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The arc arises: The links between volcanic output, arc evolution and melt composition

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ABSTRACT

Subduction initiation is a key process for global plate tectonics. Individual lithologies developed during subduction initiation and arc inception have been identified in the trench wall of the Izu–Bonin–Mariana (IBM) island arc but a continuous record of this process has not previously been described. Here, we present results from International Ocean Discovery Program Expedition 351 that drilled a single site west of the Kyushu–Palau Ridge (KPR), a chain of extinct stratovolcanoes that represents the proto-IBM island arc, active for ∼25 Ma following subduction initiation. Site U1438 recovered 150 m of oceanic igneous basement and ∼1450 m of overlying sediments. The lower 1300 m of these sediments comprise volcaniclastic gravity-flow deposits shed from the evolving KPR arc front. We separated fresh magmatic minerals from Site U1438 sediments, and analyzed 304 glass (formerly melt) inclusions, hosted by clinopyroxene and plagioclase.

Compositions of glass inclusions preserve a temporal magmatic record of the juvenile island arc, complementary to the predominant mid-Miocene to recent activity determined from tephra layers recovered by drilling in the IBM forearc. The glass inclusions record the progressive transition of melt compositions dominated by an early ‘calc-alkalic’, high-Mg andesitic stage to a younger tholeiitic stage over a time period of 11 Ma. High-precision trace element analytical data record a simultaneously increasing influence of a deep subduction component (e.g., increase in Th vs. Nb, light rare earth element enrichment) and a more fertile mantle source (reflected in increased high field strength element abundances). This compositional change is accompanied by increased deposition rates of volcaniclastic sediments reflecting magmatic output and maturity of the arc. We conclude the ‘calc-alkalic’ stage of arc evolution may endure as long as mantle wedge sources are not mostly advected away from the zones of arc magma generation, or the rate of wedge replenishment by corner flow does not overwhelm the rate of magma extraction.

1. Introduction

Subduction initiation and accompanying onset of arc magmatism are critical processes in global plate tectonics. However, the precise temporal, spatial, and compositional evolution of the early stages of island arc magmatism are poorly understood even though they play a major role in the generation of new continental crust (Davidson and Arculus, 2005). The first magmatic products related to subduction initiation in the Izu–Bonin–Mariana (IBM) subduction system (Fig. 1) are 52–48 Ma basalts exposed on the arc-ward trench wall and have accordingly been termed forearc basalts (FAB) (e.g., Ishizuka et al., 2011a; Reagan et al., 2010). A FAB-like igneous basement of similar age was penetrated in a reararc position at International Ocean Discovery Program (IODP) Site U1438; this

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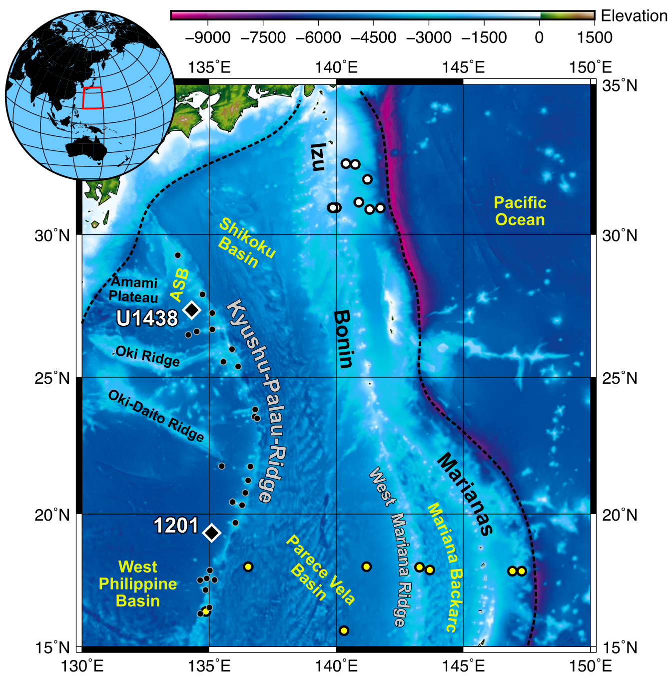

Fig. 1. Bathymetric map with key geological features of the northern Izu–Bonin–Mariana subduction system and locations of Sites U1438 (IODP Expedition 351) and 1201 (ODP Expedition 195). ASB: Amami Sankaku Basin. Grey dots correspond to drilled/dredged samples of the KPR with age data (Ishizuka et al., 2011b), white dots represent Izu–Bonin tephra samples recovered from ODP Sites 782, 784, 786–788, 790–793 and yellow dots represent Mariana arc tephra recovered from DSDP Sites 53 and 54 and ODP Sites 448, 449, 451, 453, 458, 459. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

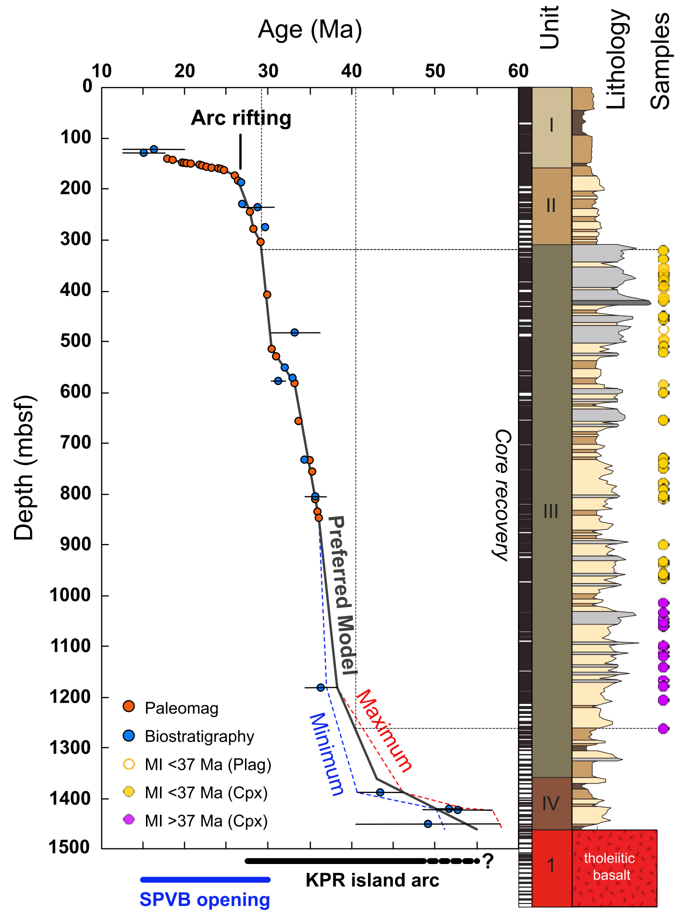

Fig. 2. Overview of the drilled sequence at Site U1438, sampling intervals and age constraints from paleomagnetic and paleontological onboard studies (Arculus et al., 2015b) plotted versus depth (in meters below seafloor). Our preferred age versus depth model is shown by a black line and the limits of uncertainty in the lower part of the sequence are illustrated by a red (maximum) and blue (minimum) dashed line. Note that in the core recovery column, white intervals represent gaps in core recovery, indicating that the Unit III interval sampled in this study is remarkably complete. Note that the paleomagnetic ages represent the depth of each geomagnetic polarity timescale chron and thus do not include uncertainties. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

magma type was clearly extensively distributed both along- and across-strike of the proto-IBM arc (Arculus et al., 2015a, 2016). The bathymetry, crustal structure, and pre-IBM sediments in basins between the Mesozoic–Lower Cenozoic arc ridges (Amami Plateau, Daito and Oki-Daito) west of Site U1438 show no sign of compressional uplift and sediment shedding, consistent with subsidence and extensional rifting accompanying a spontaneous mode of subduction inception for the IBM system (Leng and Gurnis, 2015; Arculus et al., 2016).

The timing of subduction initiation has been dated at ∼52 Ma (e.g., Ishizuka et al., 2006, 2011a). Subsequent formation of new oceanic igneous crust (submarine lava flows, sheeted dyke complex and plutonic gabbros) with a FAB-like geochemical signature lasted for 2–4 Ma. In the arc-ward trench wall of the Izu–Bonin (Ishizuka et al., 2011a) and Mariana trenches (Reagan et al., 2010), FABs are overlain first by low-silica boninites and high-magnesia andesites followed by high-silica boninites (e.g., Pearce et al., 1992; Kanayama et al., 2014; Reagan et al., 2015). This type of magmatism lasted for about 4 Ma and then from 44 Ma onwards (∼8 Ma after subduction initiation), volcaniclastic sediments indicative of arc maturation and volcanic edifice (i.e., stratovolcano) buildup and erosion are preserved in the IBM forearc.

The important phenomena we address in this paper relate to the post-subduction initiation evolution of the volcanic arc system, the subarc mantle and slab sources. We compare our results from IODP Site U1438 with comparable rock suites recovered from other IBM sites via dredging or drilling. Our aim is to investigate magmatic evolution and provincialism during the early phase of intra-oceanic island arc volcanism in the western Pacific because a corresponding detailed record of volcanic arc products has been recovered neither from the Kyushu–Palau Ridge (KPR) nor the active IBM island arc. In fact, geologic records of the juvenile arc are sparse and previously restricted to settings in the present forearc (e.g., Ishizuka et al., 2006; Reagan et al., 2008). Thus, Site U1438 (Fig. 1) in the Amami Sankaku Basin represents probably the best and most complete record of island arc evolution beginning with subduction initiation in the Early Eocene to arc rifting and backarc opening in the Late Oligocene and Early Miocene.

Furthermore, the volcaniclastic record at Site U1438 provides a more complete and also 'averaged' record of the magmatic evolution of island arcs than individual lava flows (Gill et al., 1994). Widely disseminated ash preserves the best 'averaged' record of island arc evolution but is highly biased to explosive volcanism and thus the highly evolved end of melt compositions and lack spatial information. Turbidites, in contrast, can be linked to some degree via seismic stratigraphy (e.g., thickening of depositional units towards volcanic edifices) and their rapid transport and burial minimizes chemical alteration prior to deposition (Gill et al., 1994). Our study focuses on glass inclusions hosted in fresh clinopyroxene and minor plagioclase crystals that span a depositional age from 29 to 40 Ma (Fig. 2). This 11 Ma long record of early arc magmatism sourced from the proto-IBM (KPR) is a key to further our understanding of island arc evolution and mass transfer in subduction zones.