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Dispersed ash in deeply buried sediment from the northwest Pacific Ocean: An example from the Izu–Bonin arc (ODP Site 1149)

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ABSTRACT

A multi-elemental geochemical and statistical methodology was applied to the sedimentary sequence recovered at Ocean Drilling Program Site 1149 (Leg 185) to characterize and quantify the abundance of dispersed ash–as distinct from discrete ash layers–in sediment from a critical region of the Northwest Pacific. Visual descriptions of sediment from the past 11 Ma describe both clay and volcanic ash (25–35 wt.%) as the dominant components, with many discrete layers observed. Factor analysis of the multi-element dataset indicates that statistical variability is best explained by mixing between three factors. Multiple linear regressions based on refractory trace- and rare earth element end-members of potential sources identified from the literature suggest that wind delivered Chinese loess, Ryukyu Dacite, and an average of Izu–Bonin Front Arc material yield the best statistical mixing that explains the bulk sedimentary composition. All three sources are characterized by gradual increases beginning from ~5–6 Ma to 4.5 Ma with occasional spikes in each of the sources. Ryukyu Trough extension has been active since ~6 Ma which may help to explain the increase in the Ryukyu Dacite source at Site 1149 as both the abundance and MAR rapidly increase at ~3.5 Ma. Comparing the total dispersed ash accumulation rate to the sedimentation rate of the discrete layers documents paired increases beginning at ~3.5 Ma, although the dispersed ash increases by a greater relative amount (8–9 fold) than does the sedimentation of discrete layers (~a factor of four). Collectively, the ability to resolve the dispersed component and study its compositional changes through time, in the context of coupling (or lack thereof) with discrete ash layer records, adds an additional parameter to studies of geochemical budgets ("Subduction Factory") as well as to the arc- and tectonic evolution of the region.

1. Introduction

The occurrence of ash in marine sediment has long been recognized to be an important component of the global sedimentary system. Many studies of ash focus on discrete layers found in sequences at a variety of locations and timescales, and how to link their presence with explosive volcanism, climate, arc evolution, biological productivity, and other processes (e.g., Kennett et al., 1977; Ninkovich et al., 1978; Ledbetter and Sparks, 1979; Sigurdsson et al., 1980; Carey and Sparks, 1986; Cambray et al., 1993; Straub, 1995; Lee et al., 1995; Cambray et al., 1995; Carey, 1997; Straub and Schmincke, 1998; Bryant et al., 1999; Sigurdsson et al., 2000; Carey and Sigurdsson, 2000; Straub and Layne, 2002, 2003a,b; Bryant et al., 2003; Rose et al., 2003; Straub, 2003; Straub et al., 2004; Kutterolf et al., 2008a,b,c; Jones and Gislason, 2008). Reconstructions of eruption intensities and atmospheric wind patterns have been based on grain size characteristics and inferred dispersal patterns of the ash found in these discrete layers, both at sea and on land (as cited above). Furthermore, ash has been recognized to potentially play an important role in global geochemical budgets, in the context of understanding the chemical nature of sediment entering subduction zones and becoming part of Subduction Factory fluxes (e.g., Plank and Langmuir, 1998; Stern et al., 2006; Plank et al., 2007, and references therein).

Less widely recognized is the ash that is mixed into the bulk sediment, which has been referred to as "disseminated" or "dispersed" ash. This dispersed ash is the result of bioturbation of pre-existing discrete ash layers, the settling of airborne ash through the water column (e.g., Ninkovich et al., 1978), and other mixing processes. Dispersed ash, if present in significant amounts, could potentially have a considerable effect on subduction zone chemistry and subsequently on crust and mantle composition (e.g., Plank and Langmuir, 1998; Plank et al., 2007), just as does the ash that occurs in discrete layers.

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Additionally, comparing the dispersed ash record with that of the discrete layers may provide information about arc evolution and erosional histories of landmasses (e.g., Peters et al., 2000).

Visual techniques have commonly been employed to estimate the abundance of ash in sediment. Dispersed ash, however, is difficult to identify petrographically due to alteration of ash grains to authigenic clay (Sigurdsson et al., 1997; Plank et al., 2000; Schacht et al., 2008) as well as its commonly very fine grain size (Rose et al., 2003, and references therein). Such alteration often results in fine-grained material that is unable to be differentiated optically during visual sedimentological study. As such, other approaches (e.g., mineralogy, chemistry) have attempted further identification.

For example, in an effort to quantify to a greater precision the concentration of dispersed ash in the Caribbean Sea, Peters et al. (2000) developed a chromium (Cr)-based normative calculation and documented on a sample-by-sample basis that dispersed ash comprises 15–20 wt.% (weight percent, with a maximum of 45 wt.%) of the bulk sediment in the western Caribbean. They also observed that the timing of dispersed ash accumulation paralleled that of discrete layers, although the maxima in dispersed ash preceded the Miocene and Eocene maxima in discrete layers by ~2–4 Ma (Supplementary material Section 1, Fig. S1). They interpreted the relative timing as recording aspects of arc evolution, with the dispersed ash being generated by smaller volcanoes characteristic of the more juvenile arc. The larger discrete layers were interpreted as representing the mature arc characterized by larger stratovolcanoes that were, as suggested by Carey and Sigurdsson (2000) and Sigurdsson et al. (2000), capable of injecting large plumes of Central American ash to the upper reaches of the stratosphere, that is, high enough to become entrained in the west-to-east blowing wind field (e.g., rather than from east-to-west in the lower elevation trade winds).

Ocean Drilling Program (ODP) Leg 185 focused on the Izu–Bonin and Mariana subduction systems in the western Pacific (Fig. 1). One of the objectives of Leg 185 was to determine ways to test whether subducted sediments control along-strike geochemical differences in arc magma composition (Plank et al., 2000). In addition to the potential influence of the terrigenous (non-ash) sedimentary component, the amount of ash in the sediment column is critical to constrain, not only for the determination of absolute geochemical fluxes into the Subduction Factory (Plank and Langmuir, 1998), but also in order to determine how much of the input is in fact “recycled” from the arc itself. That is, if the fraction of ash subducted (both as discrete layers and dispersed ash) is a significant portion of the bulk flux, more accurately quantifying the amount of this ash will help constrain a potentially important sub-loop in the overall geochemical budget of the subduction environment.

As such, there are two main goals for this paper. First, we aim to develop a multi-elemental analytical and statistical methodology to characterize and quantify the abundance of dispersed ash in marine sediment in the Northwest Pacific, using Site 1149 as an illustrative sequence. Different methodologies are considered to quantify dispersed ash, such as smear slide analysis, chemical normative calculations (e.g., Peters et al., 2000), as well as multivariate statistical techniques such as factor analysis and multiple linear regression (e.g., Leinen and Pisias, 1984; Ziegler et al., 2007; and references therein). Second, we use these results to discuss the geological significance of the provenance of the dispersed ash in relation to the terrigenous input and in the context of identifying the specific volcanic sources supplying ash to the ODP Site 1149 location.

2. Geochemical methods, multivariate statistics, stratigraphy, and discrete ash determinations

2.1. Geochemical methods

Samples were first analyzed on-board the *JOIDES Resolution* during Leg 185 by X-ray fluorescence (XRF) (Plank et al., 2000). Further post-cruise samples were taken at evenly spaced downcore intervals (Kelley et al., 2003; Plank et al., 2007), and were freeze-dried, powdered, and acid-digested for geochemical analysis. Guided by the shorebased XRF results, a total of 95 samples were analyzed at Boston University for major elements, Sr, and Ba by inductively coupled plasma emission spectrometry (ICP-ES), with a sub-set of 45 samples also analyzed for additional trace elements by inductively coupled plasma mass spectrometry (ICP-MS), as described in Kelley et al.

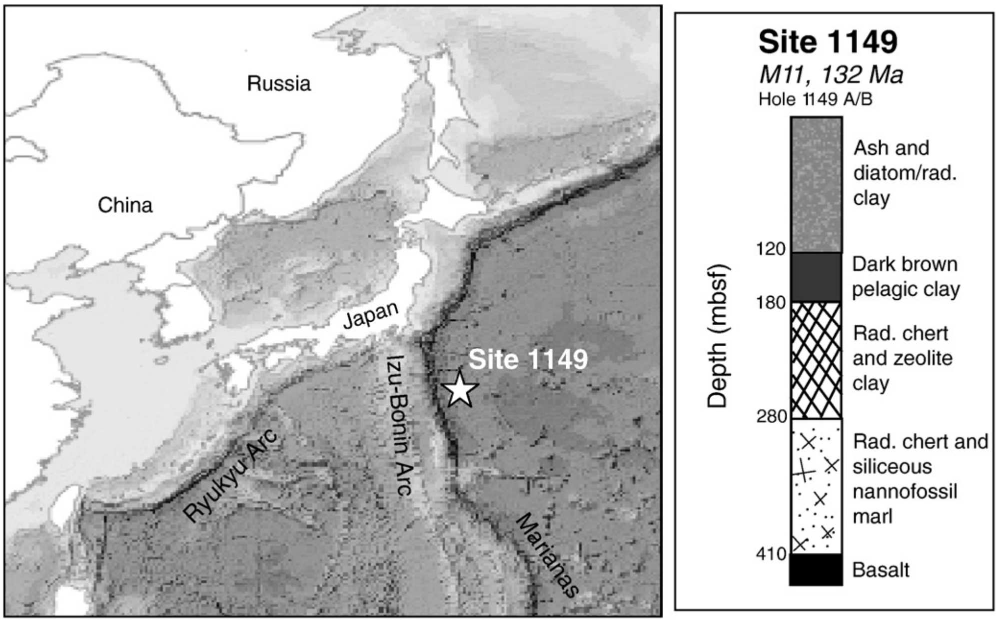

Fig. 1. Location of Ocean Drilling Program Site 1149 (31°20.099′N, 143°21.805′E, 5830 m water depth) in the northwest Pacific Ocean and the summarized stratigraphic column from Plank et al. (2000). Unit I (0–118.2 mbsf) consists primarily of dark greenish gray, dark gray, or dark brown clayey lithologies with varying amounts of siliceous microfossils and volcanic grains. Siliceous microfossils are common to abundant. Unit IIA (118.2–149.5 mbsf) is characterized by dark brown pelagic clay with rare volcanic glass grains and intercalated ash layers. The upper boundary of Unit IIA was placed below the last downhole occurrence of dissolution-susceptible radiolarian and diatom tests. Apart from the disappearance of silica, the mineralogical composition of Unit IIA sediments is similar to that of Unit I, especially in the upper part.