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Contrasting styles of deep-marine pyroclastic eruptions revealed from Axial Seamount push core records

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ABSTRACT

A comprehensive understanding of explosive basaltic eruption processes in the deep-sea relies upon detailed analysis and comparison of the variety of volcaniclastic lithologies on the seafloor, which has been challenged by insufficient sample recovery. A dedicated ROV-based sampling approach using long push cores offers an unparalleled opportunity to fully characterize the diversity of unconsolidated volcaniclastic lithofacies on a recently active seamount. Lithofacies from Axial Seamount record two styles of pyroclastic eruptions, strombolian and phreatomagmatic, at 1.5 km water depth. Strombolian eruptions are represented by abundant fluidal and highly vesicular (up to 50%) vitriclasts within limu o Pele lapilli tuff and tuffaceous mud lithofacies. Lapilli-ash grain size, normal grading, good sorting, rip-up clasts and homogeneous glass geochemistry characterize individual limu o Pele lapilli tuff beds, and imply proximal deposition from a turbidity flow associated with a single eruption (i.e. event bed). Limu o Pele lapilli tuff beds are interbedded with poorly sorted, chemically heterogeneous and bioturbated tuffaceous mud units that preserve reworking and biologic habitation of more distal pyroclastic fallout and dilute turbidity flows. The phreatomagmatic eruption style is preserved by hydrothermal mineral-bearing muddy tuff that exhibits characteristics distinct from lapilli ash and tuffaceous mud lithofacies. Hydrothermal muddy tuff lithofacies are well-sorted and fine-grained with notable components of non-fluidal basaltic ash (∼45%), fluidal ash (∼30%) and accessory lithics (∼25%). Heterogeneous geochemistry of ash shards implies that juvenile components are minimal. The abundance, mineralogy and texture of lithic components (Fe–Mg clays, pyrite, epidote, actinolite, altered glass, basalt/diabase, hydrothermal breccia and agglutinate), and very fine-grain size of basaltic ash, are consistent with phreatomagmatic eruption deposits. A lack of bioturbation or other interbedded lithofacies, and presence of normal grading suggests prolonged eruption activity and deposition via turbidity flows or suspension fallout. The proximity of ancient hydrothermal muddy tuff lithofacies and active hydrothermal vents to caldera walls suggest that phreatomagmatic activity was linked to shallow circulation of fluids along caldera ring-faults rooted to underlying magma conduits and shallow reservoirs. This study provides evidence for two distinctly different pyroclastic eruption styles and provides a framework to further develop existing models of deep-sea explosive volcanism.

1.1. Introduction

Deep-sea pyroclastic eruptions of basalt occur throughout the world's ocean basins, and are preserved by modern to ancient deposits exposed on the seafloor, emergent ocean crust and ophiolites (Staudigel and Schmincke, 1984; Gill et al., 1990; Hekinian et al., 2000; Clague et al., 2003a; Sohn et al., 2008; Portner et al., 2010). Theoretical modeling, laboratory experiments, and direct observation of active pyroclastic eruptions have refined the paradigm that magmatic volatile build-up can overcome high hydrostatic pressure on the deep-seafloor sufficient for eruption explosivity (e.g., Head and Wilson, 2003; Embley et al., 2006; Resing et al., 2011; Stix and Phillips, 2012). Nevertheless, the association of volcaniclastic deposit characteristics to eruption style and dispersal process is still debated (Maicher et al., 2000; Clague et al., 2009a; Schipper and White, 2010). This association is fundamental

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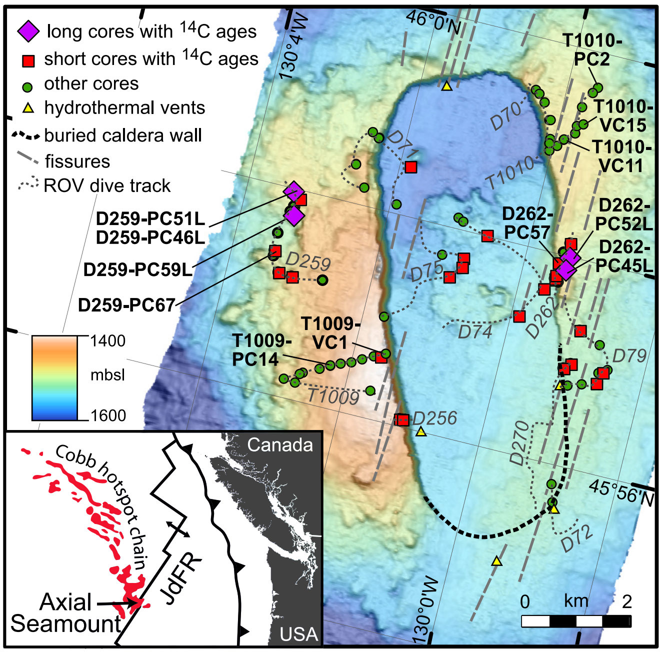

Fig. 1. Map of Axial Seamount showing ROV dive locations (grey text labels) and push core sites. Cores used for sedimentologic analysis in this study are labeled (bold). Volatile and calorimetry data from cores collected during 2006 (dives T1009 and T1010) are presented in Helo et al. (2011, 2013). Bathymetry is gridded at 20 m resolution from ship-based EM300 multibeam sonar. Inset shows position of Axial Seamount along the Juan de Fuca Ridge (JdFR).

for understanding fragmentation processes, particle transport and sedimentary budgets along the mid-ocean ridge system, and can be critically evaluated using traditional lithofacies analysis.

In this study, we describe volcaniclastic and sedimentary lithofacies formed ~1500 m below sea level (mbsl) on Axial Seamount in order to better understand the formation, transport and deposition of clastic material produced by some deep-marine eruptions of mid-ocean ridge basalt (MORB). Componentry, granulometry, glass shard chemistry and ^{14}C chronostratigraphy are used to investigate trends between particle components and grain sizes, characterize lithofacies, and understand eruption and depositional processes. Enhanced sampling methodologies provide a new suite of long ROV-collected sediment push cores that contain lithofacies assemblages much more diverse than previously recognized on Axial Seamount. An advantage of working with poorly consolidated deposits, compared with ancient consolidated sample suites (e.g. Portner et al., 2014), is the ability to conduct componentry and granulometry analyses, and examine particle morphologies in great detail. Such detail is invaluable in understanding fragmentation mechanisms and associated eruption styles (e.g. Büttner et al., 2002). Results presented here provide a modern analog for understanding the lithostratigraphy of ancient ocean crust and ophiolites.

2.1. Axial Seamount

Axial Seamount is an active on-axis volcano located on the central segment of the intermediate spreading-rate Juan de Fuca mid-ocean ridge (JdFR; Fig. 1). It is the youngest seamount formed by the Cobb hotspot, which has created a chain of submarine volcanoes that stretches for 1800 km to the northwest of the JdFR to the Aleutian Trench (Desonie and Duncan, 1990). Axial Seamount produces normal to transitional MORB that is slightly more enriched and primitive than basalts generated immediately to the north and south along the spreading ridge axis (Chadwick et al., 2005; Dreyer et al., 2013). Glass inclusions hosted by plagioclase crystals in some deposits described here (see T1009 and T1010 samples in Fig. 1) indicate that some magmas on Axial Seamount contained primary volatile contents up to 9000 ppm CO_2, which is proposed to have caused pyroclastic eruptions on Axial Seamount (Helo et al., 2011).

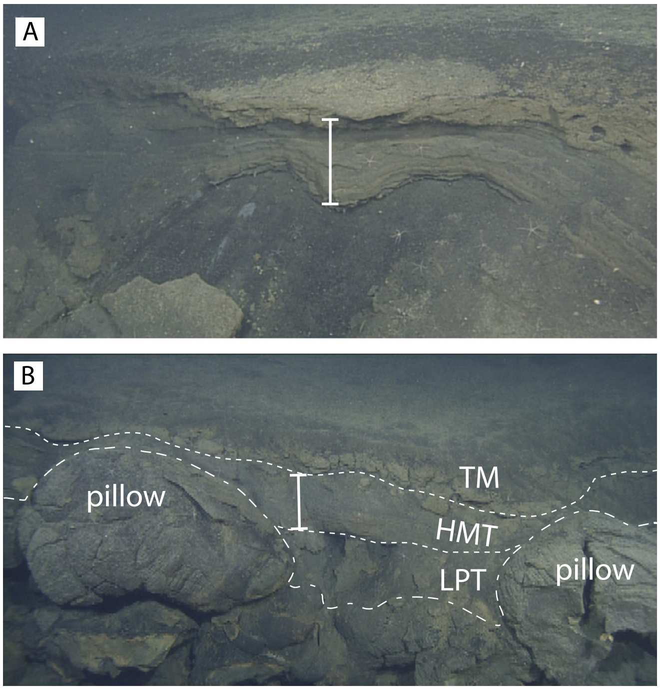

Fig. 2. ROV dive photos of thick clastic sequence exposed in the sides of small fissures on central east caldera rim of Axial Seamount. Scale bars represent 33 cm. A) Horizontally layered section near push core D262-PC52L (see Fig. 1). B) Pillow basalt bedrock-confined section exposed 650 m to the south of D262-PC45L (see Fig. 1). Lithofacies abbreviations are defined in Table 1 and discussed in the text.

The summit of Axial Seamount is 1400–1600 mbsl and contains a centrally located 8 × 3 km caldera that contains lava most recently erupted in 1998 and 2011 (Embley et al., 1999; Chadwick et al., 2012b, 2013). Fault offsets that bound the caldera range from 160 m high in the west and north to no apparent offset where buried by young lava flows in the southeast and south, which is where the recently active fissure system is located (Fig. 1). Coherent lava flows exposed in the caldera walls typically have reddish-orange hydrothermal staining and typically show truncated pillow morphologies that are locally overlain by cascading elongate pillows from rare post-caldera rim eruptions. Lava flow morphologies within the caldera and along its rims are variable and typically change from lineated and hackly sheet flows to lobate to pillows moving away from the vent source (Clague et al., 2013). Much of the seafloor is covered by horizontally layered volcaniclastic and sedimentary deposits that form the basis of this study (Fig. 2A). These clastic deposits are typically much thicker (~60 to >150 cm) on the rims of the caldera than on the caldera floor (<25 cm), where younger flows are concentrated (Clague et al., 2013; Dreyer et al., 2013).

3.1. Methods

Unconsolidated clastic (volcaniclastic and sedimentary) deposits on Axial Seamount were collected with short (30 cm) and long (100 cm) push cores using the ROVs *Tiburon* and *Doc Ricketts* aboard the R/V *Western Flyer* during expeditions to the JdFR in 2006 (dives T1009–1010 in Fig. 1), 2009 (dives D70–D79) and 2011 (dives D256–D262). Cores collected in 2006 provided samples for volatile analysis (Helo et al., 2011) and the bases of cores collected