Extensive volcaniclastic deposits at the Mid-Atlantic Ridge axis: results of deep-water basaltic explosive volcanic activity?

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ABSTRACT

A recent mapping survey followed by submersible diving investigations revealed the existence of extensive volcaniclastic deposits on three adjoining, progressively deeper, segments of the Mid-Atlantic Ridge, south-west of the Azores. The maximum water depth at which submarine spreading is documented for the first time. Submersible observations, volcaniclastic sample descriptions and chemical analysis, evidence of extensive deep water (up to 1700 m) magmatic explosive activity of basalt at the axis of a spreading Mid-Atlantic Ridge is documented for the first time. Terra Nova, 10, 280–286, 1998

Introduction

Present estimates of the maximum depth for submarine explosive fragmentation of basaltic magma vary from ≈ 200 m to several thousand metres (McBirney, 1963; Moore and Schilling, 1973; Batiza et al., 1984; Staudigel and Schmincke, 1984; Smith and Batiza, 1989; Gill et al., 1990; Binard et al., 1991; Bizard et al., 1992; Cas, 1992; Fouquet et al., 1993; Haymon et al., 1993; Moore et al., 1995) and this depth has been studied in various environments such as Capelinhos, Surtsey, Sumburc rift, Lai basin, intraplate volcanoes as well as from the geological record on land. Basaltic volcaniclastic deposits formation depends on several factors, including magma composition, volatile concentration, eruption depth and rate and magma-water interaction mechanisms. The processes that may be responsible for this fragmentation are magmatic explosivity, contact-surface steam explosivity, bulk interaction steam explosivity, cooling-contraction granulation, or any combination of these (McBirney, 1963; Thorarinsson, 1967; Colgate and Sigurgeirsson, 1973; Peckover et al., 1973; Nairn and Wiradindji, 1980; Sparks et al., 1980; Sheridan and Wohletz, 1983; Wohletz, 1983; Kokelaar, 1986; Wohletz, 1986; Cas, 1992). The first three processes are explosive and strongly dependent on hydrostatic pressure, becoming more efficient at shallow depths, whereas cooling-contraction granulation (a result of mechanical fragmentation during quenching) can occur at any water depth; at great depth they depend mainly on the effusion rate (Batiza et al., 1984; Smith and Batiza, 1989). Clast generation by an explosive process should be limited to depths shallower than the depths where the critical pressure of water is exceeded (Kokelaar, 1986). The critical point of seawater is 407 °C at 298.5 bar (about 3 km in seawater) (Bischoff and Rosenbauer, 1984; Smith and Batiza, 1989). There is very little evidence for explosive fragmentation deeper than several hundred metres in the modern ocean, and this at a very local scale (Haymon et al., 1993).

New data are presented herein on the occurrence and characteristics of extensive and thick volcaniclastic deposits observed and sampled for the first time on three active segments of the Mid-Atlantic Ridge (MAR) close to the Azores. The discussion will briefly address the problem of the mechanism of basaltic magma fragmentation between 500 and 1700 m water depth, and the constraints it places on the understanding of volcanic eruptions involving seawater–magma interaction.

Geological context

The three ridge segments investigated are the shallowest segments of the MAR located west to south-west of the Azores (Fig. 1). They are, respectively, from north to south: (i) the 38°20'N segment (≈ 400 m minimum depth to ≈ 930 m maximum depth) (ii) the Menez Gwen segment (≈ 700 m to ≈ 1050 m), and the Lucky Strike segment (≈ 1570 m to ≈ 2000 m). These areas were studied during the Diva I and Flores expeditions with the submersible Nautilus and mapped using the EM 12 DUAL combined multibeam bathymetric and seabottom reflectivity tool (Ondréas et al., 1997). In this report, we focus on the interpretation of mapping results, detailed observations by the submersible and initial preliminary sample studies which address the nature of the basaltic volcaniclastic deposits observed at all three ridge segments. The 38°20'N segment (Fig. 1a) is ≈ 45 km long, lacks a deep axial rift valley and has a circular central volcano ≈ 25 km in diameter and ≈ 1200 m high. The axial graben which bisects the top of the volcano is ≈ 2 km wide, ≈ 800 m long and 500 m deep (510 m to 930 m water depth). From an extrapolation of the present spreading rate (2–2.5 cm yr−1; DeMets et al., 1990), the timing of the axial graben formation can be constrained to less than 100 kyr.

The graben floor and inner walls consist of gently inward-dipping, layered volcaniclastic ejecta (Fig. 2d) at least 400 m thick. Individual layers typically are a few mm to a few cm thick, consisting of sand and lapilli-sized clasts (Fig. 2e). Rarer beds are metre-thick, poorly sorted lapilli layers. The Menez Gwen segment (Fig. 1a,b,c) is a ≈ 60 km long segment and morphologically similar to the 38°20’N segment to the north; its central volca-
Fig. 1  (a) Location map for the three volcanic segments west of the Azores islands on the Mid-Atlantic Ridge. The minimum depth for the topographic high of each segment is indicated; (b) EM12 sonar image (reflectivity of the bottom) of the Menez Gwen segment; and (c) Schematic interpretation of the sonar image of the Menez Gwen segment. 1, Volcanic ejecta; 2, Lava flows; 3, Pelagic sediments; 4, No data. Solid lines are structural lineaments. Line A–B shows the position of the cross section presented on Fig. 3.
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Fig. 2. Aspects of the volcaniclastic deposits from outcrop to thin sections: Menez Gwen segment: (a) Vertical outcrop of layered volcanic ejecta. (b) Macroscopic section of sample DV-13-5. Note the clast size variation of the different layers. The lower part of the sample in contact with seawater is slightly encrusted with Fe-Mn oxyhydroxide. Sample DV-13-5 is a coarse-grained volcanosedimentary tuff with glass up to 3 mm long containing nonvesicular glass fragments (≈ 15%), scoriaceous clasts (≈ 40%) often attached to broken plagioclase phenocrysts (≈ 15%) set in a fine-grained sediment-rich dark matrix (≈ 30%) containing coccoliths fragments. The compositions of the vesicular and nonvesicular glasses fit very consistently in two groups: (i) less differentiated more vesicular (TiO$_2$ \( \approx \) 1.30; FeO*/MgO \( \approx \) 1.0); (ii) slightly more differentiated nonvesicular (TiO$_2$ \( \approx \) 1.52; FeO*/MgO \( \approx \) 1.6) for the nonvesicular glasses. (c) Micrograph of sample DV-13-5 (38°20'N segment) showing two types of glass fragments; juvenile scoriaceous (2) with attached broken plagioclase phenocrysts (P) and nonvesicular angular glass fragments (1). Calcareous microfossil fragments are observed in the matrix. (d) Layered volcanic ejecta as observed from submersible. (e) Macroscopic section of sample DV-10-9 showing layers of various grain size granulometry (much finer than on the previous sample) with sharp contacts and bioturbations. Sample DV-10-9 is a coarsely laminated, fine-grained tuff with numerous plate-like glass shards (≈ 40%) and vesicular clasts (≈ 30%), a few nonvesicular glass fragments (≈ 10%) and lithic clasts (≈ 20%). (f1) Micrograph of sample DV-10-9 showing one elongated glass shard with comet shape and stretched vesicles (arrow); (f2) Stretched vesicles (V) in glass shards.

No is ≈ 16 km in diameter and ≈ 700 m high and has an axial graben ≈ 6 km long, ≈ 2 km wide and ≈ 300 m deep (700 m to 1050 m water depth). The graben floor is mostly relatively fresh to very fresh lava, including a ≈ 1400-m
long, 400-m wide and up to 8-m deep lava lake at its deepest point (1045 m) (Fouquet et al., 1995b). The timing of the axial graben formation is constrained by the spreading rate to less than 100 kyr.

Volcanoclastic deposits in the Menez Gwen segment are less extensive than on the shallower 38°20′N segment and restricted to the central part of the segment (Fig. 1b,c). A cross-section of the western graben wall, interpreted from observations from the submersible (Fig. 3), suggests a 290-m thick volcanoclastic unit overlying a 60-m thick section of lava flows, each up to 3-m thick with columnar joints and rubbly flow tops. From seabottom observations, the volcanoclastic layers are similar (Fig. 3) to those described for the 38°20′N segment. The contact between the lava flows and the overlying deposits is sharp. One pillow lava flow was observed near the upper part of the volcanic unit on the eastern graben wall (Fig. 3).

The Lucky Strike segment is the southernmost and deepest (∼1700 m) segment studied. This segment has a 60-km long and 15-km wide rift valley (1570 m to 3650 m water depth). The central part of the rift is occupied by a 12 × 8 km central volcano whose summit consists of three, predominantly scoriaceous breccia summit cones surrounding a restricted area of layered volcanoclastic deposits localized near the centre of a 1-km wide and 100-m deep caldera. The central part of the caldera is occupied by a lava lake 300 m in diameter made of fresh non vesicular lobate and sheet flows (Fouquet et al., 1995a). The well-layered volcanoclastic deposits outcropping within the caldera are similar to those described on the other two segments but are thinner (probably less than 10 m thick) and much less extensive. Furthermore, they have been variably indurated by hydrothermal circulation related to the Lucky Strike hydrothermal field (Fouquet et al., 1995b; Langmuir et al., 1997). Volcanic breccia deposits related to the three summit cones around the caldera at ∼1700 m are dominated by massive fragmental formations that grade laterally into in situ breccia and coherent, highly vesicular scoriaceous-lava flows locally forming pillow lava.

**Extension of the deposits**

Correlation of detailed submersible observations with EM 12 DUAL seabottom reflectivity images show that the volcanoclastic deposits have a specific acoustic signature. They are grey on the images, intermediate between that of lava flows (black) and pelagic sediment (white) (Fig. 1b,c). The reflectivity images enable an extrapolation of the dive observations and indicate that volcanoclastic material is restricted to the centre of the segments where it forms most of the surface of the volcanic cones. The area of the surface covered by volcanoclastic deposits decreases with increasing depth; ∼67 km² at the 38°20′N segment, ∼15 km² at the Menez Gwen segment and ∼2.8 km², including the scoriaceous breccia, at the Lucky Strike site. In addition to this, they also get thinner and thus less voluminous with depth. This observation suggests that hydrostatic pressure exerts a strong control over their formation processes. The reflectivity images also reveal that fresh pillow lava, sheet lava and lobate lava flows are the only volcanic formations present at the southern and northern ends of the three segments whereas they coexist with the volcanoclastic deposits in the central part of the segment. This fact indicates that the formation of the volcanoclastic deposits is also linked to the spreading axis segmentation, and is partially independent of the overall range of water depth covered (1700–500 m). The preservation of well-sorted, commonly well-stratified ash layers (Fig. 2a, b, e), with normal and possibly reverse grading, the very sharp nature of bedding planes between the lapilli and finer ash units, and the frequent presence of worm burrows at the tops of some beds (Fig. 2e) suggest that most of these deposits are near-primary (Cas et al., 1989). Most of the nongraded layers appear to be restricted to the very centre of the segments as would be proximal facies. Reworked material does exist, as distal facies of turbidite flows on the external, outward-dipping, slopes, or as spatially restricted intra-sedimentary reworked layers, sometimes near small tectonic faults. The extent of these facies seems to be quite limited. Extensively reworked material is restricted to very recent deposits formed along the steepest slopes of central neovolcanic cones and inner graben faulted walls.

The presence of abundant mm-thick layers of fissional calcalcic pelagic sediment intercalated with the volcanoclastites and abrupt changes in grain size indicate that individual eruptive events were episodic and probably short lived. However, the total thickness of the deposits (> 400 m for the 38°20′N segment, 270 m for the Menez Gwen segment, but only a few metres

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**Fig. 3** Cross-section of Menez Gwen axial graben showing the four lithological units: 1, Volcanic ejecta; 2, Massive lava; 3, Pillow and lobate flows; 4, Lava lake; 5, Fissure; 6, Normal faults. Section based on submersible observations. Note that the volcanic ejecta formation is symmetric and observed on both sides of the graben. Outcrops are observed at the base of the ejecta formation and observations at the west summit show a westward very regular dipping of the volcanic ejecta layers that correspond to the outer slope of the volcano. Individual layers may be broken in small plates that are sliding along the inner graben slope.

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for the Lucky Strike segment) demonstrates that this kind of volcanic activity occurred repeatedly over relatively long periods of time. On the northernmost segments, these multiple explosive events may have lasted for a minimum of several 1000 years to possibly 10 Ka.

Sample descriptions and volatile contents

Macroscopic and microscopic (thin-section) observations of all the volcaniclastic rock samples collected by the submersible Nautilus and more detailed investigations of a few representative samples shed additional light on their origin and the mechanisms involved in their formation.

Individual layers of volcanic clasts are generally relatively well-sorted, ranging from coarse-ash to fine lapilli without any matrix or with a much finer matrix of pelagic sediment and volcanic ash. The finer volcaniclastic layers are generally devoid of a sediment intercalation whereas the coarser lapilli layers frequently contain fine sediment particles, probably incorporated from overlying beds after deposition. Pelagic sediment-rich layers contain variable amounts of volcaniclastic fragments (5–20% in volume).

In thin sections, the samples display a wide variety of grain-supported and matrix-supported textures and variable amounts of pelagic carbonate matrix. The predominant clast type in all the deposits is scoriaceous (30–50% in volume of vesicles) to pumiceous (50–80% in volume of vesicles) glass fragments (Fig. 2c,f). These vesicular glasses are either fresh or altered (palagonitized) and frequently surround broken phenocryst fragments (Fig. 2c). Highly vesicular glassy clasts show variable stretching of vesicles (Fig. 2f) and this stretching is usually extreme, indicating rapid deformation prior to and during quenching. Deformation of still fluid highly vesiculated magma in a submarine environment implies a relatively high effusion rate and/or explosive activity. We assume that these vesicular glasses represent the juvenile magma of the eruptions that generated these deposits.

Glass with low vesicularity, devitrified glass and a variety of glassy rock fragments (with textures ranging from variolitic to interstitial or equigranular) are also observed along with frequent broken phenocrysts; predominantly plagioclase. They probably represent that generated these deposits.

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Table 1

<table>
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<tr>
<th>Segment</th>
<th>38°20’N</th>
<th>500–900 m</th>
<th>DV-10-2 vesicular</th>
<th>DV-10-9 massive</th>
<th>DV-10-9 vesicular</th>
<th>DV-13-5 massive</th>
<th>DV-13-5 vesicular</th>
<th>DV-13-9 vesicular</th>
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<td>100.08</td>
<td>100.22</td>
<td>100.01</td>
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Nevertheless, the dissolved volatile concentration of the vesiculated glasses of, i.e. sample DV-10-9 (0.47 wt%) and DV-13-5 (0.26 wt %) must have been significantly higher prior to vesiculation if vesiculation predominantly resulted from a juvenile magmatic volatile exsolution.

**Discussion and conclusion**

The layered nature of the deposits observed at all three segments is indicative of fallout type deposits after magma fragmentation. In contrast, the volcanic breccia from Lucky Strike appears to have been produced by autobrecciation with down slope redistribution and/or cooling-contraction (Kokelaar, 1986) fragmentation. All of these layered volcanioclastic deposits appear to be near-primary deposits based on the very sharp nature of bedding planes between the lapilli and finer ash units and the presence of worm burrows in their original position at the tops of beds (Cas et al., 1989) (Fig. 2e). Extensively reworked material is restricted to recent deposits forming along the steepest slopes of central neovolcanic cones and inner graben walls. The large volumes, thickness, location, nature, granularity, and chemistry of these deposits preclude an origin as submarine fallout deposits from subaerial eruptions on the Azores (Ledbetter and Spark, 1979; Cashman and Fiske, 1991).

Almost all the studied samples provide strong evidence for explosive fragmentation caused by the combined effects of expanding magmatic volatiles as well as hydromagmatic processes involving seawater.

The highly vesicular nature, scoriaeous to pumiceous, of the glassy clasts, often broken into fine shards, also shows that magmatic volatiles must have played an important role in lowering the density and viscosity of the erupting melt. Most of the glassy clasts of samples DV-10-1 and DV-10-9 exhibit typical ‘plate-like’ shapes, commonly orientated parallel to bedding (Fig. 2f). These shards are characteristic of ash less than 100 μm in diameter resulting from hydrovolcanic explosive fragmentation after a strong vesiculation similar to those produced experimentally (Wohletz, 1986; Wohletz, 1983; Zimanovski et al., 1991). These shards represent fragmented bubble walls. Elongate shards with comet shapes and stretched vesicles (Fig. 2f) plus the abundant stretched vesicles in most samples show that magma was accelerated and/or fragmented to high velocity when it was still viscous.

The presence of abundant lithic clasts and of broken crystals is usually a strong argument in favour of magmatic–water explosive interaction of maars, tuff cones, or Surtsey hydromagmatic volcanism (Honnorez and Kirst, 1975; Cas and Wright, 1987) but does not distinguish between the respective roles of magmatic or external water. Despite careful observations, no textural evidence of welding was found in any of the studied samples indicating that hot facies of the eruptions were generated, as submarine pyroclastic flows (Kokelaar and Busby, 1992; Cash, 1992), they were not extensive. Based on many independent lines of evidence at different scales, we interpret the bedded volcanioclastics as resulting from submarine explosions involving a combination of expansion of magmatic volatiles, bulk/surface steam explosivity of sea water and possibly thermal-contraction fragmentation, which can occur at any depth, perhaps aided by a rapid extrusion rate. The preferential location of these deposits at the centres of segments suggests a preferential concentration of volatiles near the topographic high of the segment. This interpretation may also suggest a role for hydrothermal circulation (Fouquet et al., 1995b). Water concentrations measured in most samples are not much higher than for N-MORB (Table 1), this indicates either that magmatic water was lost during eruption or that hydrothermal or seawater interacted with magma very shortly before eruption resulting in explosive activity.

Our observations indicate that explosive eruptions can occur and produce extensive deposits much deeper than commonly believed along mid-ocean ridge spreading centres, although the MAR near the Azores is shallower than most normal ridge segments. These new observations place important constraints on the interpretation of modern and ancient submarine volcanioclastic deposits.

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