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Origin of spectacular fields of submarine sediment waves around volcanic islands

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ABSTRACT

Understanding how large eruptions and landslides are recorded by seafloor morphology and deposits on volcanic island flanks is important for reconstruction of volcanic island history and geohazard assessment. Spectacular fields of bedforms have been recognised recently on submerged flanks of volcanic islands at multiple locations worldwide. These fields of bedforms can extend over 50 km, and individual bedforms can be 3 km in length and 150 m in height. The origin of these bedform fields, however, is poorly understood. Here, we show that bedforms result from eruption-fed supercritical density flows (turbidity currents) in some locations, but most likely rotational landslides at other locations. General criteria are provided for distinguishing between submarine bedforms formed by eruptions and landslides, and emphasise a need for high resolution seismic datasets to prevent ambiguity. Bedforms associated with rotational landslides have a narrower source, with a distinct headscarp, they are more laterally confined, and internal bedform structure does not suggest upslope migration of each bedform. Eruption-fed density currents produce wide fields of bedforms, which extend radially from the caldera. Internal layers imaged by detailed seismic data show that these bedforms migrated up-slope, indicating that the flows that produced them were Froude supercritical. Due to the low density contrast between interstitial fluid and sediment, the extent and dimensions of submarine eruption-fed bedforms is much greater than those produced by pyroclastic density currents on land.

1. Introduction

Silicic caldera-forming eruptions and landslides on volcanic islands represent some of the highest sediment flux events on Earth. They can transport tens to hundreds of cubic kilometres of material (Pyle, 1995; Hunt et al., 2013), most likely over a few hours to days. Both caldera-forming eruptions and landslides are extremely hazardous for local populations, and can generate far-travelling tsunami that effect more widespread distal coastlines. Explosive eruptions produce large amounts of material that can be rapidly transferred from the vent to submarine slopes and basins via volcaniclastic density flows (Cas and Wright, 1991; Allen et al., 2012). The landslides that occur on volcanic flanks can be unusually large, and involve both the subaerial and submarine domains of the edifice (White, 2000; Masson et al., 2006; Watt et al., 2012). Further, they can also evacuate material to surrounding basins through density flows (Le Friant et al., 2015; Watt et al., 2015). It is therefore important to understand how eruptions and landslides are recorded on submerged volcanic island flanks, and to distinguish between caldera-forming density current deposits and large submarine landslides as they pose distinctly different types of hazards.

Worldwide, recent work has recognised extensive fields of bedforms on submerged volcanic island flanks (Wright et al., 2006; Silver et al., 2009; Gardner, 2010; Leat et al., 2010 and references

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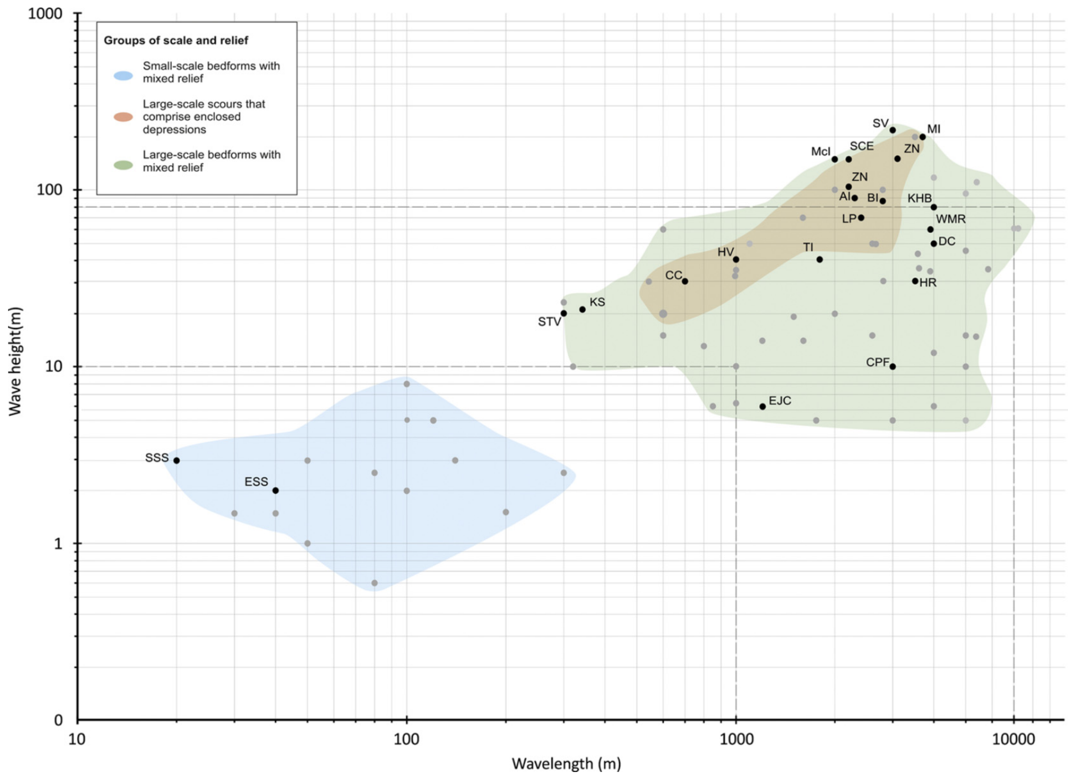

Fig. 1. Logarithmic plot of wavelength versus wave height for global submarine bedform examples. Black points indicate volcanic setting. Grey points indicate other settings. AI – Adventure Island; BI – Bristol Island; CC – Cilaos Canyons; CPF – Cilaos Proximal Fan; DC – Dakataua Caldera, New Britain; EJC – El Julan Channel; ESS – Etang-Salé Sector, La Reunion; HV – Haleakala Volcano; HR – Hawaiian Ridge; KS – Kahouanne Seamounts; KHB – Kimbe and Hixon Bay; LP – La Palma; McI – Macauley Island; MI – Montagu Island; SCE – South Candlemas Embayment; STV – Stromboli Volcano; SV – Sumisu Volcano; TI – Tolokiwa; WMR – West Mariana Ridge; ZN – Zavodovski. Adapted from Symons et al. (2016). See Symons et al. (2016) for full reference list. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

therein) that are some of the largest amplitude bedforms yet documented on the seafloor (Fig. 1; Symons et al., 2016). 'Bedform' is used here to denote undulations without any reference about their origin. These undulating areas of seafloor can extend for over 50 km, and individual bedforms have wavelengths up to 3 km, and wave heights of 10–150 m. However, the origin of these bedforms is uncertain. As shown by debate over the origin of such bedforms in non-volcanic settings, they can potentially result from both rotational landslide blocks and remoulding of the seabed by density flows (Lee et al., 2002).

The origin of these submarine bedforms is also particularly interesting because they are larger than any known bedforms on the subaerial flanks of volcanoes. Identified submarine bedform fields are extensive and contain large amplitude bedforms. In contrast, subaerial volcanic flank bedform fields are less extensive and contain smaller-scale bedforms associated with terrestrial dilute pyroclastic density currents (e.g. Sigurdsson et al., 1987; Branney and Kokelaar, 2002; Brown and Branney, 2004), or irregular hummocky terrain formed by debris avalanches and landslides (e.g. Crandell et al., 1984; Cas and Wright, 1991). We therefore seek to understand what the contrasting dimensions of submarine and subaerial bedform fields can tell us about important general differences between subaerial and submarine volcanic mass flows (Moorhouse and White, 2016).

Eruption-fed submarine density flows sourced from either subaerial or submarine vents can be initiated by either collapse of eruption columns or disintegration of active lava domes (Cas and Wright, 1991; Kokelaar and Busby, 1992; Head and Wilson, 2003). Sediment waves (cyclic steps, anti-dunes, etc.) and scours are thought to be the submarine slope expression of these flows (Kostic and Parker, 2006; Spinewine et al., 2009; Cartigny et al., 2011).

Failure of submarine volcanic shelves and slopes can result from earthquakes, edifice uplift, magma intrusion and extrusion or the sudden accumulation of large volumes of pyroclasts during volcanic eruptions (Watt et al., 2014). These failures commonly affect deep substrate and terminate proximally at steep headwall scars (Masson et al., 2006). Landslide deposits include rotated domains, huge individual blocks, and various types of density flow deposits (Masson et al., 2006; Watt et al., 2015). Landslide deposits made up of rotated blocks can form an undulating seafloor that shares some surficial similarities to sediment waves emplaced by eruption-fed density flows (Lee et al., 2002; Leat et al., 2010). This can make it difficult to distinguish landslide block and sediment flow deposits, as previously noted for bedforms in non-volcanic sites (Lee et al., 2002).

Our lack of understanding of proximal submarine volcanic slope deposits is a consequence of the lack of attention that they have received. Basin records of volcanic deposits are relatively well understood from the rock record (Trofimovs et al., 2006; Allen and McPhie, 2009; Jutzeler et al., 2014a) and ocean drilling (Nishimura et al., 1991; Le Friant et al., 2015; Busby et al., 2017). In contrast, scientific drilling has never been successful in proximal environments (ODP135; IODP340), high-resolution geophysical data is limited (Gardner, 2010; Leat et al., 2010; Casalbore et al., 2014a, 2014b), and extensive subaerial exposures of these deposits are rare and often incomplete (Cas and Wright, 1991; Allen and McPhie, 2009).

1.1. Aims

Our overall aim is to understand the origin and wider significance of extensive fields of bedforms on volcanic island flanks, whose occurrence has been recently recognised in locations world-