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Three-dimensional lithofacies variations in hyaloclastite deposits

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ABSTRACT

Analysis of the spatial lithofacies variability within lava-fed delta formations in southern Iceland has revealed complex three-dimensional volcanic architectures in hyaloclastite deposits in non-glacial settings. Two depositional environments are studied, (a) lava entering a marine embayment (Stóri-Nupur) and; (b) lava advancing into a body of water of the flanks of a Surtseyan cone (Hjörleifshöfði). Interaction between environmental factors such as shoreline geomorphology, water depth, wave energy levels, the nature of the lava transport system, lava supply rate all affect the resulting lava deltas creating complex lithofacies arrangements and stacking patterns. Recognised here are two types of hyaloclastite deltas. One of syn-sedimentary origin (Hjörleifshöfði) and one derived from primary fragmentation processes (Stóri-Nupur). Syn-sedimentary systems are dominated by destabilisation of the hyaloclastite pile leading to reworking downslope and share similarities to alluvial delta systems. Conversely, primary fragmented systems are controlled by waxing and waning cycles in volcanic effusivity whereby the hyaloclastite unit recorded is not the product of one lava flow rather than one eruptive event.

1. Introduction

The abundance and importance of volcaniclastic deposits, such as lava deltas and phreatomagmatic products, in predominantly mafic volcanic systems, is becoming increasingly recognised (e.g. Jerram and Widdowson, 2005; Ross et al., 2005; Manville et al., 2009). Volcaniclastic deposits are diverse and include peperites (Jerram and Stollhofen, 2002; Petry et al., 2007; Waichel et al., 2007), pyroclastic rocks (Ukstins-Peate et al., 2003; Ross et al., 2005), and suites of hydromagmatic successions collectively termed hyaloclastite deposits (Ross et al., 2005). The latter deposits loosely termed 'hyaloclastites', can include a wide range of volcaniclastic rocks formed from primary fragmentation of lava to the secondary reworking of such products by wave action and sea-level fluctuations, particularly in emergent volcanic systems (e.g. Schmincke et al., 1997). Current models of these systems are relatively simple and focus on the large scale structure, with limited information on internal lithofacies variations at small-scales and the 3D lithofacies variability. Improved definitions and a better understanding of hyaloclastite facies types, particularly the detail within delta sequences, is therefore needed. This paper describes two examples of basaltic hyaloclastite successions in Iceland. Detailed field documentation and geological mapping has allowed key hyaloclastite and lava lithofacies and lithofacies associations to be used to document the sequence of events and identify the emplacement processes. For this study, two types of hyaloclastite deposits were identified: A) deposits formed distally from vents in a marine embayment at a coastal margin and; B) deposits formed as part of a Surtseyan volcanic system. A model for each case study is provided documenting the variations in 3D geometry and the stacking of hyaloclastite lithofacies in relation to their environmental setting and parent lava flows. In light of these findings, we discuss the application of siliciclastic terminology to lava-fed delta systems.

1.1. Hyaloclastite terminology and definition

Hyaloclastite deposits are the products of lava contact with water or ice. Morphologically hyaloclastite deposits commonly form a blocky breccia composed of sideromelane glass, volcanic fragments, altered clay phases (palgonite and smectite) and zeolites (cf. Fischer and Schmincke, 1984; Moore, 2001; Stronick and Schmincke, 2002; Walton and Schiffman, 2003; Johnson and Smellie, 2007). However, the term hyaloclastite has been used to cover a variety of fragmental rock types associated with the interaction of magma and lava with water, which can make the meaning of the term hyaloclastite difficult to define. Hyaloclastite has been used to describe material formed in the following environments/processes; brecciated margins of intrusive rhyolite bodies (Hanson and Schweickert, 1982), quenched brecciated material intruded into wet sediment (sensu. intrusive hyaloclastite, McPhie et al., 1993), inter-pillow matrix material (Silvestri 1961; Moore et al., 1973; Fumes and Fridleifsson, 1974), fragmented talus slope breccia

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(Jones and Nelson, 1970; Moore et al., 1973; Tribble, 1991; Skilling, 2003), ice confined fragmented basalt ridges (cf. Gudmunsson et al., 1997; Schopka et al., 2006), water-quenched marginal breccias to rhyolitic edifices (Scutter et al., 1998) or subglacial flows (cf. Tuffen et al., 2001; McGarvie et al., 2007; Tuffen, 2007), associated with littoral cone formation (Clague and Moore, 1991; Jurado-Chichay and Rowland, 1995), the product of explosive volcanic eruptions (cf. Fischer and Schmincke, 1984; Schmincke et al., 1997, Palagonia and Vizzini, Sicily) and distally-deposited fragmented volcanic material in deep water setting (Silvestri, 1963; Ollier et al., 1998; Wells et al., 2009) or those transported via fluvial processes (Tolan and Beeson, 1984). Therefore, the term hyaloclastite includes deposits and rocks formed by both primary fragmentation processes (explosive and non-explosive), as well as those formed by syn-eruption resedimentation and reworking (Carlisle, 1963; Kokelaar, 1986; Tribble, 1991; Mattox and Mangan, 1997; Umino et al., 2006; Stewart and McPhie, 2006).

In this study, the term hyaloclastite is used to describe rocks that are result of passive quench fragmentation of coherent lava with only mild phreatomagmatic/explosive interactions occurring periodically throughout the construction of the sequences (sensu. White and McClintock, 2001). However a non-genetic use of the term hyaloclastite in this manuscript refers to deposits composed of >90% quenched sideromelane glass (with limited vesicularity) as a matrix component to encompass hyaloclastite deposits that have been locally reworked. The interaction of passive fragmentation and the active, explosive contribution of glass through phreatomagmatic processes are difficult to quantify in hyaloclastite deposits (see Supplementary data Table 1 for discrimination methods used). However, none of these parameters can be used on its own and the identification of hyaloclastite deposits requires analysis from macro to micro scale textural analysis.

1.2. Hyaloclastite depositional settings

Large hyaloclastite and pillow lava piles are formed during the initial phases of submarine volcano growth or during Surtseyan eruptions (cf. Schmincke, 1967; Staudigel and Schmincke, 1984; Moore, 1985; Schmincke et al., 1997; Seaman et al., 2000) or during sea floor eruptions at axial spreading ridges (Lonsdale and Batiza, 1980). Near Hilo, Hawaii, the hyaloclastite pile reaches c.1 km thickness (Moore, 2001, Hawaiian Scientific Drilling Project Phase II). Hyaloclastite deposits in these settings radially dip from a central fissure to form sheets of brecciated material. At smaller scales, dome-like formation of pillow lavas and hyaloclastite form under shallow water depths in lacustrine setting. These sequences when unconfined in shallow but expansive lake systems can prograde out from vent over 2–3 km. Examples of these deposits are documented in the in Snake River Plain under lakes and shallow level (Godchaux and Bonnichsen, 2002).

When lava flows envelop fluvial systems, hyaloclastite deposits form in river channels. These deposits form hyaloclastite dams blocking or diverting the rivers (Hamblin, 1994). Subsequent breakout of water from these dams can lead to catastrophic flooding episodes (cf. Tolan and Beeson, 1984; Fenton et al., 2006). Hyaloclastite deposits can be reworked as a component in a fluvial system and deposited downstream.

Subglacial volcanism commonly forms pillow lava and hyaloclastite ridges up to 300 m in height (e.g. 1995 Gjálp eruption at Vanajökull, Gudmunsson et al., 1997; Schopka et al., 2006). Differing ice thicknesses and styles of confinement lead to significant lithofacies variation (see Smellie and Skilling, 1994). In unconfined setting where melt water lakes form hyaloclastite morphologies can closely resemble those seen in Surtseyan settings where lavas cap a hyaloclastite and pillow lava succession. Ice confinement at the margins of the volcanic pile increases its steepness (cf. Werner and Schmincke, 1999; Skilling, 2009; Smellie et al., 2011). However, the distinction between lacustrine and subglacial environments can be difficult (Loughlin, 2003). This study concentrates on hyaloclastite lithofacies morphologies that formed within unconfined open water settings, and makes reference to examples where significant melt-water lakes allow similar (unconfined) depositional processes (e.g. Smellie et al., 2011).

Acidic to intermediate hyaloclastite deposits form their own unique deposits and depositional styles often quite separate to their more basaltic cousins. Commonly acid to intermediate deposits form small domes or mega pillow sequences accompanied by jigsaw-fit breccia (cf. Yamagishi and Dimroth, 1985; Scutter et al., 1998 for submarine examples and Furnes et al., 1980; Tuffen et al., 2001; Tuffen, 2007; McGarvie et al., 2007) for subglacial acidic hyaloclastite deposits).

1.3. Basaltic hyaloclastite delta deposition

Most documented hyaloclastite deposits are deltas that formed from the progradation of breccia sheets (Fuller, 1931; Jones and Nelson, 1970; Moore et al., 1973; Fischer and Schmincke, 1984; Schmincke et al., 1997; Pedersen et al., 1998; Skilling, 2003; Shervais et al., 2005; Jerram et al., 2009; Wells et al., 2009; Wright et al., 2011; Stevenson et al., 2012). These deposits occur where subaerial lava flows enter a large body of water. Prograding clinoform packages have been documented in several outcrops, including Antarctica, Japan and Sicily (Yamagishi, 1987; Porębski and Gradziński, 1990; Schmincke et al., 1997) and seismically within the Møre, Vøring (offshore Norway) and the Faroe–Shetland Basins (UK and Faroes) (e.g. Planke, 2004; Thomson, 2005; Jerram et al., 2009; Wright et al., 2011). Morphologically most hyaloclastite deposits are thought to compare well to Gilbert-style, high-energy, gravity-driven coarse-grained deltas (Porębski and Gradziński, 1990; Ollier et al., 1998; Skilling, 2003) (in Supplementary data). The key to understanding hyaloclastite depositional morphologies are fundamental processes, such as fragmentation and reworking that occur during delta formation and progradation. Fragmentation in hyaloclastite delta systems is covered in detail along with summary tables in the Supplementary data files submitted in support of this contribution.

Models of hyaloclastite deposition are often simplified as subsiding prograding clinoform packages (e.g. Schmincke et al., 1997). This approach is analogous to Jones and Nelson's (1970) model where relative sea level controls the height of the passage zone (the point of lava fragmentation) with the additional effects of subsidence. The passage zone refers to the vertical representation of fragmentation at the contact between subaerial lava flows and subaqueous hyaloclastite or pillow lavas. Changes in the height of the passage zone can also be attributed to tidal changes (Fumes and Fridleifsson, 1974).

1.4. Reworking processes

Resedimentation of hyaloclastite material can occur soon after deposition or after shallow burial and where the degree of reworking is controlled in part by the environmental setting (Fischer and Schmincke, 1984; Bergh and Sigvaldson, 1991; Mattox and Mangan, 1997; Ollier et al., 1998; Head and Wilson, 2003; Sohn et al., 2008). Hyaloclastite material that is deposited in unstable regimes (e.g. on volcanic flanks) is prone to sediment remobilisation (Lonsdale and Batiza, 1980) and gravity-driven mass flows (White, 1996; Schmincke et al., 1997). Conversely, deposition in a tectonically inactive shallow water basin or lacustrine environment is likely to avoid these secondary resedimentation processes unless wave undercutting leads to lava bench collapse (cf. Mattox and Mangan, 1997). In emergent settings hyaloclastite material can occur in a complex relationship between lava, tephra and hyaloclastite units in a volcaniclastic apron (Busby-Spera and White, 1987; Sohn, 1995; White, 1996). The process of reworking can be enhanced by progressive emergence of the volcano.

1.5. Volumetric importance of hyaloclastite deposits

Basalt-dominated volcaniclastic deposits constitute a significant portion (>40%) of the volcanic successions in Large Igneous Provinces