Possible distinguishing characteristics of very deepwater explosive and effusive silicic volcanism

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ABSTRACT

Recent seafloor exploration has shown that volcanic-hosted massive sulfides (VHMS) occur in modern silicic calderas formed by highly explosive eruptions at substantial water depths. Sampling of these has so far been restricted to surficial deposits. Ancient analogs provide a time-integrated view of the structure and fill of deepwater calderas, but constraints on paleo-water depths have previously been lacking. The Ordovician Bald Mountain VHMS (northern Maine, USA) is unique in its degree of preservation, not only permitting detailed textural and structural analysis of the enclosing volcanic rocks, but also allowing fluid inclusion analysis to determine a paleo-water depth of eruption of greater than 1.45 km. The deposits that result from very deepwater explosive eruptions have distinctive textural characteristics recognized in other ancient examples where paleo-water depths are less well constrained. I propose that hydrostatic pressure suppresses the explosivity of the eruption sufficiently to retard the formation of fine ash, producing ignimbrite composed largely of pumice lapilli. It also inhibits exsolution of dissolved water in the magma, producing fluidal rhyolite eruptions and intrusions. These include silicic fire fountaining to produce proximal cones of hyalotuff or spatter accumulations, and intrusions of globular peperite.

Keywords: silicic volcanism, deepwater eruptions, ignimbrites, volcanic-hosted massive sulfides, explosive volcanism.

INTRODUCTION

Subaqueous eruptions are the most abundant on earth, and the proportion of these that are explosive, although poorly known, is significant (White et al., 2003). As recently as 1992, it was proposed that explosive eruptions never occur in water depths greater than 1 km, and generally not in water depths greater than 500 m (Cas, 1992). Furthermore, pumice has been widely perceived as a product of only subaerial or shallow marine eruptions (Doyle and McPhie, 2000). Recent exploration of the sea floor, however, has documented pumiceous caldera fills 1–2 km below sea level, with major massive sulfide deposits on the caldera floors (Izu-Ogasawara arc: Fiske et al., 1995; Okinawa backarc rift: Halbach et al., 1999). At least nine deepwater silicic calderas lie along the Izu-Ogasawara arc (see references in Yuasa and Kano, 2003), and other deepwater silicic calderas have been discovered in the Tonga-Kermadec arc (Wright et al., 1998; Worthington et al., 1999; Wright et al., 2003) and the Marianas arc (Bloomer et al., 2001). Furthermore, theoretical modeling of explosive eruptions suggests that volatile supersaturated magma can produce explosive eruptions in subaqueous settings beyond that of the critical point of water, in water depths of 3100 m or more (Lentz et al., 1998; Gibson et al., 2000; Wallace and Anderson, 2000).

Despite these recent discoveries, observations of the deposits of deepwater eruptions at modern volcanoes remain limited, and are restricted to surficial deposits. For this reason, most of our knowledge of deepwater silicic volcanic processes comes from inferences based on ancient successions. A major shortcoming of previous studies of ancient successions, however, is that paleo-water depths of eruption are far more poorly constrained than they are at modern volcanoes.

This study draws attention to the Ordovician Bald Mountain volcanic-hosted massive sulfide (VHMS) in northern Maine, United States, because it is unique in its degree of preservation. This not only permits detailed textural and structural analysis of the enclosing volcanic rocks (Busby et al., 2003; Kessell and Busby, 2003; Foose et al., 2003), but also allows fluid inclusion analysis to determine a paleo-water depth of eruption of greater than 1.45 km (Foley, 2003). This is the only caldera complex in the stratigraphic record with tight paleo-water depth constraints.

I suggest distinctive characteristics that may be used to recognize the products of silicic magmatism in very deepwater settings (Fig. 1), using observations from the Bald Mountain sequence and comparing these data with published and unpublished data from other ancient sequences where paleo-water depths are less well constrained, as well as with limited data available from modern settings. (The terminology of volcaniclastic rocks is complicated and contentious, but a clear statement of usage of terms is provided in the Data Repository.)[1] First, fine-ash-poor ignimbrites may be typical of very deepwater explosive eruptions, where hydrostatic pressures may be sufficient to suppress magmatic vesiculation. This, in turn, reduces the violence of the eruptions, thereby dramatically decreasing the production of bubble wall shards, and producing a thick, massive sheet composed largely of pumice lapilli. A second distinctive feature of very deepwater silicic eruptions is fluidal rhyolite. Fluidal rhyolite may be produced when hydrostatic pressure inhibits exsolution of dissolved water in the magma. Fluidal rhyolite

[1]GSA Data Repository item 2005168, pyroclastic terminology, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

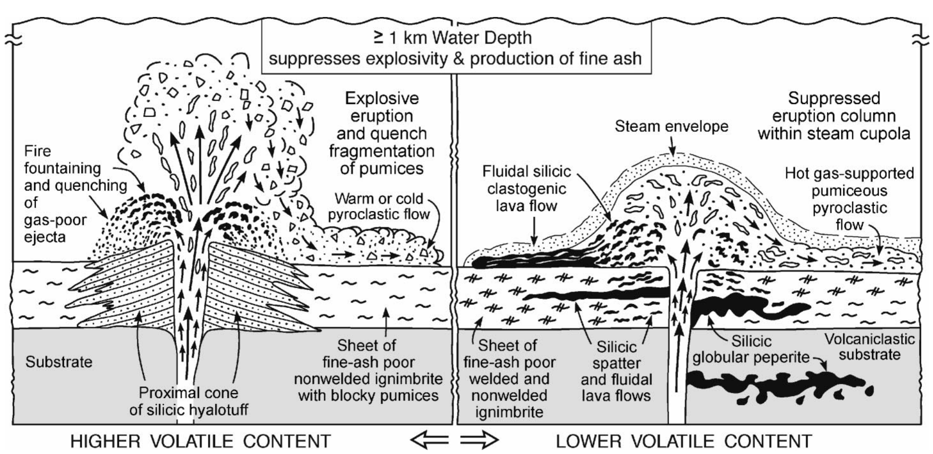

Figure 1. Possible distinguishing characteristics of very deepwater explosive and effusive silicic volcanism.

eruptions produce silicic fire fountain deposits, including very well quench-fragmented proximal rings of hyalotuff that form from relatively gas-rich fountains, as well as hot deposits of agglutinated/welded spatter that form from relatively gas-poor fountains under a steam cupola. Fluidal rhyolite intrusions tend to produce globular, rather than blocky, peperite.

GEOLOGIC SETTING OF THE BALD MOUNTAIN VHMS AND CONTROLS OF EXTENSION ON VERY DEEPWATER SILICIC VOLCANISM

Lithogeochemical data from the rocks enclosing the Bald Mountain massive sulfide indicate a primitive arc setting (Schulz and Ayuso, 2003), and evidence for synvolcanic normal faults is described by Foose et al. (2003). Hydrothermal fluids used these faults, and movement of zinc-rich and copper-rich fluids was controlled by the faults (Slack et al., 2003). The Bald Mountain VHMS lies within a 5-km-thick deepwater marine section that can be divided into three phases (Busby et al., 2003).

Phase 1 records outpouring and ponding of basalt lavas and breccia–hyaloclastite. The outpouring of basalts that defines phase 1 continued during phase 2. Phase 2 records explosive deepwater ignimbrite eruptions and associated exhalative activity. Up to 1 km of ignimbrites host the Bald Mountain massive sulfide, separated into the footwall ignimbrite that underlies the massive sulfide, and the hanging-wall ignimbrite that overlies the massive sulfide. The footwall and hanging-wall ignimbrites were deposited in nested calderas, and the Bald Mountain massive sulfide formed in a small synvolcanic graben that was the vent for the footwall ignimbrite. The vent for the footwall ignimbrite lies within a small (370 m $\times$ 275 m) but deep (215 m) synvolcanic graben with footwall ignimbrite welded onto its walls. The Bald Mountain VHMS formed within this graben vent soon after eruption of the footwall ignimbrite. Fluidal rhyolite eruptions and globular peperitic intrusions also record relatively high volatile contents during phase 2. Phase 3 records waning volcanism, and eruption and intrusion of gas-poor rhyolites. In summary, the Bald Mountain sequence records a very high rate of basalt magma discharge (Phases 1 and 2) contemporaneous with normal faulting, culminating in silicic caldera-forming eruptions and formation of a massive sulfide (Busby et al., 2003).

FINE-ASH–POOR IGNIMBRITES: A DIAGNOSTIC FEATURE OF VERY DEEPWATER ERUPTIONS?

Both the footwall and hanging-wall ignimbrites at Bald Mountain are poor in fine ash (Figure 1; see granulometric analyses by Kessel and Busby, 2003), and are best described as pumice lapillistones. The footwall ignimbrite is a poorly sorted mixture of blocky pumice and lesser medium-to-coarse ash that occurs in massive units up to 150 m thick, separated by basalt lavas; it lacks internal stratification and contains no ash interbeds. The ignimbrite is dominantly nonwelded and has blocky pumices (see photos in Kessel and Busby, 2003), indicating that hydroclastic fragmentation followed magmatic fragmentation (Fig. 1).

Like the footwall ignimbrite, the hanging-wall ignimbrite is a massive, fine-ash–poor mixture of pumice and medium-to-coarse ash, but it occurs as thinner flow units (1–150 m thick), separated by well-sorted and stratified lapilli tuff and tuff (Busby et al., 2003). The hanging-wall ignimbrite thus represents the product of a less steady eruption than the one that produced the footwall ignimbrite. The very thick massive units in the hanging-wall ignimbrite contain abundant compacted pumice that may record welding, and the units lack blocky pumices and shards or other evidence of hydroclastic fragmentation (see photos in Kessel and Busby, 2003). Thus, a lower volatile content (relative to the footwall ignimbrite) resulted in a lower eruption column, leading to minimal interaction with ambient water in a purely magmatic eruption (Fig. 1). Instead, the hydrostatically suppressed eruption column was likely enclosed in a cupola of steam (Kessel and Busby, 2003), similar to that inferred for the generation of Mesozoic deepwater welded ignimbrite in the southern Sierra Nevada, California (Kokelaar and Busby, 1992).

An alternative interpretation is that the ignimbrites at Bald Mountain represent pyroclastic flows in which the fine ash was winnowed away from the pumices by mixing with ambient water during eruption and transport. Kano (2003) presents a model for large-scale ingestion of ambient water by subaqueous eruption columns, resulting in fines-depleted, stratified, and sorted deposits, also referred to as pumice breccias (Allen and McPhie, 2000). This model does not apply to the very deepwater (>1.45 km) ignimbrites at Bald Mountain, or to the deepwater welded ignimbrite of uncertain paleo-water depth (>150 m) in the southern Sierra Nevada, because these are nonstratified. Kano's (2003) model may be more applicable to shallow marine or slightly deep marine settings, where hydrostatic pressure is not great enough to hold a suppressed column largely within a steam cupola.

The footwall ignimbrite at Bald Mountain is texturally and sedimentologically identical to the footwall at the Rosebery mine in Tasmania, which is described as a ''very thick, mass-flow emplaced pumice breccia,'' and referred to as ''ignimbrite-like'' by Allen and Cas (1990, p. 31). The Rosebery footwall is a pumice lapillistone, and not a pumice breccia, because it consists of lapilli-sized, not block-sized, clasts; it forms massive to weakly graded flow units hundreds of meters thick (my field and drill core observations; also see graphic logs and photographs in McPhie and Allen, 2003). By analogy with Bald Mountain, I suggest it is a true (albeit fines-poor) ignimbrite (Data Repository; see footnote 1), erupted at bathyal water depths; unfortunately, there are no direct controls on the paleo-water depths of eruption of the Rosebery footwall ignimbrite. The textural and sedimentological characteristics of the footwall ignimbrite at Bald Mountain are also similar to the Devonian Tamarack tuff (Brooks, 2000) in the Northern Sierra terrane, California (my field and thin section observations); like the Bald Mountain ignimbrites, the Tamarack tuff contains enigmatic fluidal rhyolites.

FLUIDAL RHYOLITES IN THE DEEPWATER REALM

Fluidal rhyolites appear to be relatively common in ancient deep marine deposits, but they remain enigmatic partly because they have not yet been discovered in modern deepwater settings. These include thin, extensive silicic lava flows (Cas, 1978; De Rosen-Spence et al., 1980), silicic pillow lavas (Bevins and Roach, 1979), silicic spatter or fire fountain accumulations (Mueller and White, 1992; Fackler-Adams and Busby, 1998), and silicic globular peperites (Soriano and Marti, 1999). Fluidal rhyolites are also enigmatic because rhyolitic magmas are generally considered to be too viscous to fountain or to exhibit other fluidal behaviors; the exception to this is high-temperature eruptions, usually from fissures (Duffield, 1990; McCurry et al., 1997). The fluidity of deepwater rhyolites has been attributed to confining pressure of the water column, which inhibits exsolution of dissolved volatiles, resulting in lower magma viscosity (Cas, 1978; Yamagishi and Dimroth, 1985). The difficulty with all previously published (ancient) examples is that confining pressures are very poorly constrained; the Bald Mountain example is the only one with well-constrained paleo-water depth estimates.

The viscosity of rhyolite is more reduced by unexsolved water than is the viscosity of mafic magmas. This led Bridges (1997) to suggest that Venusian volcanic landforms with fluidal features, formed at 90 bars, are rhyolite (not basalt) lava flows. The confining pressures inferred for the Bald Mountain sequence are even greater, at least 150 bars, and are presumably even more likely to produce fluidal rhyolites.

Silicic fire fountaining at Bald Mountain built proximal ejecta rings of hyalotuff, which grew within (and during accumulation of) the much more extensive Bald Mountain footwall ignimbrite sheet (Fig. 1). These rings are 30 and >100 m thick adjacent to the vent for the footwall ignimbite, and wedge out completely within 1 km of the vent. The proximal ejecta rings are thick nonstratified accumulations of poorly vesiculated, perlitically fractured rhyolite glass fragments of dominantly coarse ash to fine lapilli sizes, with blocky to polyhedral outlines and jigsaw fractures. Thick sections of uniformly comminuted glass are not produced by effusive eruptions, but instead record at least mildly explosive eruptions, and for this reason are referred to as hyalotuffs (Heiken and Wohletz, 1985). The poorly vesiculated nature of the rhyolite glass clasts in the Bald Mountain hyalotuff rings indicates low gas content, suggesting a fire fountain style of eruption rather than a more violent eruption, which would produce well-vesiculated fragments (Mueller and White, 1992; White et al., 2003). The proximal ejecta at Bald Mountain probably represents the products of a relatively unstable collar of low-fountaining, gas-poor ejecta that quenched during extensive interaction with water, producing a deposit of uniformly sized glass fragments totally lacking in fluidal clasts or welded clasts. This collar wholly or partially sheathed the core of higher-velocity, gas-rich ejecta that generated the more widespread footwall ignimbrite. Subaerial analogs of a fountaining collar on an explosive column include historical eruptions in New Zealand and Alaska (Walker et al., 1984; Fierstein et al., 1997). Few studies have documented cone building eruptions coeval with sheet forming eruptions (Pyle, 1989), however, because the proximal deposits associated with sheet forming eruptions are rarely exposed, due to burial or collapse of those areas in most large eruptions (Fierstein et al., 1997). They are thus more likely to be exposed in ancient successions.

Proximal subaqueous ejecta with fluidal clast morphologies have been most commonly reported at mafic volcanoes; modern examples and ancient examples are summarized by Cas et al. (2003). Silicic examples are all ancient, and include those described by Mueller and White, (1992) and Fackler-Adams and Busby (1998), and my own observations in the Devonian Northern Sierra terrane of California and the Cretaceous Alisitos arc terrane of Baja California, Mexico. Textures in all of these examples include cow-pie (flattened), amoeboid, or irregularly elongate or twisted clasts. Clasts with flattened, welded/agglutinated morphologies presumably require insulation of the fire fountain from surrounding water within a cupola of steam (Fig. 1), whereas nonwelded amoeboid/spatter clast accumulations with chilled rims probably form in contact with water.

Deepwater fluidal rhyolites are also common as peperitic intrusions, which form globules on the centimeter to meter scale (pseudopillows) in volcaniclastic hosts (Fig. 1). These are common in phase 2 of the Bald Mountain sequence (gas-rich rhyolite magmatism), whereas blocky peperites dominate phase 3 (gas-poor rhyolite magmatism). Globular peperites are also commonly associated with deepwater ignimbrites in the Cretaceous Alisistos arc (Fackler-Adams and Busby, 1998) and the Devonian Sierra Buttes arc (my observations). I speculate that unexsolved volatiles in very deepwater rhyolites promotes the occurrence of peperites as globular or fluidal peperites, rather than as blocky peperites.

CONCLUSIONS

Testing of the hypotheses outlined in the introduction awaits further oceanographic research in modern settings, and the discovery and detailed study of ancient successions that are well preserved enough to infer paleo-water depths of eruption using fluid inclusion analysis. Meanwhile, I suggest prospectors for VHMS deposits look further at fine-ash–poor ignimbrites with associated fluidal rhyolites.

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