Explosive activity on the ocean floor: purely magmatic or magma-seawater interaction origin? Geochemical and isotopic arguments

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Since deep seated submarine explosive activities have not yet been observed directly, the study of submarine pyroclastites and hyaloclastites and their setting could give some indication about the nature and origin of underwater explosive events. Pyroclastic deposits occur in a wide range of environments, such as back-arc basins, intraplate regions and accreting ridges. Recently other pyroclastic deposits (volcanic ejecta) were observed on the Mid Atlantic Ridge (MAR) axis up to 1700 m depths near 38°20'N (Ondreas *et al.*, 1997). During the 1995 submersible expedition (Oceanaut diving cruise) a segment of Mid-Atlantic Ridge (MAR) between 34°40'N and 35°N was explored and sampled (Bideau *et al.*, 1998). The volcanics characterized by pyroclastic and hyaloclastite deposits were associated with flows having different degrees of vesicularities. The samples collected were studied for their major and trace elements as well as their isotopic composition. The isotopes ratios and concentrations of water and carbon preserved in the vesicles or still dissolved in glassy phases will constrain the mechanism responsible for explosive eruptive events on the ocean floor.

Geological setting

The Rift valley of the MAR near 34°50'N is ~10 km wide and is characterized by a Median Ridge (MR) consisting of linear volcanic constructions ~4 km wide and 22 km long, centrally located with respect to the main Rift Valley walls of the MAR axis near 35°N. This MR separates two depressions (>2300 m deep), the eastern and the western Rift Valleys. The eastern rift is the site of the most recent volcanic activities and the western valley is more in a tectonic regime and with sediment cover (Bideau *et al.*, 1997). The MR is topped by several volcanic edifices with elongated and circular cones. Some of these cones located in the middle (end of dive OT 01) and southern (end of dive OT 03) extremity of the Median Ridge are characterized by volcanoclastic and hyaloclastite deposits. Most samples studied are from a volcanic cone at the southern end of the Median Ridge (dive 0T 03) which is believed to represent the collapsed elliptic rim of a volcanic crater. The geological section OT 03, conducted along the southern slope showed sheet flows near the base, followed mainly by pillow lavas and pelagic sediment along the slope, up to 1740 m depth where rubbly and scoriaceous material occur (sample 0T 03-09). Pyroclasts of unsorted or poorly sorted volcanic ejecta and hyaloclastite slabs associated wih other vesicular lava are also found up to 1594 m. depth.

Morphologically the samples have been classified into four groups: (1) poorly vesicular (vesicle content <6–10%), sheet flows and pillow lavas; (2) vesicular pillow flows, with vesicularity >15–30 vol.%; (3) highly vesicular (scoria-like) pyroclasts (>30 vol.% vesicles); and (4) hyaloclastites.

Geochemical characteristics

The data from the dive site OT 03 are discussed and compared to other volcanics collected in the vicinity. The degree of vesicularity correlates with a change in the magmatic composition of the various lavas such as: (1) the least vesiculated N-MORB have K/Ti < 0.2 and Na_2O+K_2O < 2.8%; (2) the enriched E-

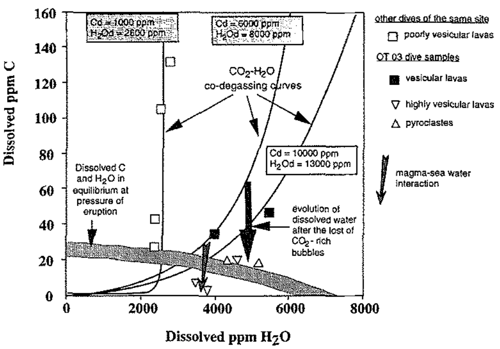

FIG. 1. Evolution of dissolved carbon and water during co-degassing.

MORBs with K/Ti = 0.30–0.55, Na_2O+K_2O = 2.8–3.5% correspond to volcanites with an intermediate amount of vesicles; and (3) the most vesiculated samples have the higher K/Ti ratio (> 0.45–0.55) and Na_2O+K_2O > 3–3.5% and are classified as alkali basalts. This change in the degree of rock vesicularity corresponds also to the increase of total water (dissolved in melt+vesicle water, see below). This is a strong argument to consider that at least part of the water is of magmatic origin. The isotopic study of the main volatiles (CO_2 and H_2O) contained in these samples will put some constraints on the possible connection between the 'enriched character' and the type of eruption observed.

Carbon and water: concentrations and isotopic ratios in vesicles and glass

The volatiles were extracted by crushing under vacuum for vesicle gas, and dissolved carbon and water using stepwise heating experiment (Pineau and Javoy, 1994). Vesicles from vesicle-poor lavas have CO_2/CO_2+H_2O ratios varying from 1–0.5, except one moderately vesicular sample which falls in the upper limit of the pyroclast lavas. For the highly vesicular lavas this ratio varies from 0.2–0.002, which means that they are dominated by water.

To degas significant amounts of water at pressures greater than 150 bars is not an easy task. The study of CO_2-H_2O co-degassing curves demonstrate that water-rich vesicle is obtained only by degassing a magma initially enriched in carbon and water, (at least 6000 ppm C and 8000 to 13000 ppm H_2O). Most carbon now reside in bubbles while about 5000 to 6000 ppm dissolved water stayed in the melt. Using CO_2/CO_2+H_2O ratios, the vesicularity and the pressure of eruption, the total dissolved water present in magmas before lava vesiculation is estimated. N-MORB lava flows have water content varying from 0.25–0.50 wt.% H_2O whereas in dive OT-03 samples it varies from 0.5–2.35 wt.%.

The absence of CO_2 in vesicles of highly vesiculated samples (alkalic lavas) indicates that CO_2-rich bubbles were lost. It is believed that they were accumulated at the top of the magmatic conduit, responsible for the explosive events and loss in sea water.

Bubble-magma decoupling is normal in volatile-rich basalt and coherent with the variability of the $\delta^{13}C$ of the small amount of CO_2 found in vesicles (−4.7 to −6.9‰) or still dissolved in glasses (−5.8 to −22.5‰) which are typical of strong degassing during rapid magmatic ascent which introduces Rayleigh distillation at the bottom of the magmatic column and preservation of conditions close to equilibrium condition at the top (Pineau and Javoy, 1994). On the contrary, vesicle-poor basalts have very constant $\delta^{13}C$'s in vesicle (-5.3 ± 0.1‰) and $\delta^{13}C$'s dissolved in glass are typical of what is regularly found in N-MORB (−5.8 to −9‰).

D/H ratios found in pyroclasts' vesicles vary strongly from one aliquot to another and cover the range +2.9 to −40‰. Such variability is difficult to explain without interaction with sea water vapour just before or during eruption. Carbon-water-rich magmas formed their CO_2-water-rich bubbles, under equilibrium conditions at 20–30 km depth, leaving a very constant δD at -73.3 ± 1.4‰ in the melt. The work of Pineau *et al* (1998) can predict that water in vesicle should have δD's not higher than −40 or −50‰. Dissolved water was stabilized in the melt by loss of the CO_2-rich bubbles and did not exsolve anymore.

Conclusion

Detailed examination of the behaviour of carbon and water of the ejecta of an on-ridge volcano, where alkali-rich magmas appear, shows that most of the explosive activity has a magmatic origin. This magma can produce a large amount of vesicles only if it is initially very rich in carbon with a CO_2/CO_2+H_2O ratio = 0.5. Water exsolution favours bubble-magma decoupling, accumulation of vesicles to form a foam and then explosive eruption. Magma-sea water interaction processes can happen during gas expulsion and/or deflation phase of the volcanic construction.