey to black fine tuffs of facies Am. The deformation was produced by sediment sliding induced by gravitational instability of sloped beds of the tuff cone.

Conclusions

The southern slopes of the Bibby Hill (relic of a tuff cone, Pliocene, James Ross Island) were studied during the summer field season in February 2013.

Sedimentological study allows recognition of twelve lithofacies and three facies associations. Facies association of pyroclastic currents represents the volumetrically prevalent association forming 78.6% of the logged succession. This association can be subdivided into two sub-associations *i.e.* the sub-association of low-density pyroclastic current (dominant one - forming 62%), and the sub-association of high-density pyroclastic current one (minor one - forming 16.6%). The facies association of pyroclastic flows represents the 11.4% of the logged succession. Finally the facies association of subaerialy resedimented pyroclastic deposits represents only 7% of the studied succession. Sedimentary characteristics point to resedimentation and subaerial reworking processes by rill and overland flows.

The pre-eruption surface was probably exposed subaerially, because of occurrence of pebbles of Cretaceous sandstones within the scour infill and missing evidence of marine processes (wave action, cliff formation, *etc.*) contemporaneous with deposition of volcaniclastics. Vertical distribution of facies associations within the succession is not uniform.

Dominance of the deposits of pyroclastic flows in the lower part of succession, accompanied by deposits of pyroclastic currents (both high- and low-density ones), can be explained by proximal position to the vent and/or generation of the flows by generally wet phreatomagmatic eruptions of Surtseyan-type. The subangular blocks and coarse lapilli cobbles originated as ballistic fall were further transported on the slopes of the tuff cone within pyroclastic flows. The deposition from the main body of pyroclastic currents alternated with deposits from its tail in the middle part of the succession. The eruptions produced dry tephra, the efficiency of magma fragmentation increased and large volume of fine ash and tephra was produced during this stage of tuff cone evolution ('Taalian' explosivity - Kokelaar 1986). Occurrences of both subaerially reworked pyroclastic deposits, pyroclastic currents and pyroclastic flows in the upper part of the succession point to frequent disruption of volcanic activity and remobilization of the cone deposits, and could sign „inter-eruptive“periods.

Vertical (spatial?) variations in the occurrence of recognised facies and facies associations are preliminary interpreted as response to the variations in the intensity and type (Surtseyan, Taalian) of phreatomagmatic eruptions, water availability and morphology of the cone. For the better understanding of the ruling factors of depositional processes and for detailed model of the Bibby Hill formation further study of lateral facies relationships and facies architecture is necessary. Moreover only a very small part of the upper section of the cone was observed. Study of the lower part of the cone is necessary for better understanding of its evolution.

References

BAAS, J. H. (2000): Duration of deposition from decelerating high-density turbidity currents. *Sedimentary Geology*, 136: 71-88.

BAAS, J. H., BEST, J. L. and PEAKALL, J. (2011): Depositional processes, bedform development and hybrid flows in rapidly decelerated cohesive (mud-sand) sediment flows. *Sedimentology*, 58: 1953-1987.

BEST, J., BRIDGE J. (1992): The morphology and dynamics of low amplitude bedwaves upon upper stage plane beds and the preservation of planar laminae. *Sedimentology*, 39: 737-752.

BRANNEY, M. J., KOKELAAR, P. (2002): Pyroclastic density currents and the sedimentation of ignimbrites. *Geological Society London Memoir*, 27: 143 p.

BULL S. W., CAS R. A. F. (2000): Distinguishing base-surge deposits and volcaniclastic fluviatile sediments: an ancient example from the Lower Devonian Snowy River Volcanics, south-eastern Australia. *Sedimentology*, 47: 87-98.

CAREY, S., SIGURDSSON, H., MANDEVILLE, C. W. and BRONTO, S. (1996): Pyroclastic flows and surges over water: an example from the 1883 Krakatau eruption. *Bulletin of Volcanology*, 57: 493-511.

CAS, R. A. F., WRIGHT, J. V. (1987): Volcanic Successions: Modern and Ancient. Allen and Unwin, London, 528 p.

CAS, R. A. F., WRIGHT, J. V. (1991): Subaqueous pyroclastic flows and ignimbrites: an assessment. *Bulletin of Volcanology*, 53**:** 357-380.

CAS, R. A. F., LANDIS, C. A. and FORDYCE, R. E. (1989): A monogenetic, Surtla-type, Surtseyan volcano from the Eocene-Oligocene Waiareka-Deborah volcanics, Otago, New Zealand: a model. *Bulletin of Volcanology*, 51: 281-298.

CHARBONNIER S. J., GERSTISSER R. (2012): Deposit architecture and dynamics of the 2006 block-and-ash flows of Merapi Volcano, Java, Indonesia. *Sedimentology*, 58: 1573-1612.

CHOUGH, S. K., SOHN, Y. K. (1990): Depositional mechanics and sequences of base surges, Songaksan tuff ring, Cheju Island, Korea. *Sedimentology*, 37: 1115-1135.

COLE, P. D. (1991): Migration direction of sand-wave structures in pyroclastic surge deposits: implications for depositional processes. *Geology*, 19: 1108-1111.

COLELLA, A., HISCOTT, R. N. (1997): Pyroclastic surges of the Pleistocene Monte Guardia sequence (Lipari Island, Italy): depositional processes. *Sedimentology*, 44: 47-66.

DEROSA R., DELLINO P. (1999): Pyroclastic surges of the Pleistocene Monte Guardia sequence (Lipari Island, Italy): depositional processes. *Sedimentology*, 46: 577-580.

DRUITT, T. H. (1992): Emplacement of the 18 May 1980 lateral blast deposit ENE of Mount St. Helens, Washington. *Bulletin of Volcanology*, 54: 554-572.

EDMONDS, M., HERD, R. E. (2005): Inland-directed base surge generated by the explosive interaction of pyroclastic flows and seawater at Soufrie`re Hills volcano, Montserrat. *Geology*, 33: 245-248.

FISHER, R. V. (1990): Transport and deposition of a pyroclastic surge across an area of high relief – the 18 May 1980 eruption of Mount St Helens, Washington. *Geological Society of America Bulletin*, 102: 1038-1054.

FISHER, R. V., SCHMINCKE, H. U. (1984): Pyroclastic Rocks. Springer-Verlag, Berlin, 472 p.

FREUNDT, A. (2003): Entrance of hot pyroclastic flows into the sea: experimental observations. *Bulletin of Volcanology*, 65: 144-164.

JOBE, Z. R., LOWE, D. R. and MORRIS, W. R. (2012): Climbing-ripple successions in turbidite systems: depositional environments, sedimentation rates and accumulation times. *Sedimentology*, 59: 867-898.

KANE, I. A., HODGSON, D. (2010): Submarine channel levees: criteria for recognition of levee subenvironments: exhumed examples from The Rosario Fm (Baja, Mexico) and the Laingsburg Fm. (Karoo Basin). *Marine and Petroleum Geology*, 28: 807-823.

KANO, K. (1998): A shallow-marine alkali-basalt tuff cone in the Middle Miocene Jinzai Formation, Izumo, SW Japan. *Journal of Volcanology and Geothermal Research*, 87: 173-191.

KOKELAAR, B. P. (1983): The mechanism of surtseyan volcanism. *Journal of Geological Society London*, 140: 939-944.

KOŠLER J. MAGNA T., MLČOCH B., MIXA P., NÝVLT D. and HOLUB F. V. (2009): Combined Sr, Nd, Pb and Li isotope geochemistry of alkaline lavas from northern James Ross Island (Antarctic Peninsula) and implications for back-arc magma formation. *Chemical Geology*, 258: 207-218.

LAJOIE, J., LANZAFAME, G., ROSSI, P. L. and TRANNE, C. A. (1992): Lateral facies variations in hydromagmatic pyroclastic deposits at Linosa, Italy. *Journal of Volcanology and Geothermal Resources*, 54: 135-143.

LEAT, P. T., THOMPSON, R. N. (1988): Miocene hydrovolcanism in NW Colorado, USA, fuelled by explosive mixing of basaltic magma and wet unconsolidated sediment. *Bulletin of Volcanology*, 50: 229-243.

LENHARDT, N., HORNUNG, J., HINDERER, M., HNEL, H. B., TORRES-ALVARADO, I. S. and TRAUTH, N. (2011): Build-up and depositional dynamics of an arc front volcaniclastic complex: the Miocene Tepoztla´n Formation (Transmexican Volcanic Belt, Central Mexico). *Sedimentology*, 58: 785-823.

LEVINE, A. H., KIEFFER, S.W. (1991): Hydraulics of the August 7, 1980 pyroclastic flow at Mount St. Helens, Washington. *Geology,* 52: 279-297.

LOWE, D. R. (1988): Suspended-load fallout rate as an independent variable in the analysis of current structures. *Sedimentology*, 35: 765-776.

MCCAVE, I. N. (1984): Size spectra and aggregation of suspended particles in the deep ocean. *Deep Sea Resources*, 31: 329-352.

MIALL, A. D. (1978): Lithofacies types and vertical profiles models in braided river deposits: a summary. *In*: A. D. Miall (ed.): Fluvial Sedimentology. *Canadian Society of Petroleum Geologists Memoir*, 5: 597-604.

MIALL, A. D. (1985): Architectural-element analyses: a new method of facies analyses applied to fluvial deposits. *Earth-Science Review*, 22: 261-308.

MLČOCH, B. (2013): Geologické mapování ostrova Jamese Rosse. *In*: P. Prošek (ed.): ANTARKTIDA. 249-252, Academia, Praha.

MOORE, J. G. (1967): Base surge in recent volcanic eruptions. *Bulletin of Volcanology*, 30: 337-363.

MOORE, J. G., NAKAMURA, K. and ALCARAZ, A. (1966): The 1966 eruption of Taal Volcano. *Science*, 151: 955-960.

MOORE J. G., PHILLIPS R. L., GRIGG R.W., PETTERSON D. W. and SWANSON D. A. (1973): Flow of lava into the sea 1969-1971, Kilauea Volcano, Hawaii. *Bulletin Geological Society America*, 84: 537-546.

NELSON, P. H. H. (1975): The James Ross Island Volcanic Group of North-East Graham Land. *British Antarctic Survey Scientific Report*, 54, 62 p.

NEMEC, W. (2009): What is a hyperconcentrated flow? *In*: 27th IAS Meeting of Sedimentology, Alghero Italy, 20-24.09.2009, Abstract book, p. 267.

NEMEC, W., MUSZYNSKI, A. (1982): Volcaniclastic alluvial aprons in the Tertiary of Sofia district (Bulgaria). *Annales Societatis Geologorum Poloniae*, 52: 239-303.

NEMEC, W., KAZANCI, N. and MITCHELL, J. G. (1998): Pleistocene explosions and pyroclastic currents in west-central Anatolia. *Boreas*, 27: 311-332.

NEMEC, W., STEEL, R. J. (1984): Alluvial and coastal conglomerates: Their significant features and some comments on gravelly mass-flow deposits. *In*: E. H. Koster, R. J. Steel (eds.): Sedimentology of Gravels and Conglomerates. *Canadian Society of Petroleum Geologists Memoir*, 10: 1-31.

NEMETH, K., CRONIN, S. J., CHARLEY, D., HARRISON, M. and GARAE, E. (2006): Exploding lakes in Vanuatu – 'Surtseyan style'eruptions witnessed on Ambae Island. *Episodes*, 29: 87-92.

NÝVLT, D., KOŠLER, J., MLČOCH, B., MIXA, P., LISÁ, L., BUBÍK, M. and HENDRIKS, B. W. H. (2011): The Mendel Formation: evidence for Late Miocene climatic cycllicity at the northern tip of the Antarctic Peninsula. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 299: 363-384.

PIERSON, T. C., SCOTT, K. M. (1985): Down-stream dilution of a lahar – transition from debris flow to hyper-concentrated streamflow. *Water Resources*, 21: 1511-1524.

PIRRIE, D., SYKES, M. A. (1987): Regional significance of proglacial deltafront reworked tuffs, James Ross Island area. *British Antarctic Survey Bulletin*, 77: 1-12.

PIRRIE, D., CRAME, J. A., RIDING, J. B., BUTCHER, A. R. and TAYLOR, P. D. (1997): Miocene glaciomarine sedimentation in the northern Antarctic Peninsula region: The stratigraphy and sedimentology of the Hobbs Glacier Formation, James Ross Island. *Geological Magazine*, 134: 745-762.

ROSS, G. M. (1986): Eruptive style and construction of shallow marine mafic tuff cones in the Narakay Volcanic Complex (Proterozoic, Hornby Bay Group, Northwest Territories, Canada). *Journal of Volcanology and Geothermal Resources*, 27: 265-297.

SCHEIBER, J., SOUTHARD, J. (2009): Bedload transport of mud by floccules ripples – Dirrect observation of ripple migration processes and their implications. *Geology*, 37: 483-486.

SCHMINCKE, H. U., FISHER, R. V. and WATERS, A. C. (1973): Antidune and chute and pool structures in the base surge deposits of the Laacher See area, Germany. *Sedimentology*, 20: 553-574.

SHULTZ, A. W. (1984): Subaerial debris flow deposition in the Upper Paleozoic Cutler Formation, western Colorado. *Journal of Sedimentary Petrology*, 54: 759-772.

SMELLIE, J. L. (1999): Lithostratigraphy of Miocene and recent, alkaline volcanic fields in the Antarctic Peninsula and eastern Ellsworth Land. *Antarctic Science*, 11: 362-378.

SMELLIE, J. L. (2001): Lithofacies architecture and construction of volcanoes erupted in englacial lakes: Icefall Nunatak, Mount Murphy, Eastern Marie Byrd Land, Antarctica. *In*: J. D. L. White, N. R. Riggs (eds.): Volcaniclastic Sedimentation in Lacustrine Settings. International Association of Sedimentologists, Special Publication, 30: 73-98. Blackwell Publishing Ltd., Oxford, UK. doi: 10.1002/9781444304251.ch2

SMELLIE, J. L., MCARTHUR, J. M., MCINTOSH, W. C. and ESSER, R. (2006): Late Neogene interglacial events in the James Ross Island region, northern Antarctic Peninsula, dated by Ar/Ar and Sr-isotope stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 242: 169-187.

SMELLIE, J. L., JOHNSON, J. S., MCINTOSH, W. C., ESSER, R., GUDMUNDSSON, M. T., HAMBREY, M. J. and VAN WYK DE VRIES, B. (2008): Six million years of glacial history recorded in volcanic lithofacies of the James Ross Island Volcanic Group, Antarctic Peninsula. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 260: 122-148.

SMELLIE, J. L., JOHNSON, J. S. and NELSON, A. E. (2013): Geological map of James Ross Island. I. James Ross Island Volcanic Group (1:125 000 Scale). BAS GEOMAP 2 Series, Sheet 5, British Antarctic Survey, Cambridge.

SMITH, G. A. (1988): Sedimentology of proximal to distal volcaniclastics dispersed across an active foldbelt: Ellensburg Formation (late Miocene), central Washington. *Sedimentology*, 35: 953-977.

SMITH, G. A. (1991): Facies sequences and geometries in continental volcaniclastic sediments. *In*: R. V. Fisher, G. A. Smith (eds.): Sedimentation in Volcanic Settings. *Society for Sedimentary Geology Special Publication*, 45: 1-257.

SOHN, Y. K. (1996): Hydrovolcanic processes forming basaltic tuff rings and cones on Cheju Island, Korea. *Geological Society of America Bulletin*, 108: 1199-1211.

SOHN, Y. K., CHOUGH, S. K. (1989): Depositional processes of the Suwolbong tuff ring, Cheju Island (Korea). *Sedimentology*, 36: 837-855.

SOHN, Y. K., CHOUGH, S. K. (1992): The Ilchulbong tuff cone, Cheju Island, South Korea: depositional processes and evolution of an emergent, Surtseyan-type tuff cone. *Sedimentology*, 39: 523-544.

SOHN, Y. K., CHOUGH, S. K. (1993): The Udo tuff cone, Cheju Island, South Korea transformation of pyroclastic fall into debris fall and grain flow on a steep volcanic cone slope. *Sedimentology*, 40: 769-786.

SOHN, Y. K., PARK, J. B., KHIM, B. K., PARK, K. H. and KOH, G. W. (2002): Stratigraphy, petrochemistry and Quaternary depositional record of the Songaksan tuff ring, Jeju Island, Korea. *Journal of Volcanology and Geothermal Resources*, 19: 1-20.

SOHN Y. K., PARK K. and YOON S. (2008): Primary versus secondary and subaerial versus submarine hydrovolcanic deposits in the subsurface of Jeju Island, Korea. *Sedimentology*, 55: 899-924.

SPARKS, R. S. J. (1976): Grain size variations in ignimbrites and implications for the transport of pyroclastic flows. *Sedimentology*, 23: 147-188.

SULPIZIO, R., MELE, D., DELLINO, P. and LAVOLPE, L. (2007): Deposits and physical properties of pyroclastic density currents during complex Subplinian eruptions: the AD 472 (Pollena) eruption of Somma-Vesuvius, Italy. *Sedimentology*, 54: 607-635.

TALLING, P. J., MASSON, D. G., SUMNER, E. J. and MALGESINI, G. (2012): Subaqueous sediment density flows: Depositional processes and deposit types. *Sedimentology*, 59: 1937-2003.

THORARINSSON, S., EINARSSON, T., SIGVALDASON, G. and ELISSON, G. (1964): The submarine eruption off the Vestmann Islands 1963–1964. *Bulletin of Volcanology*, 27: 435-445.

TUCKER, M. (ed.) (2004): Techniques in Sedimentology. Blackwell Science, 394 p.

VALENTINE, G. (1987): Stratified flow in pyroclastic surges. *Bulletin of Volcanology*, 49: 616-630.

VESSEL, R. D., DAVIES, D. K. (1981): Nonmarine sedimentation in an active fore arc basin. *In*: F. G. Ethridge and R. M. Flores (eds.): Nonmarine Depositional Environments: Models for Exploration. *Society for Sedimentary Geology Special Publication*, 31: 34-45.

WALKER, R. G., JAMES, N. P. (1992): Facies Models. Response to sea level changes. Geological Association of Canada, 380 p.

WATERS, A. C., FISHER, R. V. (1971): Base surges and their deposits: Capelinhos and Tall volcanoes. *Journal of Geophysical Research*, 76: 5596-5614.

WHITE, J. D. L. (1996): Pre-emergent construction of a lacustrine basaltic volcano, Pahvant Butte, Utah (USA). *Bulletin of Volcanology*, 58: 249-262.

WILLIAMS, M., SMELLIE, J. L., JOHNSON, J. S. and BLAKE, D. B. (2006): Late Miocene Asterozoans (Echinodermata) from the James Ross Island Volcanic Group. *Antarctic Science*, 18: 117-122.

WOHLETZ, K., SHERIDAN, M. (1983): Hydrovolcanic eruptions II. Evolution of basaltic tuff rings and tuff cones. *American Journal of Science*, 283: 385-413.