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High and highly variable cooling rates during pyroclastic eruptions on Axial Seamount, Juan de Fuca Ridge

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ABSTRACT

We present a calorimetric analysis of pyroclastic glasses and glassy sheet lava flow crusts collected on Axial Seamount, Juan de Fuca Ridge, NE Pacific Ocean, at a water depth of about 1400 m. The pyroclastic glasses, subdivided into thin *limu o Pele* fragments and angular, blocky clasts, were retrieved from various stratigraphic horizons of volcaniclastic deposits on the upper flanks of the volcanic edifice. Each analysed pyroclastic sample consists of a single type of fragment from one individual horizon. The heat capacity (c_p) was measured via differential scanning calorimetry (DSC) and analysed using relaxation geospeedometry to obtain the natural cooling rate across the glass transition. The *limu o Pele* samples (1 mm grain size fraction) and angular fragments (0.5 mm grain size fraction) exhibit cooling rates of $10^{4.3}$ to $10^{6.0}$ K s^{-1} and $10^{3.9}$ to $10^{5.1}$ K s^{-1}, respectively. A coarser grain size fraction, 2 mm for *limu o Pele* and 1 mm for the angular clasts yields cooling rates at the order of $10^{3.7}$ K s^{-1}. The range of cooling rates determined for the different pyroclastic deposits presumably relates to the size or intensity of the individual eruptions. The outer glassy crusts of the sheet lava flows were naturally quenched at rates between 63 K s^{-1} and 10^3 K s^{-1}. By comparing our results with published data on the very slow quenching of lava flow crusts, we suggest that (1) fragmentation and cooling appear to be coupled dynamically and (2) ductile deformation upon the onset of cooling is restricted due to the rapid increase in viscosity. Lastly, we suggest that thermally buoyant plumes that may arise from rapid heat transfer efficiently separate clasts based on their capability to rise within the plume and as they subsequently settle from it.

1. Introduction

There is compelling evidence for magmatic CO_2 exsolution as the dominant driving force of many submarine pyroclastic eruptions (Clague et al., 2003b; Helo et al., 2011; Resing et al., 2011). Yet the exact nature of the fragmentation process itself remains enigmatic. In particular, the mechanism whereby comparably small grain sizes are generated is poorly understood.

Transport of heat from a magmatic melt to its surrounding environment strongly influences any style of eruption, whether effusive or explosive. It influences diffusivities (Dingwell, 1990), degassing (Navon et al., 1998), crystallisation (Muncill and Lasaga, 1988) and most profoundly affects viscosity (Giordano et al., 2008) and fragmentation (Papale, 1999). The rate of heat loss is largely dictated by the constitution of the ambient environment. During a subaerial eruption initial cooling of the lava or pyroclastic fragments will mainly be controlled by the thermodynamic and transport properties of the surrounding air, especially its low thermal conductivity. With the addition of meteoric water, molten-fuel-coolant (MFCI) interaction is thought to be one of the key mechanisms to trigger highly energetic phreatomagmatic eruptions in shallow subaqueous to subaerial environments (Zimanowski and Büttner, 2003).This process strongly relies on premixing of melt (molten-fuel) and water (coolant) under stable vapour-film boiling, i.e., reduction of heat loss by an insulating, stable vapour (Zimanowski et al., 1997).

In contrast, heat transfer in deep-sea environments occurs dominantly in the direct melt-water contact regime under non-stable vapour-film boiling and heat flux depends on the thermodynamic properties of the liquid/super critical water rather than the insulating vapour film forming under lower pressures (Zimanowski and Büttner, 2003). Consequently, extraordinary rates of heat transfer can be expected in this environment.

Natural cooling rates of pyroclastic and hyaloclastic fragments reported in previous studies span a surprisingly wide range of several orders of magnitude, from 10^6 to 10^{-2} K s^{-1} (Wilding et al., 2000; Potuzak et al., 2008; Nichols et al., 2009). The lowest of these rates fall below those of most, generally rapid, processes operating during explosive eruptions, and are thought to reflect post-eruptive annealing (Wilding et al., 2000; Nichols et al., 2009) whereas the

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timescales associated with the cases of very rapid quenching compare favourably with timescales of fragmentation and vapour expansion. This convergence of timescales can be expected to have an important impact on fragmentation and on overall eruption dynamics.

In order to understand better the effect of cooling as one important aspect of the fragmentation process, the temperature–time evolution of the melt during the course of an eruption needs to be quantified. One approach is to characterise the rate of cooling as the melt passes through the glass transition where the thermal history is locked in by the physical state of the glass, i.e., its atomic configuration. In principle, any pristine volcanic glass contains a record of its natural cooling rate. This information can be extracted via relaxation enthalpy geospeedometry using differential scanning calorimetry (DSC) (e.g., Wilding et al., 1995, 1996). Within the past 15 yr this technique has proven a powerful tool when applied to the emplacement of basaltic as well as silicic glasses (Gottsmann and Dingwell, 2001, 2002; Nichols et al., 2009).

Here we present calorimetric analysis of a suite of basaltic pyroclastic glasses and glassy sheet lava crusts from Axial Seamount on the Juan de Fuca spreading centre, Pacific Ocean. We quantify the thermal histories of the samples in terms of the temperature at which the samples entered the glassy state, the associated stored internal excess energies, and their respective cooling rates using enthalpy relaxation-based geospeedometry. We demonstrate how the extraordinary rates of heat loss achieved during submarine pyroclastic eruptions contribute to the fragmentation process, strongly impeding viscous deformation as it becomes coupled to the cooling process. We conclude by discussing the impact of such rapid heat transfer from the pyroclastic glasses to seawater upon the submarine eruption plume and clast dispersal in the submarine environment.

2. Background

2.1. Axial Seamount

Axial Seamount is the surface expression of an enhanced melting regime beneath a central segment of the Juan de Fuca Ridge (JdFR), an intermediate spreading-rate ridge with a total full-spreading rate of 6 cm yr^{-1} (Wilson, 1993; Fig. 1). The volcano is associated with the Cobb–Eickelberg seamount chain on the Pacific Plate (Johnson and Embley, 1990; Rhodes et al., 1990). Erupted lavas on Axial Seamount reflect mixing of a normal MORB source with a chemically distinct plume source (Chadwick et al., 2005). The prominent Axial volcanic edifice rises to about 1400 m below sea level, and is elevated up to 1000 m relative to the adjacent rift zones and basins. The summit is characterised by a U-shaped, 3 × 8 km diameter caldera, deepening towards the north end (Embley et al., 1990; Johnson and Embley, 1990). Its dimensions are similar to Kilauea caldera, Hawaii, and slightly smaller than Krafla caldera in Iceland (Rymer et al., 1998; Rowland et al., 1999). Adjacent to the main volcanic centre, rift zones extend ~50 km to the north and south. Due to enhanced magma supply from Axial Seamount (e.g., West et al., 2003), these rift zones form distinctive ridges dominated by constructional volcanic features. This situation is unique along the JdFR in that these constructional ridges overlap significantly with the contiguous extensional rift segments of the ridge itself (Appelgate, 1990; Embley et al.,

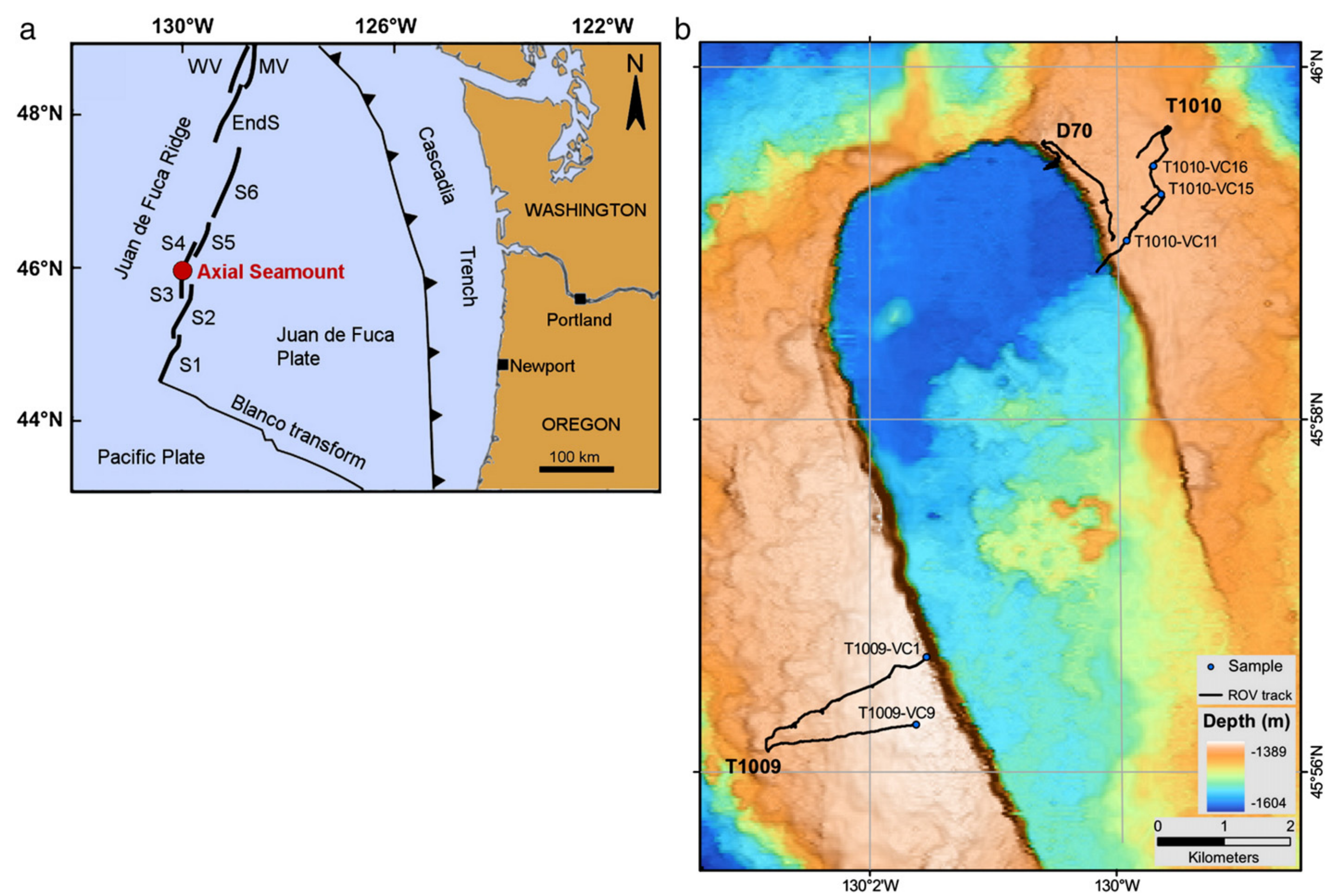

Fig. 1. a) Schematic overview map depicting the tectonic setting of the Juan de Fuca ridge and adjacent oceanic plates. b) Bathymetric map showing the summit caldera and flanks of Axial Seamount and the location of dive sections T1009, T1010 and D70. Sampling sites for the pyroclastic horizons are shown along T1009 and T1010. The map is at a 20-m resolution.