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A 65 k.y. time series from sediment-hosted glasses reveals rapid transitions in ocean ridge magmas

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ABSTRACT

Studies of ocean ridge magmatism have been hampered by the difficulty in constructing time-series data over more than a few thousand years. Sediment rapidly covers newly formed ocean crust, and older rocks, even when recovered from fault scarps, cannot be dated accurately. Ridge eruptions, however, disperse pyroclastic glass over distances as far as 5 km, and these glasses have been shown to persist for thousands of years in on-ridge sediment push cores (Clague et al., 2009). Here we present data on such glasses from a piston core that impacted basement in much older (600 ka) sediment. The age of deposition was determined using established stratigraphic methods to date the host sediment, yielding an average sample resolution of a few thousand years and a continuous 65 k.y. time series. The new time-series data show systematic temporal variations in magma compositions related to a change to the dynamics of crustal storage, which led to greater extents of pre-eruptive differentiation. Shortly thereafter was a small but discernable shift toward more enriched primary melt compositions. These events coincide with the onset of enhanced crustal production, previously identified using seismic data and interpreted to reflect the capture of a hotspot by the ridge. These results show the long-term preservation of pyroclastic glasses and suggest that the construction of high-resolution volcanic stratigraphy over a million years or more may be possible at ocean ridges, using multiple piston cores that impact basement. Sediment-hosted glasses have the potential to transform ocean ridges from the volcanic setting with the worst time-series data to that with the best.

INTRODUCTION

A long-standing limitation to our understanding of mid-ocean ridges (MORs) has been the difficulty in obtaining quantitative time series for volcanic compositions. Sediments accumulating at ~1 cm/k.y. rapidly cover older lavas on the ridge flanks, making them mostly inaccessible to traditional sampling methods. Even if obtained, these rocks cannot be accurately dated because absolute radiometric dating methods have not been successfully applied to mid-oceanic ridge basalts (MORBs), making time-series interpretations problematic. Previous successes in obtaining samples from off-axis fault scarps via dredging (Batiza et al., 1996; Regelous et al., 1999) or submersible (Cordier et al., 2010) have suggested changes in magma compositions over periods of tens to hundreds of thousands of years, however the sampling resolution of these studies is very coarse (a handful of samples per 100 k.y.) and ages are inferred from spreading rates. While drill cores may offer more detailed records for older lavas (i.e., >6 Ma; Brandl et al., 2016), internal age estimates are simply stratigraphic rather than quantitative. Discriminating between models of MOR evolution (e.g., Carbotte et al., 2006; Kappel and Ryan, 1986; Smith et al., 1994; Perfit and Chadwick, 1998; Crowley et al., 2015) would benefit from high-resolution, quantitative time-series observations of the magmatic behavior of ridges through time (e.g., Clague et al., 2013).

A promising new approach to develop such time series is via sampling and analysis of small pyroclastic glass fragments deposited in seafloor sediments (Clague et al., 2009). While pyroclasts were previously known from several submarine settings (e.g., Loihi Seamount [Clague et al. 2000], Seamount 6 near the East Pacific Rise [Maicher and White, 2001], and the Gakkel Ridge [Sohn et al., 2008]), Clague et al. (2009) documented their widespread occurrence even at normal ocean ridges low in volatile content. A few high-resolution time series from such deposits, spanning periods of ~<10 k.y., exist for short on-axis push cores (i.e., Dreyer et al., 2013; Portner et al., 2015). The extent to which such glasses might be preserved in older sediments and over longer time periods, however, has not previously been demonstrated. Here we show using a piston core that reached 600 ka basement that ancient glasses are indeed preserved and permit high-resolution observations over tens of thousands of years.

TIME SERIES FROM SEDIMENT-HOSTED VOLCANIC GLASS

Although the detailed formation mechanisms remain poorly understood, pyroclastic material is generated during seafloor volcanism (Clague et al., 2000, 2003, 2009; Schipper and White, 2010), with likely dispersal via incorporation into buoyant thermal plumes (e.g., Barreyre et al., 2011; Clague et al., 2003, 2009). In an exhaustive study using a grid of 139 push cores, Clague et al. (2009) documented widespread (~5 km) dispersal from a single modest eruption on the Gorda Ridge (northeast Pacific). Although further work is required to understand the volcanological and sedimentological aspects of submarine glass generation and dispersal, available information strongly suggests that the production of small glass fragments is common during submarine volcanism at all depths (see Clague et al., 2009, and references therein). Sampling submarine volcanic glass from successive (stratigraphically intact) sediment layers provides an immediate relative chronology that can be quantified through correlating established isotope stratigraphies or using radiometric techniques to date the host sediments (such as ^{14}C dating: Clague, 2009; Dreyer et al., 2013; Portner et al., 2015). This approach also allows material to be collected that originates from flows that have been resurfaced by subsequent eruptions but whose dispersed glass deposits are preserved in the sedimentary record. Sediment-hosted glasses are therefore likely to provide a more comprehensive view of erupted magma compositions because sampling by rock core, dredge, or submersible is only able to sample the uppermost flows. Indeed, glasses from surficial sediments have been shown to span a wider range of compositions than those of underlying or adjacent lava flows (Davis and Clague, 2003), consistent with the fragments being derived from multiple flows distributed over space and time.

On a recent cruise to the Cleft segment of the Juan de Fuca Ridge (northeast Pacific), a piston core taken ~20 km west of the axis penetrated the entire sedimentary pile and impacted the volcanic basement (Fig. 1A). Numerous small (≤1 mm) particles of volcanic glass (Fig. 1B) are present in the lowermost meter of the 5.5-m-long sediment core, deposited when this portion of the seafloor was near the ridge axis. The chronostratigraphy of the host sediments was established by Costa et al. (2016) using an age model based on benthic oxygen isotopes (shown in Fig. 1C) mapped into a standard marine isotope stratigraphy (Lisiecki and Raymo, 2005) (mean sedimentation rate of ~1 ± 0.6 cm/k.y.; see methods and Fig. DR2 in GSA Data Repository[1]; Costa et al., 2016). The base of the core is constrained to be ca. 610 ka by the

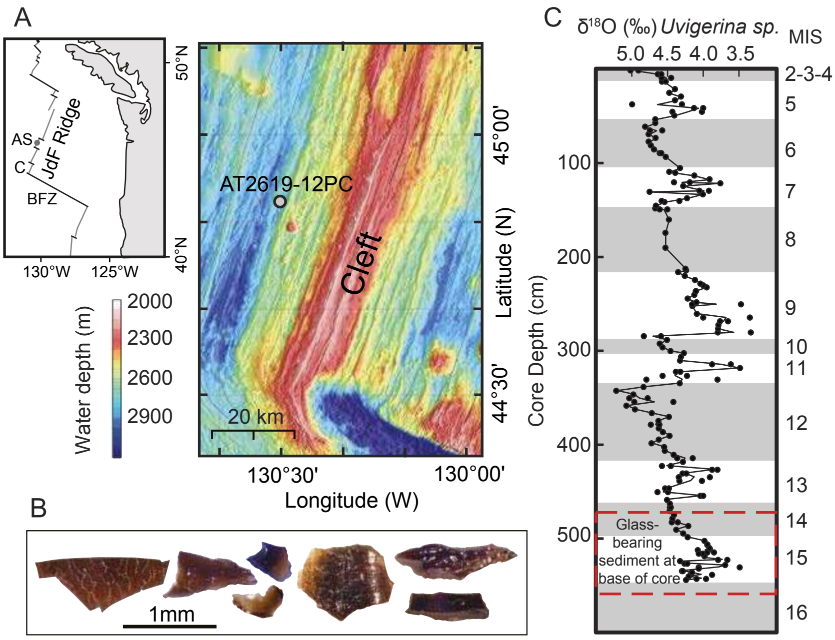

Figure 1. A: Location of sediment core AT2619-12PC collected at Juan de Fuca (JdF) Ridge (northeast Pacific; R/V Atlantis cruise AT2619). Cleft segment (C) lies north of Blanco fracture zone (BFZ) and south of Axial Seamount (AS). The coring site is located on the edge of an axial-centered bathymetric plateau, which indicates a region of thicker crust (Carbotte et al., 2008). B: Photomicrograph mosaic showing typical sizes and morphologies of sediment-hosted volcanic glasses. C: Benthic oxygen isotope data for core AT2619-12PC (Costa et al., 2016). These data provide stratigraphy and age model for host sediments. Accumulation rates over this period are shown in Figure DR2 (see footnote 1). MIS—Marine Isotope Stage.

isotope stratigraphy, the same age as that expected for the underlying lava flow, assuming emplacement near the edge of the axial rift and a half-spreading rate of 2.8 cm/yr. Because

the ages of the sediments are known, the age of glass deposition within the sediments is also known, thus providing a continuous high-resolution record of mid-Pleistocene magma compositions over several tens of thousands of years. Sampling the core every 1 cm provides a nominal temporal resolution of ~2.7 ± 0.6 k.y. per sample (see the Data Repository). Glasses from each individual sediment sample therefore give an integrated view of volcanic material generated over this time period and along a “capture region” of several kilometers of ridge length (see the Data Repository for discussion of temporal versus spatial variability). The glass-bearing sediments range in age from 545 to 610 ka, providing data on eruptions over 65 k.y. and potentially along many kilometers of ridge length.

GLASS GEOCHEMISTRY

Figure 2 illustrates the compositional range of the glasses (see the Data Repository and Tables DR1–DR2 therein for data and methods). Although most of the observed variations in parameters such as MgO and FeO can be explained by variable amounts of crystal fractionation (Fig. 2A), changes observed in some element ratios, such as K_2O/TiO_2 (Fig. 2B), require distinct parental melts. These changes occur systematically with depth in the core, and therefore with time, and are characterized by two notable transitions (Figs. 3A–3C; Figs. DR3A–DR3C). The first of these

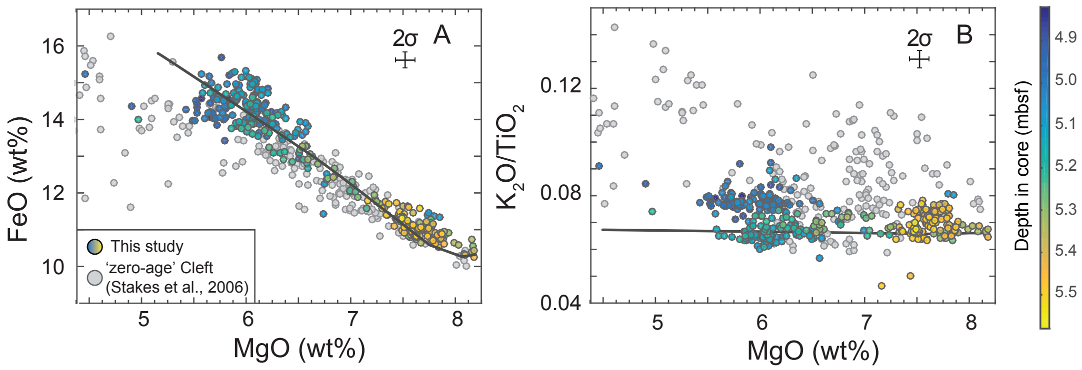

Figure 2. FeO (A) and K_2O/TiO_2 (B) versus MgO for Cleft segment glasses, Juan de Fuca Ridge (northeast Pacific). Variations in MgO and FeO can be mostly explained by variable extents of fractional crystallization (dark line shows fractional crystallization path from high to low MgO using model of Weaver and Langmuir [1990]). Other compositional variations such as K_2O/TiO_2 ratios cannot be explained by fractionation alone and require distinct parental melts. Note distinction between glass compositions in upper and lower part of sampled core section (mbsf—meters below sea floor).

is a decrease in the average MgO content from ~7.5 to ~6 wt%, occurring between ca. 600 and 590 ka. Because MgO correlates with temperature in basaltic magmas, this change shows a decrease in magma temperature, coupled with greater extents of crystal fractionation and associated increases in other elements (Figs. 3A–3C; Figs. DR3A–DR3C). The second compositional shift is another stepwise change between ca. 580 and 570 ka, when the average K_2O/TiO_2 ratio increases. This relative enrichment in K versus Ti cannot be explained by crystal fractionation alone (Fig. 2B) and therefore most likely indicates a change in the average composition of the primary melt from the sub-ridge mantle. These shifts occur relatively rapidly, essentially at the resolution of our data (see the Data Repository), and are preceded and followed by relatively long periods of low variability in average magma compositions. The change to more differentiated magmas is also accompanied by an increase in the diversity of erupted MgO contents (Fig. 3D).

TEMPORAL TRENDS IN MAGMATISM

These new data provide a unique record of MOR magma compositions over tens of thousands of years. The observed geochemical transitions (Figs. 3A–3C) demonstrate that some ridge segments can erupt magmas from a single parental composition over an extended period of time, and then experience rapid changes in magma compositions, reflecting changes in both the dynamics of pre-eruptive melt storage and fractionation, and primary melt generation. The transition to more differentiated melts implies a change in the sub-rift thermal regime and/or time scales of melt storage. A potential driver for such a change is a variation in the melt flux to the ridge. A waning melt flux could lead to increased residence time and/or faster cooling rates in the sub-axial reservoir, allowing for greater extents of pre-eruptive fractionation. Alternatively, ridges with higher melt flux are observed to erupt magmas with lower average MgO contents, most likely due to shallower and therefore cooler magma chambers (Rubin and Sinton, 2007). This is also observed when melt flux varies independently of spreading rate (Colman et al., 2012). In either scenario, provided the change in melt flux was sufficiently large and sustained, one may expect these transitions in melt chemistry to correlate with a change in crustal thickness. Seismic data from the Cleft segment shows that a significant increase in crustal production occurred at ca. 590 ka (~1 km increase in crustal

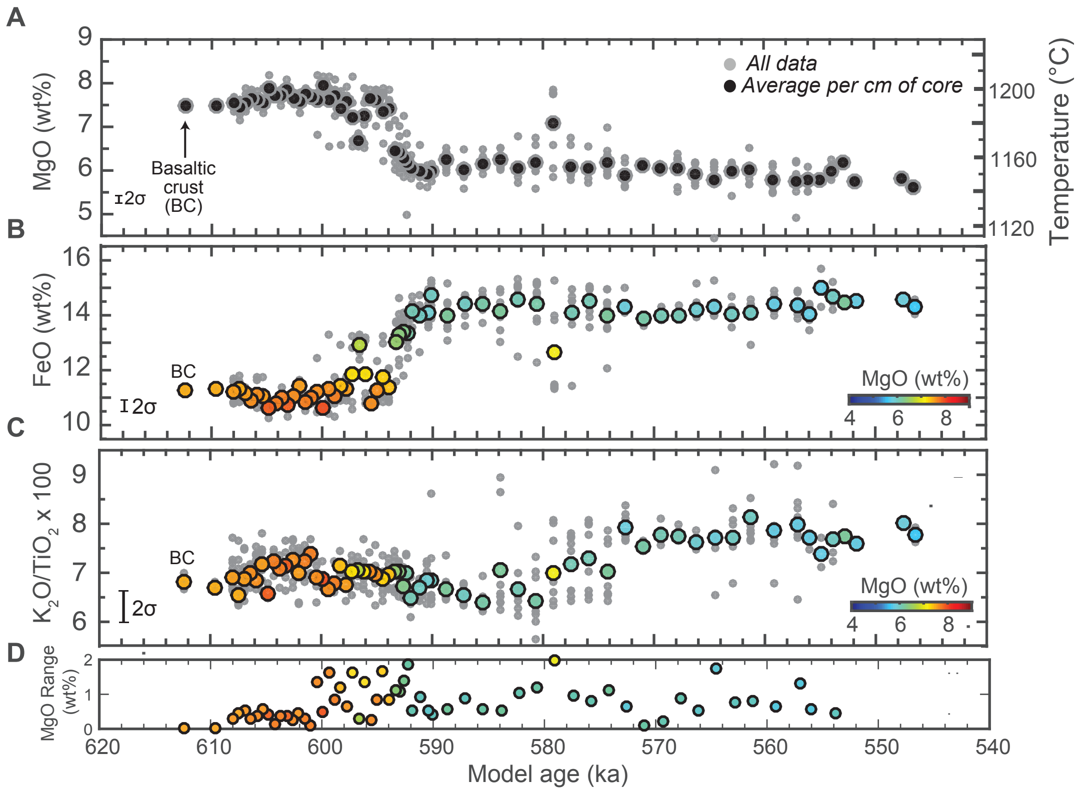

Figure 3. A–C: Time series for MgO (A), FeO (B), and K_2O/TiO_2 (C) contents for sediment-hosted volcanic glasses, Cleft segment, Juan de Fuca Ridge (northeast Pacific). D: Range of MgO for sediment-hosted volcanic glasses. Age-composition plots A–C show all data (gray circles) and average compositions per centimeter of core (colored circles). Temporal trends in MgO and FeO contents reveal rapid change in both average and total range of erupted compositions (range of MgO shown in D) consistent with change in extent of pre-eruptive fractional crystallization, and therefore cooling, of magma. Average K_2O/TiO_2 ratios remain largely constant during transition to more fractionated magmas indicating that average composition of primary melts feeding the ridge did not significantly change. Subsequent increase in average K_2O/TiO_2 values indicates more chemically enriched melts erupting from the magma system. Glasses from lowermost layer of sediment match composition of uppermost lava flow of underlying basaltic crust (marked BC in A–C), which was sampled by core cutter at base of pipe. Similar time-series plots for TiO_2, P_2O_5, and K_2O are shown in Figures DR3A–DR3C (see footnote 1).

thickness; Carbotte et al., 2008). This is visible in the seafloor morphology due to the presence of a broad (isostatically compensated) axial-centered bathymetric plateau (Fig. 1A). Carbotte et al. (2008) attributed the rise in magma volumes to melting anomalies associated with the capture of the Cobb hotspot by the Juan de Fuca Ridge (e.g., Desonie and Duncan, 1990). The close temporal correlation between the change in average MgO contents of the magmas sampled in our core and the onset of enhanced crustal production is highly suggestive of a causal relationship between these events, i.e., a change in the dynamics of magma differentiation as a response to greater melt flux.

Approximately 20 k.y. after the transition to lower MgO contents, a small but discernable rise occurs in the average K_2O/TiO_2 ratio (Fig. 3C). This could have resulted from either a decrease in melt fraction from a heterogeneous mantle or the introduction of enriched material into the melting region. Decrease in melt fraction seems less likely because it would not account for the change in crustal thickness. Instead, tapping hotter and more enriched mantle, akin to what is observed at hotspots, seems more plausible. If the change in the average K_2O/TiO_2 values is linked to the decrease in MgO, then the time lag between these changes may reflect the dynamics of melt ascent beneath the ridge. Because more fertile mantle will melt at greater depths, total melt flux might increase prior to an enriched geochemical signal, as the higher K_2O/TiO_2 melts would take time to propagate through the mantle to the ridge. If the observed changes in melt composition are related to the aforementioned increase in melt flux linked to the Cobb hotspot (e.g., Carbotte et al., 2008), then the temporal offset between the increase in magma flux (affecting MgO) versus the effects on primary melt chemistry could provide constraints on the dynamics of hotspot/plume migration along MORs (e.g., Ito et al., 2003). The hotspot is currently centered beneath Axial Seamount ~150 km north of the Cleft segment (Fig. 1A) and, although not isotopically distinct, coincides with an along-axis peak in the abundances of alkali and incompatible trace elements (Chadwick et al., 2005; Dreyer et al., 2013). This provides a feasible enriched end-member source component for the higher-K_2O/TiO_2 melts and is consistent with existing work on the origin of Cleft lavas (Smith et al., 1994). The observed change in K_2O/TiO_2 would likely require ~10% addition of Cobb hotspot material into the MORB source (Chadwick et al., 2005), of similar magnitude to the associated increase in crustal thickness (Carbotte et al., 2008).

The long intervals of relatively low compositional variability that appear in this core may seem to run counter to observations of “zero age” sampling of rocks exposed in the neovolcanic zone at the Cleft segment, which show more diversity (Fig. 2; Stakes et al., 2006). In the absence of real age constraints, however, such sampling may reflect changes occurring over a relatively long time period. Sediment-hosted glasses from cores near ridge segments with diverse compositions will help to reveal to what extent erupted magmas change smoothly with time, or have multiple compositions at a single time (e.g., Gill et al., 2016). Furthermore, oscillations between periods of more homogeneous compositions and more short-term diversity could also reveal important information about ridge processes and the extent of homogenization in sub-axial magma reservoirs. More detailed investigations of the implications of these observations for ridge magmatism, as well as studies of the relationship between the physical and chemical characteristics of the glasses, are fertile ground for future work.

SUMMARY AND FUTURE WORK

The discovery that sediments above the seafloor contain abundant fragments of volcanic glass has opened a new approach for investigating magmatism and volcanic processes at ocean ridges. The results presented in this study demonstrate that these deposits, previously documented at the ridge axis, are preserved in the sedimentary record for >600 k.y. and can be used to construct compositional time series that have both high temporal resolution and high sample density. Combining geochemical analyses of sediment-hosted glasses with chronostratigraphy of the host sediments thus offers the possibility of constraining temporal trends in magmatism and the compositional evolution of ocean ridge segments over periods of tens of thousands of years in a single core. An important test for the potential of this reconstruction method will be to determine whether geochemical stratigraphies obtained from nearby sediment cores are similar to those obtained here. Ultimately it may be possible to generate long, continuous time series of geochemical stratigraphies of a million years or more from sediment-hosted volcanic glasses by analyzing multiple overlapping cores at different distances from the ridge axis. Because the cores also receive glass from flows several kilometers away from the site of deposition, sediment-hosted glasses also offer the possibility of much more statistically representative sampling than is possible from dredges and rock cores that only sample the latest flow in one spot. This technique may therefore permit generating both better statistical representation of variability along ocean ridges and detailed chronostratigraphies for ridge magmas that stretch back into the Pleistocene, providing a hitherto unavailable perspective on ridge magmatic processes.

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[1]GSA Data Repository item 201Xxxx, supporting dataset (Tables DR1 and DR2), Figures DR1–DR3, description of methods, and further discussion, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.