ARC CRUST AND MANTLE EVOLUTION: THE ORIGIN OF ALONG- AND ACROSS-ARC VARIATIONS

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Abstract

Along- and Across-Arc (AAA) variations are widespread in subduction zones, either in the geophysical structure of the subducting slab, mantle wedge, and arc crust or in the geochemistry of the incoming plate, wedge mantle peridotite, and arc magmas. The geophysical heterogeneities have been investigated in arc scale geophysical expeditions, which have led to key developments in subduction zone studies. Geochemical heterogeneities in output magmas have been investigated by analyzing oceanic sediments and crust, supra-subduction zone peridotites in forearc ophiolites, and serpentine seamounts, as well as examining magmatic records. Samples from inputs and ouputs of the subduction zone collected during the Ocean Drilling Project (ODP) have contributed to the recognition of geochemical variations in many subduction zones.

The geophysical heterogeneities can be anything from hemispheric, through arc segment, to intra-arc in scale. Recent geochemical studies suggest that the geophysical heterogeneities have a close spatial link to the geochemical variations. Discovering the cause of this link will thus be the most exciting area of research in this field in the coming decades. To support arc mass balance, numerical geochemical models have also been proposed based on developments in theoretical and experimental petrology. However, AAA variations revealed by the geochemical investigations using ODP samples have nowhere near the spatial resolution of those obtained in the geophysical studies.

Our proposal is to drill and sample incoming plate sediments and oceanic crust, forearc peridotite (whenever available), tephra records of magmas, and back arc basin magmas and peridotites (when applicable) with greater spatial resolution than before along and across arc. The arcs that this project targets are those where geophysical 3D investigations have been completed and a close link between the geophysical and geochemical heterogeneities has been revealed. There are several candidate areas, both at continental margins and oceanic arcs. Carefully designed oceanic drilling promises successful results that can lead to transformative science in subduction zones. (298 words)

RESEARCH FOCUS:

ORIGIN OF 3-DIMENSIONAL VARIATION IN THE ARC MANTLE AND CRUST

1. INTRODUCTION

Subduction zone processes are often discussed in terms of two-dimensional model cross-sections across convergent margins. Recent geophysical and geochemical studies on island arcs, however, have revealed non-uniform geophysical and geochemical features in the subduction zone slab, mantle wedge, arc crust, and arc magmas (Kodaira *et al.* 2002; Nakajima & Hasegawa 2003; Nakajima & Hasegawa 2007; Nakajima *et al.* 2005). Such along- and across-arc（AAA） heterogeneities are observed in velocity structure and b-values in the downgoing slab (Kodaira *et al.* 2002; Miura *et al.* 2005; Tsuru *et al.* 2002; Wiemer & Beniot 1996; Wyss *et al.* 2001), seismic wave structure, Poisson ratios, attenuations, Q-values, anisotropy of the mantle wedge (Hasegawa & Nakajima 2004; Nakajima & Hasegawa 2003; Nakajima *et al.* 2005; Rychert *et al.* 2008; Tono *et al.* 2009), thickness of arc crust and magnetic anomaly (Kodaira *et al.* 2008), and magma compositions (Carr *et al.* 2007; Jicha *et al.* 2004; Kimura & Yoshida 2006; Tamura *et al.* 2009). Thus, it is vital to develop a three-dimensional model of convergent margins.

The geophysical and geochemical observations often have unexpected spatial correlations that to be understood require collaborations between geophysicists, geologists, petrologists and geochemists. For example, along arc geochemical variations in magmas relate to differences in the material being subducted (Carr *et al.* 2007; Ishizuka *et al.* 2003) or fracture zone subduction (Jicha *et al.* 2004). Seismicity of the subducting slab also differs when an aseismic ridge or fracture zone is subducted. In response to differences in slab inputs, the mantle wedge structure also differs in terms of Q values and S-wave velocity (Hasegawa & Nakajima 2004). Slab tear structures may also induce along arc mantle flow in addition to the normal convection in the mantle wedge, resulting in a disturbed anisotropic mantle structure (Abt *et al.* 2009). Variations in mantle convection patterns or slab fluid inputs can also change the mantle wedge temperature and melting structures, all of which will influence magma production rate and magma chemistry (Hasegawa & Nakajima 2004; Iwamori 2000; Kimura & Stern 2009; Tamura *et al.* 2002). In response to changes in magma production rate and magma chemistry, arc crust production rate and geochemical properties of the arc crust will also differ (Hasegawa & Nakajima 2004). Fractionation of magmas, both at the arc MOHO and within the arc crust, also enhances seismic and geochemical heterogeneities in the arc mantle-crust vertical section (Tamura *et al.* 2009; Tatsumi *et al.* 2008). Thus, over the entire history of the arc, the crust grows heterogeneously, both in terms of its geophysical and geochemical properties.

2. KEY SCIENTIFIC QUESTIONS

The key scientific questions to be addressed are (1) what governs the along- and across-arc (AAA) variations in magmas, arc crust, and the mantle wedge and thus the three-dimensional evolution of convergent margins, and (2) how do subduction inputs control the variation? These key questions can be divided further;

- *How are the different slab inputs (e.g., volatiles and solid earth elements) reflected in the chemistry of arc magmas and melt production?*
- *How do mantle wedge dynamics affect the slab derived material fluxed in arc magma genesis?*
- *What causes variations in arc crustal thickness?*
- *How do arc magmas evolve at the MOHO and in the middle crust?*

- *How is arc crust generation related to the origin of the continental crust?*

3. KEY OBSERVATIONS

One of the key observations is determining the wavelength of AAA variations. Firstly, there is the wavelength of the regular occurrence of volcanoes or volcano groups on the scale of several 10s to 100 km along the arc (ref.). Recently, progress in the geophysical and geochemical observations have enabled mantle heterogeneities, on the scale of several-hundred-kilometers, to be identified (Figure 1; Isse *et al.,* 2009). Furthermore, arc crustal thickness has been found to vary on wavelengths of 80-100 km (Figure 2, Kodaira *et al.,* 2008). Geochemical variations in the magma seem to be related to all these physical variations (Figure 3, Kodaira *et al.,* 2007; Tamura *et al.,* 2009). Moreover, a striking characteristic of orogenic andesites and associated rocks within many volcanic arcs of modest width is the consistent increase of their incompatible element concentrations, notably K_2O, away from the arc front (Gill, 1981). To explain the different wavelengths of these variations a three-dimensional model is required. This must answer the key questions above. Important geological objectives to study are (1) oceanic crust on the incoming plate, (2) stratified forearc supra-subduction ophiolites including abyssal peridotites, (3) arc magmatic products ranging from basalt to rhyolite or plutonic equivalents, and (4) back arc basin (BAB) abyssal peridotites and magmas, all of which must be sampled systematically along- and across-arc. Geophysical and geochemical surveys must have already been undertaken in the arcs targeted for study and ideally the arcs should also have been the subject of submersible geological surveys and previous drilling.

4. 3-D ARC PROJECT (AAA VARIATIONS): USING ARC INPUTS AND OUTPUTS

Our proposal is building upon recent developments that have occurred in marine geophysics, geochemistry and geology, which suggest that along- and across-arc (AAA) variations in magmas, arc crust, and mantle wedge are related to the inputs into subduction zones. These are very intriguing and further breakthroughs will be achieved if scientific drilling is utilized to further address the issue.

Essentially we propose to systematically sample subduction zone input and output materials along and across the arcs (Figure 4). The inputs include oceanic sediments and altered oceanic crust materials. Abyssal peridotites found in fore arcs or back arc basins will also be systematically sampled in order to look at residues after modification by subduction processes such as slab-flux addition and magma extraction. Erupted AAA magmas will be sampled in tephra and by drilling important geological segments to collect lava flows, volcaniclastic rocks and dykes. This will allow AAA variations in input materials, processed materials, and output materials to be collectively investigated in order to elucidate the three-dimensional evolution of subduction zones.

A key issue is to determine how these AAA magma variations are generated. Geochemical studies allow the intensive/extensive variables (e.g., pressure, temperature, degree of melting, magma production rate) that form magmas and mass balance (e.g., extent of contribution of slab materials and mantle, the identity type of slab flux such as melt/fluid) (Kelemen *et al.* 2003; Kimura *et al.* 2009) of the heterogeneous arc segments to be defined. Intermediate to felsic magmas are also used to study fractionation at the MOHO and in the arc crust in order to understand the origin of vertical stratification in arc mantle-crust sections. Slab input materials and abyssal peridotites are also used to constrain source materials that generate heterogeneous AAA magma.

To be able to elucidate arc heterogeneities in three dimensions, we propose to conduct deep ocean drilling on:

- *Incoming oceanic plate slab, with the drill sites aligned along arc in order to sample oceanic sediments and altered oceanic crust. Any along arc variations including subducting aseismic ridges or seamount chains will also be targeted.*
- *Forearc ophiolite sequences aligned along arc in order to sample modified/unmodified mantle peridotite or pre-existing oceanic crust.*
- *Forearc basin sediments that record tephra sequences aligned along arc.*
- *Volcaniclastic rocks and basement rocks between volcanoes to determine how arc volcanoes and the stability of volcano spacing and hot fingers evolved.*
- *Rear arc basin sediments that preserve tephra sequence, in order to elucidate across arc variations.*
- *BAB spreading ridges along arc in order to sample BAB abyssal peridotite and BAB magmas.*

Candidate areas do not have to satisfy all the components, but clear AAA magmatic variations should have already been documented. Moreover, tephra records can provide temporal growth of the magmas and thus would contribute to deciphering the four dimensional evolution of the arc, but only if recovery was sufficient.

There are several previous studies that have attempted to answer similar questions, but the spatial resolution of the marine records is always insufficient to resolve the real arc inputs and outputs. Only with systematic drilling can more realistic constraints be placed on recycling systems in subduction factories worldwide.

EXPECTED NEW OUTCOMES AND CAPABILITIES

We propose to use ocean drilling to sample the scale of AAA variations in materials entering, being processed by, and leaving the subduction system. This will provide insights into the mass balance in arcs and the petrological manufacture of new crust. Existing geochemical and petrological models can be developed further using such multidisciplinary endeavors involving geophysics and marine science, which will result in many new discoveries concerning the three-dimensional structure of the arc crust and mantle wedge.

PATH TO ACHIEVING THE GOALS

Arc heterogeneities range from arc-scale (few thousand kilometers), through segment scale (few hundred kilometers) to the local scale (few tens of kilometers). The geology, geochemistry of volcanic rocks, and seismology of the target area should already have been studied in detail and spatial correlation of heterogeneities should have been observed in at least two different phenomena. Proposed drilling sites will have to be sufficiently dense and cover a wide enough area to be able to resolve the heterogeneity of the along- and across- arc systems. Techniques to sample tephras in sediment cores, and volcanic rocks and peridotites in drill cores have become well established in non-riser drilling projects, so that choosing the sampling site should be the only crucial issue for the success of this project. Developments of realistic models to explain magma genesis and arc evolution are another key factor to elucidate geochemical mass balance in the arc. Additional geophysical expeditions should also be conducted before target areas are finally selected for drilling. Such background investigations will increase the likelihood of success in determining and explaining AAA variations.

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Figures

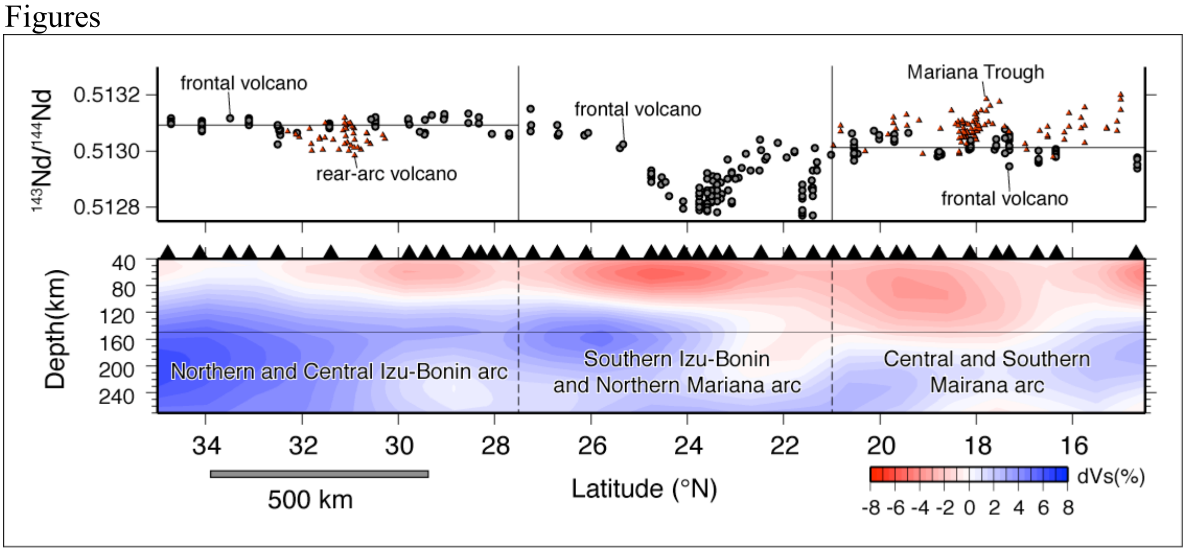

Figure 1. (a: upper diagram) Along-arc variation of ^{143}Nd/^{144}Nd values in frontal arc volcanoes and rear arc volcanoes of northern Izu and the Mariana Trough. (b: lower diagram) Along-volcanic front cross-section of shear wave speed perturbations (in percent) (after Isse et al., 2009).

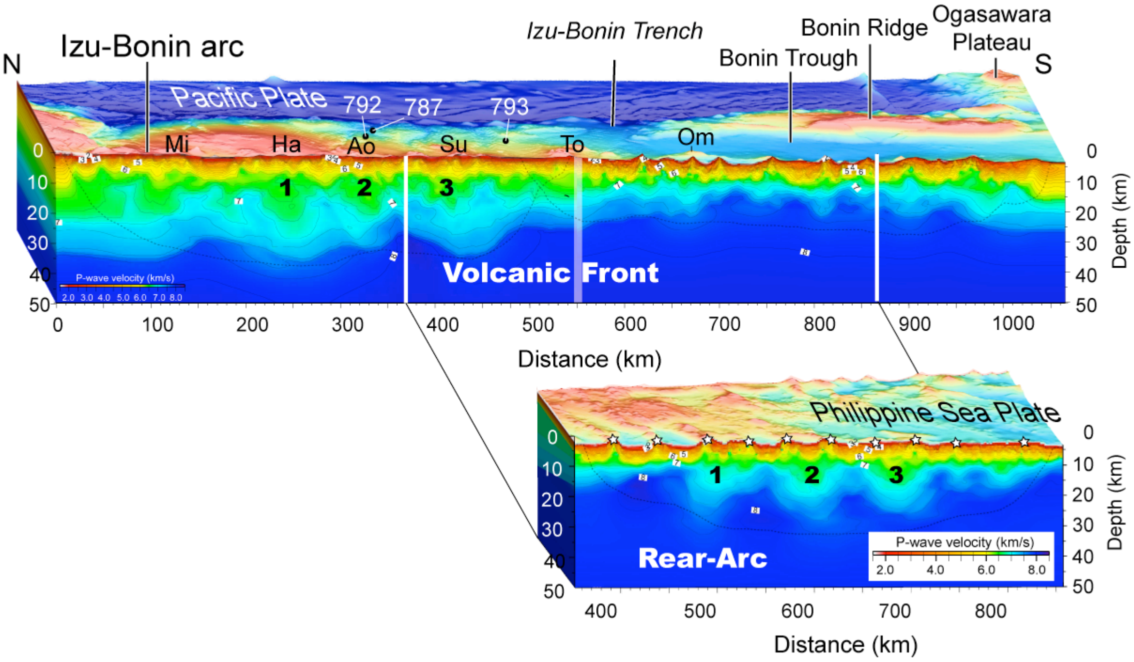

Figure 2. Three-dimensional block diagram with seismic images of both the volcanic front and the rear arc along the Izu-Bonin arc ~150 km west of the volcanic front (after Kodaira et al.*, 2008). Numbered circles indicate sites drilled on the Philippine Sea Plate in the Izu-Bonin region during ODP Legs 125 and 126, which recovered Oligocene and Neogene turbidites. Abbreviations show basalt-dominant Quaternary volcanoes (Mi, Miyake; Ha, Hachijo; Ao, Aogashima; Su, Sumisu; To, Torishima) on the volcanic front and the andesitic Oligocene volcano (Om, Omachi seamount) east of the front. The stars on the rear-arc profile indicate Mio-Pliocene volcanoes. Three discrete thick crustal segments (20–25 km thick) in the rear-arc and their possible counterparts below the volcanic front (Kodaira* et al.*, 2008) are numbered from 1 to 3.*

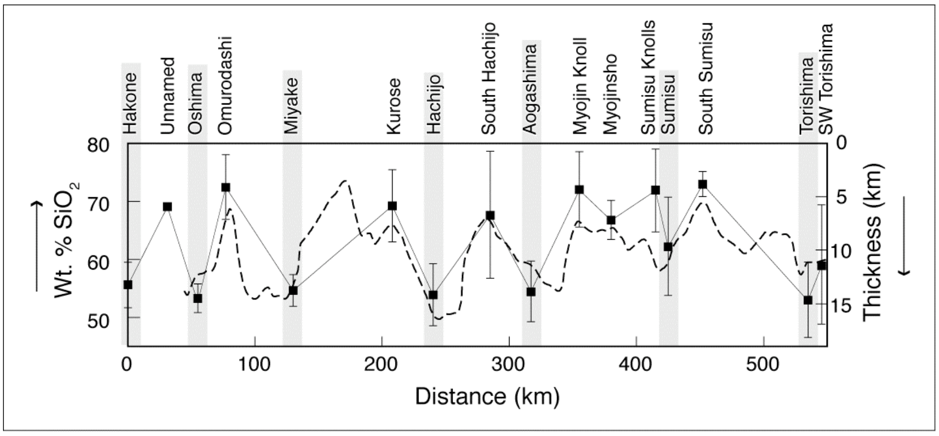

Figure 3. Along-arc crustal structure (dotted line; thickness of middle crust with Vp of 6.0-6.8 kms^{-1} at depths between 5 and 20 km) and average wt. % SiO_2 of volcanic rocks (solid squares) sampled and dredged from the 16 Quaternary volcanoes of the Izu-Bonin arc (after Tamura et al., 2009).

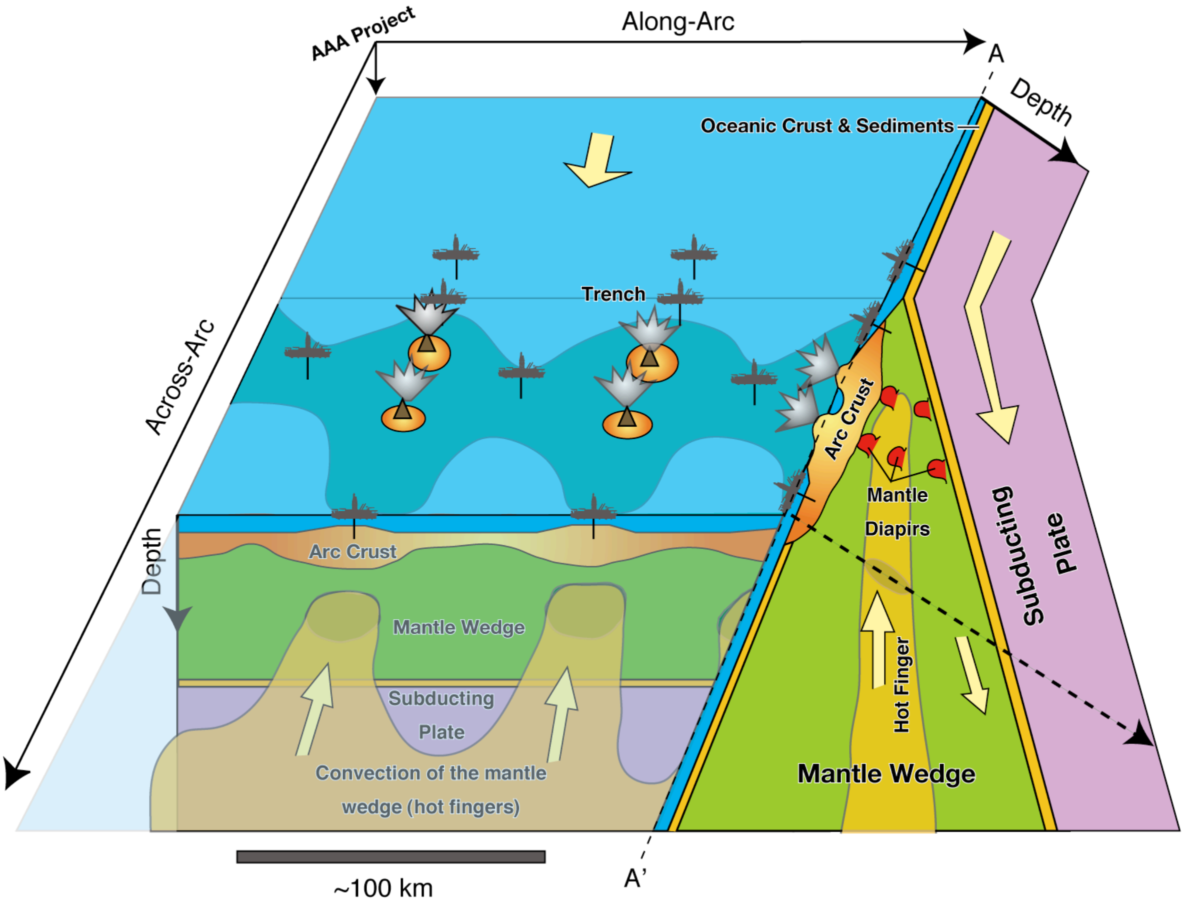

Figure 4. 3-D arc project (AAA variations): using arc inputs and outputs (see text for the details). Photocopy this figure and fold along A-A' to see the 3-D subduction zone.