Interpreting ambiguous bedforms to distinguish subaerial base surge from subaqueous density current deposits

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Abstract
Bedform geometries of volcanogenic sedimentary structures such as dune, low- to high-angle cross-stratification and planar stratification produced in subaqueous and subaerial environments can be very similar. This has historically created difficulties in unambiguously distinguishing primary from reworked deposits, and gas-deposited versus water-deposited ones. The origins of dunes and associated structures within the pyroclastic deposits of basaltic Surtseyan-style eruptions exposed in seacliffs along the Cape Wanbrow coastline of the Northeast Otago region in the South Island of New Zealand are such an example. Careful analysis of contextual information of these deposits, including granulometry, dune geometry, grading, sorting and particle hydraulic equivalence, has been completed to distinguish between major flow types in different environments. To determine the depositional setting of the Cape Wanbrow dune-bearing deposits, a number of related sediments have been examined in more detail including well-described examples of (i) subaerial dry pyroclastic deposits, (ii) subaerial moist pyroclastic deposits, (iii) aeolian deposits, (iv) deposits of unidirectional fluid-gravity water flows (e.g. rivers) and cyclic tidal flows, and (v) aqueous sediment-gravity flow deposits encompassing both pyroclastic material and those with non-pyroclastic material. From this compendium, a framework has been created that allows users to compare the physical controls that shape each example with the factors controlling bedform deposition in that environment. Identifying key characteristics of the Cape Wanbrow dunes and comparing multiple flow types and environments using the designed framework indicates that they were deposited by subaerial dry pyroclastic density currents. This conclusion has wider implications for the entire Surtseyan stack at Cape Wanbrow, because it indicates that at least this volcano (Rua²) became emergent and fully subaerial during its lifespan.

Introduction
Distinguishing between subaqueous and subaerial ancient volcanogenic deposits can be difficult if rock features are poorly preserved, exposures are limited, and independent palaeoenvironmental indicators are absent or ambiguous (Fisher & Schmincke, 1984; Cole & Decelles, 1991; Trofimovs et al., 2007). In particular, assigning a subaqueous or subaerial interpretation to sedimentary structures such as dune, low- to high-angle cross-stratification and planar stratification has proven challenging because they can form in many settings and from many types of flow. This means bedforms and stratigraphy with similar, if not identical, bedform geometries have been described from both subaerial and subaqueous environments. It is important to study such structures in great detail because recognizing a subaqueous or subaerial setting of deposition and distinguishing among major flow types is crucial for our understanding of volcano-sedimentary processes and environments (White, 1991, 1996) and for assessment of volcanic hazards during and after eruptions (Lorenz, 2007).

The issue of distinguishing between subaerially versus subaqueously formed dunes has arisen before. Wohletz &
Sheridan (1983) identified dunes at Pahvant Butte, Utah, as being of subaerial, base-surge origin and built this into a general model for subaerial emplacement of ‘tuff rings’ beneath tuff cones. The same beds were reinterpreted by White (1996) as subaqueously formed dunes deposited under combined-flow conditions prior to tuff cone emergence. Before pyroclastic density currents (surge; base-surge) dunes became widely recognized in the 1970s, many pyroclastic beds were inferred to have been reworked by water or wind simply on the basis of the presence of cross-bedding (Denny, 1940). Wentworth (1937) disagreed with Stearns (1935) about an aeolian versus primary and pyroclastic origin for the black tuff from Diamond Head tuff cone. Smith & Katzman (1991) noted the ease of incorrectly identifying aeolian tuffs as surge deposits in proximal settings. Nocita (1988) inadvertentely described soft-sediment deformation in the Puye fan, New Mexico, as affecting pyroclastic surge deposits, but later retracted his interpretation in reply to a comment by McPherson et al. (1989) that demonstrated a fluval origin for those deposits. This long history of difficulties in unambiguously distinguishing primary from reworked deposits, and gas-deposited versus water-deposited ones, illustrates the significance of the problem.

Herein, a framework has been developed using examples of dune bedforms produced by different flow types in both subaqueous and subaerial settings that will allow users to compare key characteristics of such ambiguous sedimentary structures in order to interpret depositional setting and flow type. Dunes and associated structures will be described from subaqueous and subaerial environments with the aim of introducing a set of generally applicable criteria for distinguishing subaerially from subaqueously formed dunes in ancient volcanogenic successions.

To test the robustness of the framework, dunes and associated structures have been described in pyroclastic deposits of basaltic Surtseyan-style eruptions exposed in seacliffs along the Cape Wanbrow coastline of Northeast Otago, in the South Island of New Zealand (Fig. 1). These deposits lie within a monogenetic volcanic field known as the Waiakea-Deborah Volcanics (Gage, 1957; Coombs et al., 1986; Hoernle et al., 2006) and were formed by eruptions between 38 and 33 Ma that occurred on a continental shelf during a period when it was generally submerged, and at a site 10s of kilometres offshore from the nearest inferred contemporary shorelines. The stratigraphy of Cape Wanbrow indicates that eruptions produced multiple volcanoes whose edifices overlapped within a small area, but separated by millions of years. The small Cape Wanbrow highland includes the remains of six volcanoes that are distinguished by discordant to
locally concordant intervolcano contacts marked by biogenic accumulations or other slow-formed features (Fig. 1) (Moorhouse et al., 2015). Dunes and associated sedimentary structures, including low- to high-angle cross-stratification and planar stratification, only occur within the top 40 m of the second volcano of the Cape Wanbrow stack. The deposits of this volcano, named Rua², are located at the north end of the Cape (Fig. 1). By determining whether this key suite of bedforms were emplaced subaequously or subaerially will aid in better understanding the Cape Wanbrow succession, and particularly an evolution of Rua² Volcano.

DUNE-FORMING CURRENTS IN SUBAQUEOUS VERSUS SUBAERIAL SETTINGS

Before interpreting the depositional setting and flow type responsible for the emplacement of the ambiguous dune-bearing Cape Wanbrow deposits, it was necessary to first evaluate similar structures described from both subaqueous and subaerial environments that have a primary (e.g. pyroclastic density currents) or re-worked (e.g. aeolian re-sedimentation) origin.

To do this, key features of well-described examples of dunes are considered from (i) subaerial dry pyroclastic deposits, (ii) subaerial moist pyroclastic deposits, (iii) deposits of aeolian flows, (iv) subaqueous unidirectional and cyclic flow deposits (e.g. rivers, tides) and (v) subaqueous sediment-gravity flow deposits encompassing those comprising pyroclastic material and those with non-pyroclastic material. This procedure includes examination of the physical controls that shape each example and the factors controlling bedform deposition in each environment with the goal of using key deposit characteristics to determine a specific flow type and environment for deposition.

Subaerially developed dunes

First we consider dunes in volcanic subaerial environments developed from pyroclastic sediment-gravity flows (i.e. pyroclastic density currents) or the re-sedimentation by aeolian currents. Dunes in volcanic subaerial environments deposited by the former are thought to be formed by low-density, high-velocity and turbulent pyroclastic density currents (surges; Wright et al., 1980; Cole, 1991; Valentine & Fisher, 2000; Bridge & Demicco, 2008) with a first-order distinction proposed between moist currents, in which water droplets promote particle cohesion and aggregation, and dry currents in which no particle aggregation takes place (Allen, 1982; Bridge & Demicco, 2008).

Subaerial dry deposits

Dry dilute pyroclastic density currents (pyroclastic surges; ‘dry’ base surges) are low-density, high-velocity and dominantly turbulent (Walker, 1984; Cole, 1991; Bridge & Demicco, 2008; Douillet et al., 2013). Deposits are characteristically fines-poor and therefore tend to be better-sorted than their wet equivalents (most commonly have a sorting value of 1.5-σ). A key feature is the absence or lack of accretionary lapilli and/or vesicular tuff, reflecting a lack of condensed water droplets during emplacement (Sheridan & Updike, 1975; Fisher & Schmincke, 1984; Walker, 1984; Cole, 1991; Valentine & Fisher, 2000; Bridge & Demicco, 2008).

Commonly described characteristics of dunes are alternating coarser-grained and finer-grained sand layers that grade upwards from a planar stratification into dunes with cross-beds of relatively low angles. These dunes are broadly similar in shape to those in aeolian deposits, but comparatively higher sedimentation rates are reflected in their poorly sorted nature (Valentine & Fisher, 2000). The laminae within deposits of dry pyroclastic density currents usually have progressively steepening dips on the lee sides of dunes and build up in a down-current direction from either planar beds or previously formed dunes. Layers are usually truncated and overlain by continuous stoss- to lee-side layers with a sigmoidal shape that tend to thicken on the leeward side. Dunes have down-current-migrating crests with very few displaying up-current-migrating ones. It is uncommon to see bed bases that behaved plastically beneath ballistic particle impacts, and deposits generally reflect a tractional depositional style. Ash grade deposits in particular can look similar to those of wind-blown sand and dust, but the pyroclastic dunes are not as well-sorted (Valentine & Fisher, 2000).

Particles in dry dilute pyroclastic density currents, commonly depositing at the base of the current, move in traction carpets (Valentine & Fisher, 2000). Thick sequences of alternating fine- to coarse-grained pyroclastic material represent deposition by a highly pulsatory current formed by its inherent turbulence or multiple closely timed explosions. Common erosional truncations associated with these layers indicate that currents were at times erosional (Schmincke et al., 1973; Lorenz, 1986; Cole, 1991; White, 1991; Sohn, 1996; Dellino et al., 2004). The progressive or regressive nature of dunes is thought to be due to changes in velocity and flow regime, which have been suggested as an important ways of controlling bedform migration direction (Schmincke et al., 1973; Valentine, 1987; Chough & Sohn, 1990; Cole, 1991). Examples of geometries can be seen in Fig. 2.
Subaerial moist deposits

Moist pyroclastic density currents are low-density, high-velocity currents (Walker, 1984; Cole, 1991; Bridge & Demicco, 2008) that have water droplets present which cause fine-ash grains to cohere or adhere to larger grains, leading to the formation of accretionary and armoured lapilli. Particle aggregation increases near-vent deposition of fine-grained pyroclastic material, which causes deposits to be more poorly sorted than their dry equivalents. Some authors have suggested that cohesion produces steep sided dunes and associated cross-stratification (Allen, 1982; Valentine & Fisher, 2000). Cohesion causes ash particles to enter the depositional system as clusters rather than as individual particles, leading to the aggradation of plastically behaved beds (Valentine & Fisher, 2000). Soft-state deformation is common within deposits of moist pyroclastic currents, with prominent bedding sags formed beneath emplaced ballistic fragments (Schmincke et al., 1973; Cole, 1991; Valentine & Fisher, 2000). Similar to dry pyroclastic currents, deposits of moist currents display alternating thin beds of fine-to medium-grained ash that are often truncated and overlain by a thin, fine-grained and continuous layer from stoss side to lee side.

Dunes of moist pyroclastic density currents have a large variation in wavelength across the literature due to the steepness of the density gradient. Steeper gradients will result in shorter wavelengths and may be due to the distance from the vent (Valentine & Fisher, 2000). Dunes in the deposits of moist pyroclastic density currents can display progressive, regressive or stationary migration directions due to changes in velocity and flow regime which have been suggested as important ways of controlling bedform migration direction (Schmincke et al., 1973; Valentine, 1987; Chough & Sohn, 1990; Cole, 1991). Examples of geometries can be seen in Fig. 2.

Subaerial aeolian flow deposits

The entrainment of pyroclastic material in aeolian flows is an important mechanism for re-deposition of pyroclastic material. The dunes produced by aeolian re-
sedimentation are significant as they have distinctive characteristics that aid discrimination between a primary versus reworked origin. Wind-blown volcanioclastic deposits are typically fine to medium sand and very well sorted, lacking dense lapilli, blocks and very fine-grained ash. An abundance of mixed non-volcanic detritus can exist, and generally, fragments are better-rounded than those observed in pyroclastic density current deposits (Smith & Katzman, 1991; Valentine & Fisher, 2000; Hooper et al., 2012). Wind-blown dunes have migration and facies variations that do not radiate from a central point, for example a volcanic source (Valentine & Fisher, 2000). Typically, only lee-side structures are well-preserved and dune crests are truncated by planar erosional surfaces. The geometry of wavelengths and wave heights in aeolian flow deposits tends to be intermediate between dunes of dry subaerial pyroclastic density currents (low-angle cross-laminae) and moist subaerial pyroclastic density current deposits (high-angle cross-laminae). Examples of geometries can be seen in Fig. 2.

Subaqueously developed dunes

Dunes forming under water can be produced by flows ranging from turbidity currents in the deep sea (Prave & Duke, 1990; Mulder et al., 2009) to shallow streamflow in fluvial settings (Fielding, 2006). To understand dune formation in subaqueous settings, sediment-gravity flows (e.g. marine or lacustrine density currents), unidirectional flows (e.g. rivers, streams) and cyclic tidal flows have been examined.

Dunes in deposits of unidirectional water flows (e.g. streamflow)

The bedforms developed under unidirectional flows can be plotted as a function of flow strength. Velocity at a given depth of flow is plotted against (equivalent) grain size (Fielding, 2006). At low flow velocities, termed the lower flow regime, asymmetrical ripples form in finer sands and with greater flow power a lower plane bed forms in coarser-grained sediment. The lower plane bed phase condition then transforms into a dune phase with a further increase in flow strength. At higher flow strengths, termed the upper flow regime, dunes and ripples become washed out to form an upper plane bed, and at still higher flow velocity antidunes are formed in the antidune stability field. Dunes with larger grain sizes, however, may pass directly into the antidune stability field with increasing flow velocity (Fielding, 2006). When the flow strength reaches extreme values they produce chute-and-pool conditions in the uppermost flow regime, representing positive surges slowing down and forming hydraulic jumps (Schmincke et al., 1973; Alexander et al., 2001; Fielding, 2006; Postma et al., 2009; Cartigny et al., 2014). The key features of bedforms produced by unidirectional currents in flume experiments, and their equivalents in the rock record are summarized below.

Examples from unidirectional-flow flume experiments

Flume experiments documenting the flow characteristics and resultant deposits from subcritical and supercritical flows have offered insight into the formation of dunes, antidunes, chutes-and-pools and cyclic steps (Middleton, 1965; Jopling & Richardson, 1966; Hand, 1974; Cheel, 1990; Best & Bridge, 1992; Alexander et al., 2001; Yokokawa et al., 2009; Cartigny et al., 2014). Few of the latter structures and facies have been recognized and analysed from the sedimentary record, perhaps because they form during high-energy events and have poor preservation potential. Alternatively, the scarcity may reflect common misidentification of such structures and facies (Fielding, 2006; Cartigny et al., 2014).

Subcritical and supercritical flows in flume experiments have produced repeatable deposits across numerous experiments (Middleton, 1965; Hand, 1974; Alexander et al., 2001; Duller et al., 2008; Yokokawa et al., 2009; Cartigny et al., 2014). In flume experiments, sedimentary structures such as sub-horizontal plane beds, lenticular sets with boundary-conformable laminae, lenticular sets with convex tops that increase with curvature at higher flow energies, and asymmetric dunes and antidunes with long wavelengths and low amplitudes are characteristic of deposition by increasing flow energies that pass from an upper flow regime stage through to unstable antidune stage and chute-and-pool conditions (Alexander et al., 2001; Cartigny et al., 2014). Increasing flow energies ultimately results in cyclic steps; a series of slowly upslope migrating bedforms (steps), where each downward step (the lee side of the bedform) is manifested by a steeply dropping flow passing through a hydraulic jump before re-accelerating on the flat stoss side (Middleton, 1965; Hand, 1974; Alexander et al., 2001; Duller et al., 2008; Cartigny et al., 2011, 2014). Examples of geometries can be seen in Fig. 2.

Asymmetric dunes with long wavelengths and low amplitudes that locally aggrade to form a stack of dune structures are similar to unstable antidune and chutes-and-pools described from deposits of subaqueous supercritical flows, and must therefore be added to the list of dune types to be considered during interpretation. Examples are known from deep marine deposits (Prave & Duke, 1990; Mulder et al., 2009), fluvial ones (Fielding, 2006) and density current flume experiments (Middleton, 2006).
Examples from the rock record

Unidirectional water flows are dominant in fluvial settings (Miall, 1985; Fielding, 2006). Characteristics of dunes produced in the dune, and in upper flow regime, antitune stability fields are most similar to the dune structures produced by pyroclastic density currents, so it is important to include these in the framework for determining flow type and depositional setting for dune formation. A wide spectrum of deposit architectures can be produced by streamflow, and Fielding (2006) proposed an Upper Flow Regime Sheets, Lenses and Scour Fills element (upper flow regime = UFR), established to encompass sand-dominated, large-scale, upper flow regime architectural elements. UFR elements in fluvial deposits have been rarely reported because until recently structures within the element have not been recognized as having formed under the upper flow regime. Fielding (2006) identified a multitude of such UFR elements, which include sigmoidal and low-angle cross-bedding, planar lamination, flat and low-angle lamination with minor convex-upward elements, convex-upward bedforms that dip both down-current and up-current with low-angle cross-bedding and symmetrical drapes, and backsets terminating up dip against an upstream-dipping erosion surface. These structures characteristically formed at the transition from dunes to upper plane bed, followed by a transition to the antidune stability field, and finally recording chute-and-pool conditions in the uppermost transition to the antidune stability field, and finally transition from dunes to upper plane bed, followed by a face. These structures characteristically formed at the cross-bedding and symmetrical drapes, and backsets terminating both down-current and up-current with low-angle convex-upward elements, convex-upward bedforms that laminae, flat and low-angle lamination with minor include sigmoidal and low-angle cross-bedding, planar identified a multitude of such UFR elements, which formed under the upper flow regime. Fielding (2006)

Particular structures described by Fielding (2006) are comparable with dunes at Cape Wanbrow. Type 1 bedforms (fig. 7; Fielding, 2006) were described as having a sigmoidal shape with low-angle cross-bedding that grades laterally and vertically into planar lamination and is interpreted as recording the transition between the dune and upper plane bed stability field. Type 4 bedforms (Fig. 7; Fielding, 2006) are minor, convex-upward and associated with low-angle cross-bedding and symmetrical drapes and are interpreted as having formed in the antidune stability field, therefore recording a flow broadly increasing in strength (Fielding, 2006). Examples of geometries can be seen in Fig. 2.

Preservation of structures formed in the upper flow regime is favoured by rapid changes in flow stage followed by a falling stage too short-lived to rework sediment into lower regime bedforms (Jones, 1977; Fielding, 2006). This transition allows for rapid aggradation that records first, the dune phase conditions, followed by the abrupt transition into upper plane bed conditions and ultimately recording antidune conditions. Therefore, deposition of a UFR architectural unit records the progressive infilling of a single channel that is well-preserved due to the rapid rate of sediment aggradation (Rust & Gibling, 1990; Fielding, 2006).

Dunes in subaqueous deposits of sediment-gravity flows

Subaqueous pyroclastic density currents are a mixture of erupted particles and water driven across the sea floor by gravity, and result from either a subaqueous eruption or when a subaerial current travels into and mixes with water (Cole & Decelles, 1991; Carey, 2000; Freundt, 2003; Trofimovs et al., 2007). There has been much more work on non-volcanic subaqueous density currents, or particular sediment-gravity flows, in which sediment motion is in response to gravity and moves the interstitial fluid (Middleton & Hampton, 1973, 1976; Fisher, 1983). These offer insight into the behaviour and deposits of volcanic currents in subaqueous environments. Examples of flow types are discussed below.

Examples of non-pyroclastic material

Dunes are the most common type of bed wave in subaqueous sediment-gravity flows transporting sand and gravel. They are produced when sediment-transport rate increases on rippled beds or lower-stage plane beds when mean grain size exceeds 0.1 mm (Fisher, 1983; Bridge & Demicco, 2008). Dunes produced by subaqueous sediment-gravity flows comprising non-volcanic material can form in a large range of grain sizes (–2 to 3 phi) with most comprising grains between medium sand to silt (1 to 3 phi) deposited with moderate to poor sorting (1.0 to 2.0 phi), especially on lee-side slopes. Cross-stratification with low-angle, gently dipping lee sides and stoss sides that can be both asymmetrical and symmetrical usually build-up from conformable or erosional planar surfaces. Dunes have broad wavelengths (ca 20 to 60 cm) and low amplitudes (ca 2 to 6 cm) that can occur within bedsets that extend laterally for a few tens of metres (Walker, 1967; Skipper, 1971; Prave & Duke, 1990; Mulder et al., 2009). Dunes discussed by Prave & Duke (1990) and Mulder et al. (2009) from the Upper Cretaceous calciclastic turbidites record a wave-like stratification within continuous thin layers (5 to 20 cm) that resembles hummocky or swaley cross-stratification.
Dunes within deposits of non-pyroclastic sediment-gravity flows have been interpreted as forming by subcritical flows (Cartigny et al., 2011). The wave-like structures of Prave & Duke (1990) and Mulder et al. (2009) from the Upper Cretaceous calcilastic turbidites exposed in the western Basque Pyrenees have been interpreted as the product of Kelvin-Helmholtz instabilities formed at the upper flow interface of a turbidity current with surrounding ambient sea water. The turbidity current moves down-slope but, at certain times and places during deposition, there are bedforms that migrate up-current (Hand, 1974; Prave & Duke, 1990; Mulder et al., 2009; Cartigny et al., 2014). Large-scale dune-like structures on levees and canyon floors of submarine fan systems with symmetrical geometries combined with upslope migration directions described by Cartigny et al. (2011) are interpreted as antidunes formed by transitional to supercritical flows.

**Pyroclastic material**

Reports of dunes in pyroclastic subaqueous sediment-gravity flow deposits are remarkably rare with only a handful reported in the literature (Wright & Mutti, 1981; Heinrichs, 1984; White, 1996, 2001). Where documented they commonly display architectural characteristics such as, low-amplitude dunes with broad wavelengths and associated high-angle cross-stratification. These structures exist in poorly sorted, coarse to fine-ash beds that commonly have large clasts (>50 mm) present. Deposits of sediment-gravity flows made up of non-pyroclastic material display similar characteristics, including wavy or hummocky cross-stratification-like structures, but are commonly less poorly sorted than their pyroclastic equivalents and exist in mud to medium-grained sand. The absence or rarity of impact sags in pyroclastic material could be an indication of a subaqueous rather than subaerial setting. However, if volcanogenic sediments are known to be near glacial areas, glacial dropstones would need to be considered as they are common in deep water environments. Low-relief erosion surfaces. No sag structures are observed (White, 1996). Examples of geometries can be seen in Fig. 2.

Subaqueous dune-bearing deposits dominated by pyroclastic material typically form from dilute turbulent eruption-fed currents formed entirely under water. In the case of Pahvant Butte, the structure of the dunes is interpreted as having developed by interaction between aqueous density currents (eruption-fed sediment-gravity flows) and oscillatory currents beneath surface waves that were probably long-wavelength waves formed by the eruption (White, 1996).

**Description of dunes in Cape Wanbrow Deposits**

Moorhouse et al. (2015) constructed a volcano-by-volcano overview of the Cape Wanbrow peninsula using distinct unconformable surfaces. Volcano names are in one of the national languages of New Zealand, te reo Māori, and the numbers in superscript aid identification of where in the sequence each volcano comes. Rua² Volcano was the second volcano built at Cape Wanbrow and its deposits buried the massive tuff breccias of Tahi¹ Volcano. The deposits of Rua² are the most extensively preserved and exposed of the volcanoes represented in Cape Wanbrow and are 300 m thick normal to bedding. The deposits display complex internal erosion features and sedimentary structures within interbedded fine- to coarse-grained ash and lapilli tuff. An abrupt, discordant but relatively planar erosion surface separates the deposits of Rua² from those of Toro¹ Volcano, of which only 5 m of massive tuff breccia containing rip-up clasts of underlying tuff and heavily deformed thin bedded fine- to medium-grained tuff is exposed. Three-dimensional asymmetric linguoid ripples are recorded in one bed towards the top of the Toro¹ deposits, only 1 m below the unconformity that separates Toro¹ deposits from the overlying ones of Wha¹ Volcano. The Toro¹-Wha¹ boundary is a clearly discordant unconformable surface separating underlying bedded tuffs from overlying pillow lava. The surface is relatively planar and visible for 300 m northward from
cliff top to beach level at Boatmans Harbour with an apparent dip of about 20° northwards. Where vegetation does not obstruct the contact, it is clear that underlying beds are truncated, and next to the boundary are slightly deformed (Moorhouse et al., 2015).

Thin interbeds of fine- to coarse-grained ash and fine lapilli tuff with isolated blocks (<10 cm in length) and units of massive tuff breccia make up much of the Cape Wanbrow succession that is described in detail as lithofacies E1 and E2 in Moorhouse et al. (2015) (Fig. 3). A dominant depositional feature that appears in deposits of Rua² Volcano, which lies near the top of the stack of Surtseyan volcanoes, comprises broad (ca 1 to 2 m), low-amplitude (ca 10 to 20 cm) dunes that grade laterally and vertically into sub-planar stratified tuff beds. Low-amplitude dunes often have a sigmoidal profile, or less commonly comprise lenticular bedsets with convex tops. These dunes occur within lithofacies E3 of Moorhouse et al. (2015) and are restricted to the top 40 m of the 340 m thick Rua² succession (Fig. 3). Within this 40 m interval, dunes with sigmoidal profiles occur most commonly towards the base and top, while dunes with obvious convex tops are restricted to the middle of the 40 m section (Fig. 3). No accretionary lapilli are observed in this lithofacies.

Dunes with a sigmoidal profile have progressively steepening lee-side layers that are built up from either planar beds or previously formed dunes. The steepening lee-side layers are truncated and overlain by beds that are continuous from stoss sides to lee sides and range from slightly asymmetrical to sigmoidal (Fig. 4). The steepening lee-side layers are 1 to 4 cm in thickness, but most do not exceed 2 cm. They comprise alternating layers of fine lapilli and coarse-grained to fine-grained ash which fine upwards across the structure. Therefore, a normal profile of a dune will have fine lapilli making up the shallow dipping lee-side laminae, progressing through to steeper lee-side layers of fine-grained ash (Fig. 5). The overlying sigmoidal shaped beds are always thin (1 to 2 cm), fine-grained to medium-grained and pass vertically and laterally into sub-parallel beds that are commonly thicker and of coarser grain size (Fig. 5). Continuous layers are commonly slightly thicker on the lee side, indicating they were migrating away from source and are therefore ‘progressive’ (Allen, 1982; Cole, 1991). Locally intercalated among dunes are lenses of planar bedding with low-angle

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**Fig. 3.** Stratigraphic column of the Cape Wanbrow Rua² Volcano deposits. Thin interbeds of fine-grained to coarse-grained ash and fine lapilli tuff with isolated blocks is inferred to have been deposited subaqueously. These beds grade upwards into a lithofacies characterized by dune and low-angle cross-stratification.

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cross-beds and rare examples of high-angle cross-stratification (Fig. 6). Dunes are present both in isolation, and in stacks or series that either aggraded or migrated downslope (Fig. 7).

Rare lenticular sets with three-dimensionally convex tops are composed of thin beds (1 to 3 cm) of fine-grained to medium-grained ash and resemble hummocky cross-stratification with a wavy morphology where laminae thicken and thin to form convex-upward accretion hummocks and shallow depressions. These HCS-like structures are also non-symmetrical, with sets of laminae laterally prograding over short distances, displaying a unidirectional migration in the same direction as intercalated dunes with a sigmoidal profile (Fig. 8). They grade vertically into slightly wavy and planar lamination of a similar grain size that can also display a thickening and thinning around the dune crests. Dunes locally persist laterally for several metres with bedform spacing averaging 40 to 50 cm in intervals that vary from 20 cm to 1 m, with most no longer than 30 cm (Fig. 8).

**Constituents**

The constituents of the volcaniclastic rocks of Cape Wanbrow are mainly juvenile particles (White & Houghton, 2006) with only traces of accidental material, such as quartz grains. The following constituents can be found in the rocks of Cape Wanbrow: vesicular pyroclasts originally of translucent basaltic glass (sideromelane) pyroclasts, now altered to a mixture of clay minerals and zeolites (palagonite); rare dense originally sideromelane particles; crystals and crystal fragments; lithic fragments; zeolite interstitial cement; and calcite interstitial cement. Variations in the abundance of pyroclasts, sideromelane

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**Fig. 4.** Dunes with a sigmoidal profile that comprise progressively steepening lee-side layers built up from either planar beds or previously formed dunes. Large hollow arrow indicates inferred palaeoflow direction.
pyroclasts, crystals and lithic fragments can be interpreted in terms of varying magmatic processes and eruption dynamics (Moorhouse et al., 2015). Modification to original volcaniclastic populations (e.g. destruction of vesicular sideromelane pyroclasts and/or segregation of components) indicates reworking of volcanic source materials (Moorhouse et al., 2015).

**Granulometry**

Samples were collected from three different dunes at Cape Wanbrow for standard thin section grain-size analyses in order to determine the size characteristics across dunes. Images of selected thin sections are shown in Fig. 9. The samples were collected from three points across the dune, the base, middle and top, in order to characterize visible particle size grading both vertically and laterally across the dune (Fig. 9). Unfortunately, the strong alteration of pyroclastic grains in the Cape Wanbrow deposit has destroyed details of original depositional textures, and in particular, there is local evidence for small matrix grains that seem elsewhere to have been obscured or destroyed. Cement has locally replaced even coarse ash, and therefore,
granulometry may be missing a once-present fine-ash matrix (Moorhouse et al., 2015). Image analysis was completed to determine quantitative grain-size distribution and sorting for nine samples in which sufficient textural detail was resolvable. Because of the alteration, the images had to be ‘cleaned’ by visual interpretation of grain boundaries. Grain-size bins were defined as the maximum horizontal intercept measured with a millimetre scale (Krumbein, 1935) and converted to phi (\(\phi\)) units. Results from the samples, which include the base, middle and top of dunes, were plotted as cumulative curves (Fig. 9), and the median grain size \(M_d\) and sorting coefficient \(\sigma\) were calculated (Folk, 1980) (Fig. 10):

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M_d = \phi_{50}; \sigma = \frac{(\phi_{84} - \phi_{16})}{4} + \frac{(\phi_{95} - \phi_{5})}{6.6}
\]

where \(\phi_i\) is the grain size for which \(i\%\) of the total material is smaller than the given grain size.

Measured vertical and lateral particle size grading and sorting are consistent with those apparent in the field and indicate that dunes display a fining upward trend across their internal layers, and are overall moderately to poorly sorted. Cumulative curves for each representative
sample across a dune show that the base, middle and top have distinctive size distributions and ranges (Fig. 10). Basal samples are better-sorted and coarser-grained (average $\sigma$, 0.96; $M_d$, 0.5) than those samples collected in the centres of dunes, which in turn are poorly sorted (average $\sigma$, 1.19; $M_d$, 1). Samples collected at the very tops of dunes are slightly better-sorted and finer-grained than the rest of the dune (average $\sigma$, 0.94; $M_d$, 1.5).

Superimposed onto a median diameter ($M_d$) versus sorting coefficient ($\sigma$) graph (Fig. 10) are the ‘pyroclastic flow’ and ‘fall’ fields of Walker (1971) and the ‘base-surge’ field defined by Crowe & Fisher (1973). The fields of subaqueous-gravity flows that produce dunes are also plotted from available non-pyroclastic data (Walker, 1967, 1971; Allen, 1970; Crowe & Fisher, 1973; Prave & Duke, 1990; Mulder et al., 2009) and pyroclastic data (Wright & Mutti, 1981; Heinrichs, 1984; White, 1996) as well as a fluid-gravity flow field that encompasses both aeolian and fluvial data (Rust & Gibling, 1990; McLoughlin, 1993; Fielding et al., 1996; Fielding, 2006). The Cape Wanbrow samples overlap with the ‘pyroclastic fall’ field, the ‘base-surge’ field and both pyroclastic and non-pyroclastic sediment-gravity flow fields (Walker, 1967, 1971; Allen, 1970; Crowe & Fisher, 1973; Prave & Duke, 1990; Mulder et al., 2009).

Vesicular particles have a relatively low density when compared with standard quartz, feldspar or dense lithic grains, and as a result will behave differently. Settling-velocity data for the Cape Wanbrow samples cannot be obtained because the deposits are lithified. There are, however, settling-velocity data for similar vesicular particles from deposits of a shallow subaqueous basaltic eruption at Pahvant Butte determined from rapid
sediment analysis software (RSA) (Murtagh, 2011), and these data are used here to infer the ‘quartz-equivalent’ behaviour of the measured Cape Wanbrow deposits. Using data from Palhvant Butte and the scheme presented by Oehmig & Wallrabe-Adams (1993) and Manville et al. (2002), settling-tube data were plotted against actual particle size to produce a settling-velocity curve. The median grain size of the Cape Wanbrow

Fig. 10. Actual median diameter ($M_d$) and median diameter from settling-velocity equivalent grain sizes from rapid sediment analysis software (RSA) ($M_d$) versus sorting coefficient ($n$) for all Cape Wanbrow samples. Superimposed onto graph are the flow fields and fall fields from Walker (1971), the surge field of Crowe & Fisher (1973) as well as fields created from the data on non-pyroclastic (Allen, 1970; Mulder et al., 2009; Prave & Duke, 1990; Walker, 1967) and pyroclastic (Wright & Mutti, 1981; Heinrichs, 1984; White, 1996; Murtagh, 2011) subaqueous sediment-gravity flows and fluid-gravity flows (Rust & Gibling, 1990; McLoughlin, 1993; Fielding et al., 1996; Fielding, 2006). The number ‘8’ in ‘flow’ and ‘fall’ fields represents the greatest density of Walkers samples. Pyroclastic subaqueous-gravity flow fields are split into vesicular [data from Murtagh (2011)] and non-vesicular [data from Wright & Mutti (1981) and Heinrichs (1984)] groups. In order to compare pyroclastic and non-pyroclastic flow fields the granulometry data from Murtagh (2011) has been plotted twice, once with actual grain size (black diamonds) where they fall within the vesicular field and once using the settling-velocity equivalent grain sizes from rapid sediment analysis software (RSA) (green diamonds) where they plot within the non-vesicular field.

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samples was then plotted against the curve to determine the size of quartz spheres that would settle at the same rate as the vesicular particles (Fig. 11). Coarse-sand-grade (ca −0.5 to 0 φ) vesicular pyroclasts have settling velocities equivalent to those of medium quartz sand (ca 1 to 1.5 φ) (Fig. 11). These values are consistent with the relationships between settling velocities of standard quartz grains versus vesicular particles recorded by Oehmig & Wallrabe-Adams (1993) and Manville et al. (2002).

Wavelength and wave height of dunes

Wavelengths versus wave heights of dunes are plotted in Fig. 12. The majority of dunes have wavelengths between 2 to 3 m and wave heights between 20 and 30 cm. Wave heights are determined by measuring the thickest part of a dune structure from flat base to the top of the crest due to undulations in an aggrading sequence commonly affecting the shapes of succeeding layers, resulting in the height of a single lamina changing upwards (Waters & Fisher, 1971; Crowe & Fisher, 1973; Schmincke et al., 1973). For comparison, data on the dunes from Taal Volcano (Waters & Fisher, 1971; Crowe & Fisher, 1973), Ubehebe (Crowe & Fisher, 1973) and Laacher See (Schmincke et al., 1973) have been plotted on Fig. 12. The Cape Wanbrow dunes appear to follow the same trend as those at Taal Volcano, Ubehebe and Laacher See (Waters & Fisher, 1971; Crowe & Fisher, 1973; Schmincke et al., 1973).

DISCUSSION

Having established generally applicable criteria for distinguishing subaerially from subaqueously formed dunes in ancient volcanogenic successions by examining well-described examples of deposits from five major flow types, it is now possible to evaluate characteristics of the Cape Wanbrow dunes and associated structures. Table 1 and Fig. 2 summarize the criteria created for deposit characteristics produced by each flow type.

Dunes at Cape Wanbrow have a sigmoidal profile, low-angle cross-stratification and progressively steepening lee-side layers in coarse-grained to fine-grained tuff and lapilli tuff. They built up from either planar beds or previously formed dunes and are truncated by asymmetric to sigmoidal layers that are continuous from stoss side to lee side (Moorhouse et al., 2015).

Subaerially formed dunes

Characteristics that are consistent with deposition by subaerial dry pyroclastic density currents include; (i) a coarse to medium ash grain size (equivalent hydraulic grain size is medium-grained to fine-grained quartz) for most of the deposit (Fig. 9); (ii) poorly sorted nature (1 to 2 r) (Fig. 10); (iii) consistent scale (wavelengths between 1 to 7 m) (Fig. 12) unlike those formed by non-pyroclastic sediment-gravity flows that can range from wavelengths of 50 cm (Prave & Duke, 1990; Mulder et al., 2009) to 7 km (Cartigny et al., 2011); (iv) no evidence of accretionary or armoured lapilli; (v) no soft-state deformation; (vi) no basal beds plastically deformed by ballistic blocks or bombs; and (vii) evidence for a traction-dominated sedimentation stage (Table 1). These characteristics provide robust support for the interpretation that the Cape Wanbrow dunes were deposited by dry pyroclastic density currents.

Although the Cape Wanbrow dunes have an overall coarse to medium ash grain size, they do fine upwards with tops of dunes being dominated by a fine-grain size. This feature supports deposition by moist pyroclastic density currents which usually contain more fine-grained ash material. However, the Cape Wanbrow deposits lack any evidence for accretionary or armoured lapilli, soft-state deformation or plastically behaving beds which is a strong argument against deposition by moist pyroclastic density currents and has therefore been ruled out as the flow type for these dunes (Table 1).

Dunes and associated structures deposited by wind share some features with those of Cape Wanbrow. Both have low-angle to intermediate-angle dips (25 to 35°) and an absence of soft-state deformation and plastically
deformed bed bases from ballistics. However, key characteristics that rule out deposition by aeolian re-sedimentation are that aeolian deposits are characteristically fine-grained to medium-grained (1 to 3 $\phi$), very well sorted (0.35 to 0.50 $\sigma$) and are often ungraded to inversely graded. Cape Wanbrow dunes, however, are coarse-grained to fine-grained, moderately to poorly sorted and tend to fine upwards.

**Subaqueously formed dunes**

Key characteristics that the Cape Wanbrow dunes share with deposits of subaqueous sediment-gravity flows like those that formed the Pahvant Butte deposits described by White (1996) include a sigmoidal shape, progressive migration, no accretionary lapilli, low-angle internal unidirectional cross-stratification and associated lenses of high-angle cross-stratification and dipping layers that grade laterally and vertically into sub-horizontally stratified layers (Table 1).

Smoothly undulating truncation of the tops of cross-sets, amalgamation of cross-sets and broad scours in sub-horizontal layers in the Pahvant Butte sequence are interpreted by White (1996) as being an example of form discordance produced by oscillatory motion superimposed on the density currents during deposition. Similar wave influence could be consistent with the presence of convex topped dunes at Cape Wanbrow, except the succession is erosionally truncated and thus leaves no evidence of very shallow-water deposition just prior to shoaling, such as provided by deposit context at Pahvant Butte.

Although the dunes of pyroclastic sediment-gravity flow deposits have many similarities with the Cape Wanbrow ones there are some differences that need to be considered. Deposits of pyroclastic material in sediment-gravity flows are dominantly, poorly sorted (1 to 3 $\phi$), coarse-grained (1 to 2 $\phi$) and contain very little fine-grained material (Table 1). For example, the lithofacies at Pahvant Butte lacks any fine-ash layers, although locally

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**Fig. 12.** Plot of wavelength of dunes versus wave height for the Cape Wanbrow dunes (red dots). There is a general increase of wavelength with increasing amplitude thickness, where available wavelengths and wave heights from the major flow types have also been plotted to create the most probable wavelength – wave height fields for that flow type. The most extensive data published come from Schmincke et al. (1973), from Laacher See and Crowe & Fisher (1973) and from both Taal Volcano and Ubehebe Craters. Dunes in pyroclastic aqueous sediment-gravity flow deposits are very rare and only one example from White (1996) has been plotted.
Table 1. Summary of the common features of dunes in subaqueous and subaerial flow types

| Common Features of Dunes | Scale | Erosion features |
|--------------------------|-------|------------------|
|                          | WL    | WH   | Th    | Sp    |                              |
| **Subaerial Dunes**      |       |       |       |       |                              |
| Dry pyroclastic density currents |       |       |       |       |                              |
| Grain size: Coarse-grained (0 to 1 ϕ) | 1 to 7 m | 0.2 to 1 m | 0.1 to 1 m | ca 5 m | Little if any erosion occurs on the lee side |
| Equivalent grain size in quartz: Medium-grained (1 to 1.5 ϕ) |       |       |       |       | Stoss side not always present due to erosion |
| Sorting: Poorly sorted but better sorted in comparison to their moist equivalents (1.0 to 2.0 but averaging ca 1.5ϕ) |       |       |       |       | Overlying sigmoidal layers erode and truncate underlying low-angle cross-beds |
| Cross-bed dips: Generally low-angle dips that resemble aeolian deposits. Progressively steepening lee sides in a down-current direction |       |       |       |       | |
| Nature of continuous layers: Overlying and truncating continuous stoss- to lee-side layers with a sigmoidal shape that tends to thicken on the leeward side |       |       |       |       | |
| Nature of internal strata: Alternating low-angle, unidirectional, sigmoidal shaped cross-stratified coarse-grained and fine-grained layers. Grade upwards from a planar stratification |       |       |       |       | |
| Accretionary Lapilli: Not common/None |       |       |       |       | |
| Soft-state deformation: Not common/None |       |       |       |       | |
| Plastically deformed bed bases: Not Common but localized sag structures may be present |       |       |       |       | |
| Grain size: Fine-grained (2 to 3 ϕ) |       |       |       |       | |
| Equivalent grain size in quartz: Not much difference |       |       |       |       | |
| Sorting: Poorly sorted as well as more poorly sorted in comparison to their dry equivalents (2.0 to 4.0 ϕ) |       |       |       |       | |
| Cross-bed dips: Steep sided dunes and associated structures (cross-stratification) that become progressively steeper in a down-current direction |       |       |       |       | |
| Nature of continuous layers: Overlying fine-grained beds that are continuous from stoss- to lee side |       |       |       |       | |
| Nature of internal strata: Alternating thin beds of fine-grained to medium-grained ash displaying a constant thickness or has a slightly thicker stoss-side making dunes slightly asymmetric. |       |       |       |       | |
| Moist pyroclastic density currents |       |       |       |       | |
| Grain size: Fine-grained (2 to 3 ϕ) | Large variation | Large variation | <3 m | 3 to 20 m | Little if any erosion occurs on the lee side |
| Equivalent grain size in quartz: Not much difference |       |       |       |       | Stoss side not always present due to erosion |
| Sorting: Poorly sorted as well as more poorly sorted in comparison to their dry equivalents (2.0 to 4.0 ϕ) |       |       |       |       | Overlying sigmoidal layers erode and truncate underlying low-angle cross-beds |
| Cross-bed dips: Steep sided dunes and associated structures (cross-stratification) that become progressively steeper in a down-current direction |       |       |       |       | |
| Nature of continuous layers: Overlying fine-grained beds that are continuous from stoss- to lee side |       |       |       |       | |
| Nature of internal strata: Alternating thin beds of fine-grained to medium-grained ash displaying a constant thickness or has a slightly thicker stoss-side making dunes slightly asymmetric. |       |       |       |       | |
**Table 1. Continued.**

| Common Features of Dunes | Scale | Erosion features |
|-------------------------|-------|-----------------|
|                         | WL    | WH | Th | Sp | |
| **Aeolian flows**       |       |     |    |    | Typically only lee-side structures are well-preserved and dune crests are truncated by planar erosional surfaces Can be nearly monomict – epiclastic grains, reworked pyroclastic grains, or a mixture |
| Grade upwards from a planar stratification | 20 to 40 cm | 0.5 to 1 m | 0.5 to 1-0 m | 20 to 40 cm |
| Accretionary Lapilli: Common | | | | |
| Soft-state deformation: Common | | | | |
| Plastically deformed bed bases: Common | | | | |
| **Grain size:** | Fine- to medium-grained (1 to 3 | | | |
| **Equivalent grain size in pyroclastics:** | Coarse-grained (0 to 1 | | | |
| **Sorting:** | Very well sorted (0-35 to 0.50 m) | | | |
| **Cross-bed dips:** | Low-angle dips (25 to 35°) that are steeper than dry density current dips but shallower than most density current dips | | | |
| **Nature of continuous layers:** | Not common | | | |
| **Nature of internal strata:** | Ungraded to inversely graded, thin beds (ca 2 to 10 mm) and laminae with intermediate dip angles | | | |
| Accretionary Lapilli: | Not Common/None | | | |
| Soft-state deformation: | Not Common/None | | | |
| Plastically deformed bed bases: | Not Common/None | | | |
| **Subaqueous Dunes** | | | | |
| **Aqueous sediment-gravity flow – pyroclastic deposits** | | | | |
| **Grain size:** | Coarse-grained (0 to 1 | | | |
| **Equivalent grain size in quartz:** | Medium-grained (1 to 1.5 | | | |
| **Sorting:** | Poorly sorted to very poorly sorted (1-0 to 3-0 m) | | | |
| **Cross-bed dips:** | Low-angle dips and commonly locally intercalated with lenses of high-angle cross-stratification | | | |
| **Nature of continuous layers:** | Low-angled sigmoidal shapes where fully preserved or smoothly undulating truncation of the tops of cross-sets | | | |
| **Nature of internal strata:** | Low-angle sigmoidal shaped layers with internal unidirectional cross-stratification that grade laterally and vertically into sub-horizontally stratified ash layers | | | |
| Accretionary Lapilli: | Not common/None | | | |
| Soft-state deformation: | Not common | | | |

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| Common Features of Dunes                                      | Scale | Erosion features                                                                 |
|--------------------------------------------------------------|-------|----------------------------------------------------------------------------------|
| **Plastically deformed bed bases:** Not common/None          | 0-2 to 0-6 m | Common to have erosional bases                                                   |
| **Grain size:** Medium sand to silt (1 to 3 φ)               | 0-2 to 0-6 m | Structures often truncated by erosional surfaces                                |
| **Equivalent grain size in pyroclastics:** Coarse-grained (0 to 1 φ) |       | Truncation between different generations of structures meaning only remnants of the hummocks retained |
| **Sorting:** Moderately to poorly sorted (0-5 to 2-0 φ)      |       | No erosion at the base of the swale                                             |
| **Cross-bed dips:** Gently dipping with associated low-angle cross-stratification |       |                                                                                   |
| **Nature of continuous layers:** Wavy-like stratification within continuous thin layers (5 to 20 cm) that resemble hummocky cross-stratification. Overlain by swaley-fill layers that thicken above swales and thin above hummocks |       |                                                                                   |
| **Nature of internal strata:** Low-angle and symmetrical lee- to stoss dips that increase in dip angle in a down-current direction becoming non-symmetrical. Built up on a planar, conformable or erosional surface |       |                                                                                   |
| **Accretionary Lapilli:** Not common/None                    |       |                                                                                   |
| **Soft-state deformation:** Not common (rapid deposition)    |       |                                                                                   |
| **Plastically deformed bed bases:** Not common               |       |                                                                                   |
| **Grain size:** Fine to medium-grained (1 to 2 φ)            | 1 to 2 m | Different elements separated by erosion surfaces                               |
| **Equivalent grain size in pyroclastics:** Coarse-grained (0 to 1 φ) | 0-01 to 0-03 m | Overlapping erosion surfaces                                                    |
| **Sorting:** Well sorted (0-35 to 0-50 φ)                     |       | Increasing flow strengths and formation of chute-and-pools creates an upstream-dipping erosion surface |
| **Cross-bed dips:** Low-angle cross bedding                  |       |                                                                                   |
| **Nature of continuous layers:** Sigmoidal to symmetrical drapes |       |                                                                                   |
| **Nature of internal strata:** Either a sigmoidal shape with low-angle cross-bedding or minor convex-upward bedforms |       |                                                                                   |
| **Grading upward from:** Grades laterally and vertically from and into planar lamination |       |                                                                                   |
| **Accretionary Lapilli:** Not common (rapid deposition)      |       |                                                                                   |
| **Plastically deformed bed bases:** Not common               |       |                                                                                   |
| **Aqueous sediment-gravity flow – epiclastic material**      |       |                                                                                   |
ripples in finer-grained ash advance down the gently dipping dune foresets (White, 1996). The dunes of Cape Wanbrow differ with a moderately to poorly sorted nature (0.5 to 1.2 σ), fine-grained ash tops and in particular a fine-ash sigmoidal drape. These differing features argue against aqueous sediment-gravity flows as the depositional mechanism for the Cape Wanbrow dunes.

The Cape Wanbrow dunes with their broad wavelength, low amplitude and in particular convex tops that resemble hummocky cross-stratification can be likened to deposits of non-pyroclastic subaqueous sediment-gravity flow deposits like those described by Prave & Duke (1990) and Mulder et al. (2009) (Table 1). Five major differences between the Cape Wanbrow structures and these HCS-like forms within the deposits of sediment-gravity flow deposits are notable (Table 1): (i) Cape Wanbrow deposits are overall coarser-grained, although this coarser-grained nature could be explained by the different settling velocities of low-density vesicular particles at Cape Wanbrow (Oehmig & Wallrabe-Adams, 1993; Manville et al., 2002) (Fig. 11); (ii) Cape Wanbrow dunes have a larger grain-size variation than those described from the HCS-like deposits; (iii) frequent small-scale syn-sedimentary deformation features, common within HCS-like deposits, are not common within the dunes of Cape Wanbrow; (iv) HCS-like structures frequently show migration trends with an upslope motion but mostly do not display a dominant migration direction, whereas the dunes at Cape Wanbrow show a strong down-current migration; and (v) the average wave height and wavelength is much smaller than those within the Cape Wanbrow succession (Fig. 12). Based on these major differences, deposition by subaqueous sediment-gravity flow or combined-flow HCS seems unlikely (Table 1).

Unidirectional current deposits (e.g. fluvial currents) of the upper flow regime field seem to offer a good potential analogue for the Cape Wanbrow dunes with similar deposit architecture and characteristics (Table 1). In particular, types 1 and 4 of the sedimentary structures described by Fielding (2006) formed by unidirectional currents in upper flow regime are recognized in the Cape Wanbrow deposits (Fig. 2). These dune geometries make up part of eight main types of UFR elements which together form a hierarchy that is representative of an increasing flow strength and where preservation potential is high. Taking the features of UFR deposits and the high preservation potential into consideration, if the Cape Wanbrow dunes were deposited by unidirectional currents in the upper flow regime, as were those described by Fielding (2006) it might be expected that most, if not all eight types of UFR deposits would be present. Instead, only types 1 and 4 are recognized. There are also differences in grain size (silt to fine sand in upper flow regime unidirectional currents as opposed to fine to coarse ash) and sorting (well sorted as opposed to moderately to poorly sorted) (Table 1), although part of this grain-size difference may be due to the settling velocity of vesicular particles being less than that of quartz, feldspar and lithoclasts (Oehmig & Wallrabe-Adams, 1993; Manville et al., 2002). These characteristics along with the lack of any hierarchical UFR deposit elements make deposition from unidirectional upper flow regime flows unlikely. There is also the question of where, in the context of a small island volcano, such UFR deposits could form other than in the sharply incised channels known from such volcanoes (Fisher, 1977; Verwoerd & Chevallier, 1987). Analysis of the architecture of dunes described from some flume experiments that produced broadly similar dunes to those in the Cape Wanbrow succession led to identification of significant differences between them. Key differences include (i) the average wavelength of dunes produced by Middleton’s (1965) flume experiments are ca 50 to 80 cm with the largest 1 m long in an experimental tank 40 m long (Alexander et al., 2001; Spinewine et al., 2009; Cartigny et al., 2014); these wavelength values for experimental dunes are much shorter on average than those at Cape Wanbrow (ca 2 to 3 m); and (ii) these flume dunes lacked evidence for structures with steepening lee-side layers and a sigmoidal-shaped fine-grained drape, which is a key characteristic of the Cape Wanbrow dunes. Based on the significant differences discussed, deposition by subaqueous subcritical and/or supercritical flows would have to be ruled out for at least the majority of the Cape Wanbrow deposit.

Having used the created framework (Table 1) to compare the dunes and associated sedimentary structures found at the top of Rua2 Volcano in the Cape Wanbrow succession to five major flow types in both subaerial and subaqueous environments, the geometrical and granulometric characteristics defined are most similar to the deposits of subaerial dry dilute pyroclastic density currents and pyroclastic subaqueous sediment-gravity flows. Dunes deposited by dry dilute pyroclastic density currents (Table 1) are characteristically poorly sorted, coarse-grained and fines-poor with alternating coarse-grained and fine-grained layers that grade upwards from a planar stratification (Valentine & Fisher, 2000) (Table 1). Dunes in volcanioclastic subaqueous sediment-gravity flow deposits are dominantly coarse-grained, poorly sorted and have intercalated lenses of high-angle cross-stratification. Cape Wanbrow dunes comprise alternating layers of coarse-grained and fine-grained tuff that grade upwards from planar stratification and become finer-grained upwards and become fines-dominant at dune tops.

Due to dunes in both volcanioclastic subaqueous sediment-gravity flows and dry dilute pyroclastic density
currents being characteristically coarse-grained the only remaining feature that matches the Cape Wanbrow dunes is the progressively steepening layers of alternating fine-grained and coarse-grained material found only in subaerial dry dilute pyroclastic density current deposits as described by Valentine & Fisher (2000). Based on this, the dunes of the Cape Wanbrow deposits are interpreted to have been emplaced subaerially by dry dilute pyroclastic density currents. This interpretation has major implications for the Cape Wanbrow stack as it demonstrates that at least one of the volcanoes (Rua2) became emergent during its lifespan and that subaerially formed deposits were preserved despite the offshore-island setting.

Rua2 Volcano: an emergent volcano

The study by White (1996, 2001) of Pahvant Butte, a small volcano that erupted into a now absent pluvial lake in the Pleistocene is an excellent example of a subaqueous to emergent volcano and offers an opportunity to compare the Rua2 Volcano deposits to the overall deposit characteristics of an emergent volcano.

Based on accounts of deposits at Pahvant Butte, which record the evolution from subaqueous to moist subaerial to dry subaerial, a well-preserved succession of subaquous to emergent to fully subaerial should include examples of (i) clearly subaquously deposited tephra followed by (ii) ripple-marked shoreline beds; (iii) subaerial cone moist density currents deposits with accretionary and armoured lapilli and potentially (iv) a transition to dry phreatomagmatic activity with subaerial grainflow and fallout processes.

The lower deposits of Rua2 were noted subaqueously by eruption-fed currents and offer no indications of becoming emergent, for example no ripple-marked shoreline beds or moist density currents deposits containing accretionary lapilli. The top 40 m of the Rua2 Volcano succession is interpreted as being deposited by subaerial dry pyroclastic density currents based on the geometrical and granulometric characteristics of the deposits. Therefore, Rua2 Volcano started its life subaquously and became an emergent tuff cone to form an island and shoreline.

The expected deposits of an emergent volcano, including ripple-marked shoreline beds and moist density current deposits, are missing from the Rua2 Volcano succession. There is also a general absence of shoreline and tuff cone deposits in emergent volcanoes recorded in the literature, other than Pahvant Butte. This situation is probably due to removal of most emergent deposits, because emergent tuff cone deposits of an island are subject to slumping in response to collapse of the tephra pile and/or erosion and transportation by normal wave action; such slumping can shift originally subaerial deposits into a subaqueous position. Evidence for these processes acting on the emergent deposits of the Rua2 volcano includes localized small-scale faults and truncations, onto which sedimentary sequences onlap (Moorhouse et al., 2015). These are the result of remobilized tephra by slumping as the pile over-steepens, which likely occurs during or shortly after deposition (Sohn et al., 2012; Moorhouse et al., 2015).

The conditions that allowed preservation of the subaerial pyroclastic succession of Rua2 were probably sector collapse resulting in relocation of originally subaerial deposits to sites below wave base, where preservation potential is much greater. There were global sea-level changes of sufficient magnitude to make the site subaerial at times, but no published evidence for any non-volcanic subaerial deposits in the region in the Oligocene. Other volcanoes in the field may have emerged to form islands, but there is no direct evidence of emergence (Andrews, 2003; Maicher, 2003; Corcoran & Moore, 2008), and perhaps the best known of these, Bridge Point, has been specifically inferred to have stopped erupting before doing so (Cas et al., 1989).

CONCLUSION

Distinguishing between subaqueous and subaerial deposits in ancient volcanogenic successions remains a difficult task and becomes progressively harder when rock features are poorly preserved, exposures are limited, and independent palaeoenvironmental indicators are absent or ambiguous. However, careful attention to contextual information of sedimentary structures like dunes, low- to high-angle cross-stratification and planar stratification that are commonly reported in both subaerial and subaqueous environments has meant the uncertainty over the origin of Oligocene-Eocene aged dunes at Cape Wanbrow, Oamaru, has been partially removed. It is inevitable that questions remain regarding each interpretation, for example the relationship between subaquously deposited material and dunes interpreted as deposited by dry dilute pyroclastic currents at Cape Wanbrow as well as the reason for a lack of emergent-style deposits similar to those reported at Pahvant Butte (White, 2001), but the comparisons made and distinctions drawn between deposits of the Cape Wanbrow lithofacies and broadly similar ones of other origins provide a framework for interpreting dunes and related strata of other explosive subaqueous to shallow marine, emergent and subaerial volcanoes.
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