Revised age of Aleutian Island Arc formation implies high rate of magma production

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ABSTRACT

Radioisotopic dating of subaerial and submarine volcanic and plutonic rocks from the Aleutian Island Arc provides insight into the timing of arc formation in the middle Eocene. Twenty-eight $^{40}Ar/^{39}Ar$ ages constrain the duration of arc magmatism to the last 46 m.y. Basaltic lavas from the Finger Bay volcanics, the oldest exposed rocks in the arc, gave an isochron age of 37.4 ± 0.6 Ma, which is 12–17 m.y. younger than a widely cited age of 55–50 Ma. Three main pulses of arc-wide magmatism occurred at 38–29, 16–11, and 6–0 Ma, which coincide with periods of intense magmatism in other western Pacific island arcs. Using the geochronology and volumetric estimates of crust generated and eroded over the last 46 m.y., we calculate a time-averaged magma production rate for the entire arc that exceeds previous estimates by almost an order of magnitude.

Keywords: Aleutian Arc, magma production, $^{40}Ar/^{39}Ar$ dating, arc growth.

INTRODUCTION

Subduction zones are fundamental sites of melt generation, crustal genesis, and recycling of material between the crust and mantle. It has been suggested that island arc magmatism plays an important role in the formation of continental crust, which has an average major- and trace-element composition similar to an arc andesite (Taylor and McLennan, 1985). Even though high Mg# andesite can be created in intraoceanic arcs (Kelemen et al., 2003), numerous petrologic, geochemical, and seismic studies indicate that the composition of the crust in the Aleutians is basaltic (e.g., Kay and Kay, 1994; Lizarralde et al., 2002). A solution to this inconsistency requires using a variety of tools to gain a better understanding of all of the syn- and postmagmatic processes involved in island arc and continental crust formation. Geochemical and geophysical data provide insight into the structure and composition of the arc crust, but precise geochronology of crustal rocks is essential to constrain the rate at which magma has been produced through time.

Surprisingly, few attempts to estimate long-term (e.g., tens of millions of years) magma productivity of entire active volcanic arcs are published. The Aleutian Island Arc separates the North American plate and Bering Sea from the Pacific plate and Pacific Ocean (Fig. 1). Its arc massif, although extended laterally, is volumetrically intact, which distinguishes it from virtually every other intraoceanic arc. Widely accepted magma production rates calculated for the Aleutians (Crisp, 1984; Reymer and Schubert, 1984) are based on geophysical data that are more than three decades old (Grow, 1973). Recent seismic and gravity studies suggest slightly higher Aleutian magma production rates (Holbrook et al., 1999; Lizarralde et al., 2002; Dimalanta et al., 2002). We present 28 new $^{40}Ar/^{39}Ar$ ages that bear on the long-term evolution of the Aleutian Island Arc. When interpreted in the context of new-generation seismic data, the $^{40}Ar/^{39}Ar$ ages imply an astonishingly high time-averaged magma production rate of 89–182 $km^3/km/m.y.$

TECTONIC SETTING OF THE ALEUTIAN ARC

Active and dormant volcanoes sit atop the narrow crest of the Aleutian Ridge that extends westward ~2200 km from the tip of the Alaska Peninsula to the Kamchatka Peninsula (Fig. 1). Our knowledge of the composition and structure of the Aleutian Island Arc has been greatly improved by several recent wide-angle seismic studies (e.g., Holbrook et al., 1999; Lizarralde et al., 2002), which include along- and across-arc transects in the central and eastern Aleutians. Seismic profiles indicate that the Aleutian Ridge is a 160–225-km-wide, 25–35-km-thick, flattened platform that rises from a deeply submerged base. Crustal dimensions in the central Aleutians (200 km wide, 30 km thick) likely represent an average of the entire arc. In the eastern Aleutians, the width of the ridge is >250 km because it contains accreted terrane from the former Beringian margin. Conversely, arc width decreases westward to as narrow as 80 km near the Komandorsky Islands (Scholl et al., 1987).

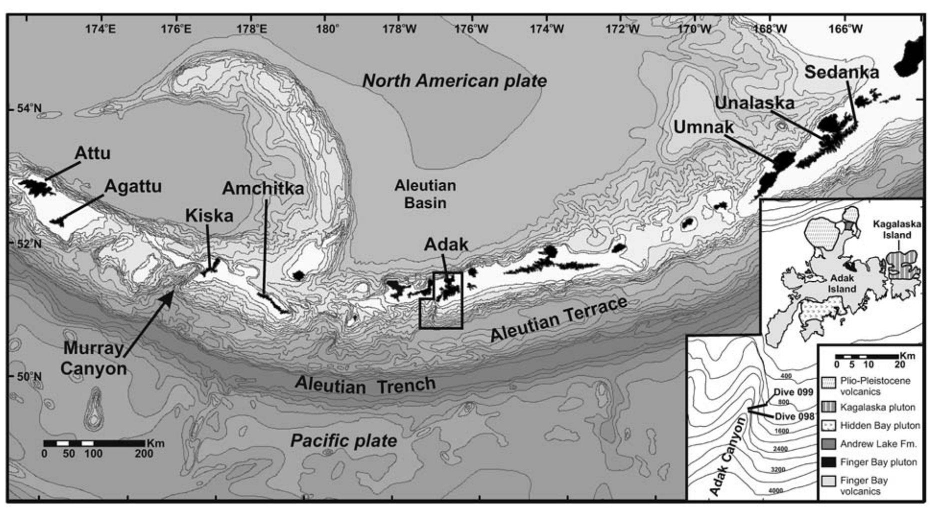

Figure 1. Bathymetric map of Aleutian Island Arc. Labeled islands contain outcrops of plutonic rocks for which age determinations have been made using K-Ar (previous studies) or $^{40}Ar/^{39}Ar$ methods (this study). Contour interval is 400 m. Inset shows enlarged view of the geology of Adak and Kagalaska Islands and locations of the two JASON II dives.

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P-wave velocity models developed from the recent seismic studies have been interpreted to reflect an overall basaltic composition of the arc crust, which is considerably more mafic than the crustal structure of other island arcs. Velocity models suggest porous or fractured extrusive and intrusive igneous rocks and volcaniclastic sediment in the upper crust, a combination of mafic and felsic plutons or an ~6-km-thick presumed remnant of Kula plate crust in the middle crust, and a mixture of mafic and ultramafic cumulates at the base. The central and western Aleutian Arc is structurally segmented into at least five blocks that have undergone clockwise rotation accompanied by arc-parallel extension (Geist et al., 1988). Numerous submarine canyons have been created as a result of block rotation. Adak Canyon, located at 177°W immediately southwest of Adak Island (Fig. 1), cuts ~3500 m into the face of the Andreanof crustal block, thus providing excellent in situ exposures of deep levels of arc crust. Murray Canyon, located to the southwest of Kiska Island, is the deepest Aleutian submarine canyon (~4200 m) (Fig. 1). We collected 37 volcanic, plutonic, volcaniclastic, and sedimentary samples from two ~1700-m-high traverses (dives 098 and 099) up the eastern wall of Adak Canyon using the remotely operated vehicle (ROV) JASON II (Fig. 1). Samples were collected during a 48 h campaign from the R/V *Roger Revelle* in 2004. In 2005, nine samples were collected from two dredges of Murray Canyon while aboard the R/V *Thomas G. Thompson.*

TABLE 1. SUMMARY OF $^{40}Ar/^{39}Ar$ INCREMENTAL HEATING EXPERIMENTS

Sample	Depth (m) or island	Material	# of expts.	^{39}Ar %	MSWD	$^{40}Ar/^{39}Ar_i$ ±2σ	Isochron age (Ma) ±2σ
Terrestrial volcanic and plutonic rocks							
AD 03 04	Adak	groundmass	1	100.0	0.16	296.7 ± 2.8	7.00 ± 0.24
		plagioclase	1	82.8	0.21	292.2 ± 15.0	7.90 ± 3.17
KAG7-32	Kagalaska	biotite	1	100.0	0.33	296.9 ± 6.3	14.14 ± 0.12
KAG7-50	Kagalaska	biotite	1	100.0	0.12	299.6 ± 13.1	14.24 ± 0.71
		hornblende	1	92.8	0.21	294.1 ± 24.7	14.66 ± 1.67
AM33	Amchitka	plagioclase	1	100.0	0.03	297.8 ± 6.2	15.36 ± 1.22
		hornblende	1	100.0	0.21	299.6 ± 27.8	15.30 ± 1.40
MR80-12	Adak	groundmass	1	100.0	0.45	295.9 ± 5.9	25.66 ± 0.69
AT80-87	Attu	plagioclase	2	88.9	0.19	296.3 ± 1.5	29.38 ± 1.48
SED-AB	Sedanka	hornblende	2	100.0	0.17	297.4 ± 2.7	29.68 ± 0.91
SED36-D	Sedanka	biotite	1	94.1	0.98	294.4 ± 10.8	30.32 ± 0.24
HB76-125	Adak	biotite	2	98.4	0.11	293.3 ± 5.9	34.50 ± 0.27
		hornblende	2	100.0	0.01	296.2 ± 3.2	34.75 ± 0.95
AT80-22	Attu	plagioclase	1	99.3	0.29	297.2 ± 2.2	34.69 ± 0.99
		hornblende	2	100.0	0.29	291.9 ± 10.5	35.37 ± 2.04
BW8-R39B	Adak	groundmass	1	100.0	1.02	302.9 ± 9.3	37.26 ± 0.74
MV80-24	Adak	plagioclase	2	91.7	0.50	299.5 ± 17.6	37.55 ± 1.00
FB8-19	Adak	biotite	1	100.0	0.92	293.2 ± 3.6	37.89 ± 0.23
Adak Canyon Dive 099							
J99S20S24	1281	groundmass	2	100.0	0.21	296.1 ± 9.7	32.90 ± 1.22
J99S13S19	1650	plagioclase	1	100.0	0.39	297.1 ± 2.2	32.89 ± 0.55
J99S12S18	1691	groundmass	1	99.2	0.66	295.1 ± 9.5	33.79 ± 0.29
J99S6S9	2021	groundmass	3	100.0	0.70	295.2 ± 11.3	36.12 ± 0.71
J99S4S7	2049	groundmass	1	100.0	0.09	295.3 ± 10.1	36.14 ± 0.48
J99S3S6	2119	plagioclase	2	100.0	0.10	296.0 ± 22.0	36.00 ± 1.50
J99S3S5	2119	groundmass	1	100.0	0.21	295.7 ± 5.9	35.87 ± 0.61
J99S2S4	2125	groundmass	2	100.0	0.01	301.0 ± 10.3	36.52 ± 0.91
J99S1S2	2203	groundmass	2	100.0	0.27	294.1 ± 7.1	36.65 ± 1.18
J99S1S1	2203	groundmass	1	100.0	0.46	297.6 ± 12.3	37.84 ± 0.86
Adak Canyon Dive 098							
J98S7S8	2035	groundmass	2	86.6	0.22	293.0 ± 2.4	28.69 ± 0.19
J98S6S7	2070	groundmass	2	100.0	0.42	297.1 ± 5.1	34.25 ± 0.51
J98S3S3	2715	groundmass	1	100.0	0.20	294.1 ± 4.6	30.38 ± 1.15
Murray Canyon Dredge							
TN182-30-001	2535	plagioclase	1	100.0	0.28	294.8 ± 1.9	22.06 ± 0.78
		biotite	1	100.0	0.22	294.7 ± 6.7	21.82 ± 1.28
TN182-30-003	3018	groundmass	3	69.2	1.20	292.3 ± 2.6	46.31 ± 0.91

$^{40}Ar/^{39}Ar$ RESULTS

At the University of Wisconsin Rare Gas Geochronology Laboratory, 0.3–4.0 mg of purified groundmass and mineral separates were incrementally heated using a defocused CO_2 laser (see the GSA Data Respository[1] for methods and data). Experiments yielded largely concordant age spectra with 5–11 steps comprising >65% of the gas released. Plateau steps were regressed to calculate isochrons and indicate that effects of low-temperature alteration or excess argon are not significant in any sample (Table 1).

$^{40}Ar/^{39}Ar$ incremental heating experiments were conducted to (1) identify the time interval over which lavas and intrusives recovered from Adak and Murray canyons were emplaced, (2) obtain age determinations for previously undated plutons, and (3) determine the ages of late Eocene to Miocene plutons exposed throughout the arc whose ages were originally determined using the conventional K-Ar method. Fifty experiments yielded well-defined age plateaux and isochrons indicating ages between 7 and 46 Ma. With the exception of unpublished and inconclusive data from one sample (Rubenstone, 1984), these are the first pre-Pleistocene $^{40}Ar/^{39}Ar$ ages available for the Aleutian Island Arc.

The Finger Bay volcanics of Adak Island, which underlie the strata of the fossiliferous Andrew Lake Formation, have been widely regarded as the oldest exposed rocks in the Aleutian Island Arc (Scholl et al., 1987) (Fig. 1). An unpublished $^{40}Ar/^{39}Ar$ incremental heating experiment on plagioclase separated from a basalt within this unit gave a strongly discordant, saddle-shaped spectrum with a pseudoplateau near 35 Ma (Rubenstone, 1984). The final steps of the experiment ramped up to ages that approach 50–55 Ma, which has been interpreted to be the true age of the Finger Bay volcanics. However, new experiments on two basaltic lavas yielded concordant age spectra and $^{40}Ar/^{39}Ar$ isochron ages of 37.6 ± 1.0 and 37.3 ± 0.7 Ma, respectively (Table 1).

Biotite from the Finger Bay pluton yielded a mean $^{40}Ar/^{39}Ar$ isochron age of 37.9 ± 0.2 Ma that is indistinguishable from the ages of the Finger Bay volcanics. This is the first radioisotopic age available for the Finger Bay pluton. Replicate experiments on biotite and hornblende separates from the Hidden Bay pluton on Adak Island yielded a younger isochron age of 34.5 ± 0.3 Ma that is similar to published K-Ar dates ranging from 31.5 to 35.9 Ma (Citron et al., 1980).

The Kagalaska pluton intrudes the Finger Bay volcanics on the northeastern edge of Adak Island and underlies the northern half of Kagalaska Island to the east (Fig. 1). Biotite from this granodiorite gave a $^{40}Ar/^{39}Ar$ isochron age of 14.1 ± 0.1 Ma. Experiments on biotite and amphibole from another sample gave an indistinguishable age of 14.3 ± 0.6 Ma. $^{40}Ar/^{39}Ar$ ages from these two samples are slightly older than published K-Ar ages, which range from 12.4 to 14.1 Ma (Citron et al., 1980; Marlow et al., 1973).

In addition to plutonic exposures on Adak and Kagalaska Islands, calc-alkaline plutons are exposed on several other islands including Attu, Amchitka, Agattu, Unalaska, and Sedanka (Fig. 1). Isochron ages of mineral separates from plutons on Attu Island (29.4–35.4 Ma) and Amchitka Island (15.4 Ma) fall within the range of published K-Ar ages (Carr et al., 1970; DeLong and McDowell, 1975; Vallier et al., 1994), but are more precise. Hornblende

[1]GSA Data Repository item 2006135, Table DR1, complete $^{40}Ar/^{39}Ar$ incremental heating results; and Table DR2, detailed descriptions of $^{40}Ar/^{39}Ar$ and major and trace element methods, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 2. ESTIMATES OF MAGMA PRODUCTION RATES OVER THE LAST 46 m.y.

Model parameters	Volume (km^3/km)	Magma production rate (km^3/km/my)
Existing crustal material fully compacted:	5500	
6-km-thick remnant of the Kula plate in the mid-crust:	1400	
Material lost via subduction erosion @ 30 km^3/km/m.y.	1380	
Material lost via glacial and subaerial erosion	1500	
Model A: Existing arc material minus the Kula plate in mid-crust	4100	89
Model A + volume lost via subduction, glacial, and subaerial erosion:	6980	152
Model B: Existing arc material (no Kula plate in mid-crust):	5500	120
Model B + volume lost via subduction, glacial, and subaerial erosion:	8380	182

and biotite from the previously undated Beaver Inlet pluton on Sedanka Island gave indistinguishable $^{40}Ar/^{39}Ar$ isochron ages of 29.7 ± 0.9 and 30.3 ± 0.2 Ma.

Groundmass and plagioclase in 13 volcanic and plutonic samples from Adak Canyon yielded ages between 28.7 and 37.8 Ma. Ten of the $^{40}Ar/^{39}Ar$ isochron ages were obtained from samples collected along a single transect up the steep eastern wall of the canyon (Fig. 1, dive 099). All of the $^{40}Ar/^{39}Ar$ ages are in agreement with stratigraphic level (i.e., water depth) (Table 1). The oldest $^{40}Ar/^{39}Ar$ age from Adak Canyon of 37.8 ± 0.9 Ma comes from an andesite sampled at 2203 mbsl, which has a major-element composition and trace-element pattern similar to the Finger Bay volcanics, and therefore likely represents the offshore equivalent of the exposures on Adak Island (Kay et al., 1983). Three incremental heating experiments on groundmass from a metavolcanic rock dredged from Murray Canyon yielded a $^{40}Ar/^{39}Ar$ isochron age of 46.3 ± 0.9 Ma, which is the oldest age of any material sampled from the Aleutian Arc (Table 1).

AGE OF THE ALEUTIAN ISLAND ARC

Prior to this study, it was widely assumed that Aleutian Arc volcanism began ca. 55 Ma. Initiation, growth, and decline of Eocene magmatism in the arc were linked to a series of plate-tectonic events in the northern Pacific region described below. Subduction accretion and arc magmatism ended along the Alaskan-Siberian continental margin ca. 55 Ma (Scholl et al., 1986), which was coincident with a southward shift in the convergence zone of the Kula and North American plates to the location of the modern Aleutian Arc. A fragment of the Kula plate was trapped north of the growing arc, thereby becoming the basement of the Bering Sea basin. A sector of this plate may have been accreted to the Aleutian Ridge. For the next 8 m.y., the Kula plate continued to move northward rapidly (~10–20 cm/yr), underthrusting the Aleutian Ridge (Scholl et al., 1987). At 47 Ma, the motion of the Pacific plate relative to the Hawaiian hot spot changed to its present west-northwest direction (Duncan and Keller, 2004). At this time, the trend of westward-increasing oblique subduction in the Aleutians was established. However, our new $^{40}Ar/^{39}Ar$ age determinations coupled with existing K-Ar ages suggest that Aleutian Arc volcanism began during the middle Eocene, at ca. 46 Ma, not at 55 Ma as previously thought. Interestingly, there is little evidence for volcanism in any of the western Pacific island arcs between 55 and 49 Ma. Aleutian Arc magmatism likely began after the major change in the Pacific plate motion at 47 Ma. The 38 Ma Finger Bay pluton and volcanics were probably emplaced during an intense period of late Eocene arc growth (Kay et al., 1990). Because the focus of arc magmatism has been migrating northward over the last 46 m.y., additional older crust (older than 40 Ma) may be located to the south in the Aleutian forearc. Alternatively, some of the oldest Aleutian Arc material may be found below the sedimentary sequences on the Komandorsky Islands in the far western Aleutians (Rostovtseva and Shapiro, 1998).

After late Eocene to early Oligocene magmatism waned at ca. 30 Ma, arc-wide plutonism and volcanism did not occur again until 16–11 Ma, which was followed by a subsequent rejuvenation from the middle Pliocene to the present. Causes of the episodic magmatic activity have been highly debated. One explanation is that pulses of magmatism were associated with periods of accelerated convergence of the Pacific plate (Citron et al., 1980). However, these speculative ideas do not seem to be supported by newer tectonic models (Atwater and Stock, 1998).

DISCUSSION

Our $^{40}Ar/^{39}Ar$ age determinations can be combined with volumetric estimates of the Aleutian Arc crust based on recently gathered seismic data to infer magma production rates over the lifetime of the arc. The existing volume of arc material in the central Aleutians is ~5500 km^3/km (Holbrook et al., 1999). This volumetric estimate includes volcanic and plutonic material that comprises the arc massif, and a 25% reduction in the volume of the upper crust to account for porosity (Table 2; Fig. 2), but it does not include the volcaniclastic deposits in Middle and Upper Series sedimentary basins on the flanks of the arc. If we subtract the ~6-km-thick remnant of the Kula crust embedded within the modern Aleutian crust, the volume reduces to 4100 km^3/km. Using 46 Ma as our preferred age of arc formation yields a magma production rate of 89 km^3/km/m.y. (Table 2, model A). This is a minimum estimate of the magma production rate for the arc, yet it is three times greater than accepted Aleutian magma production rates (Crisp, 1984; Reymer and Schubert, 1984), and 10%–25% higher than recent estimates (Holbrook et al., 1999; Lizarralde et al., 2002). Alternatively, if the ~6-km-thick mid-crustal layer is interpreted to represent a mixture of mafic and felsic plutons, and therefore is not subtracted from the existing volume, the magma production rate becomes 120 km^3/km/m.y. (Table 2, model B).

In order to obtain a more accurate assessment of the long-term magmatic productivity, we must take into account the volume of material that has been eroded away from the arc over the last 46 m.y. For example, forearc subduction erosion, which has been proposed at several Pacific rim subduction zones including the Aleutians (e.g., von Huene and Scholl, 1991), has likely removed a mass of the arc massif and submerged forearc and transferred it to the down-going oceanic plate. Using a conservative long-term erosion rate of 30

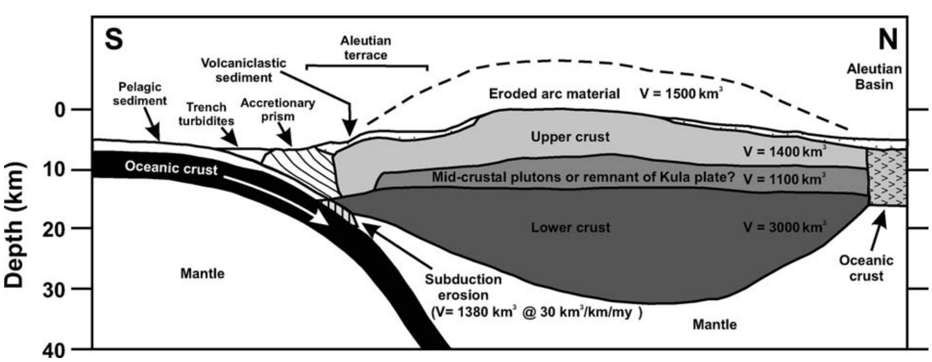

Figure 2. Cross section of central Aleutian Island Arc showing various components of the arc. Composition and volume of each layer are based on the P-wave velocity models of Holbrook et al. (1999) and Lizarralde et al. (2002). Erosional estimates are described in the text.

km^3/km/m.y. (von Huene and Scholl, 1991), ~1380 km^3/km has been removed and recycled to the mantle over the past ~46 m.y. A significant volume of the top of the Aleutian Arc has also been eroded via glacial and subaerial processes. $\delta^{18}O$ data and metamorphic mineral assemblages from the Finger Bay pluton suggest that at the time of metamorphism, ca. 34 Ma, the pluton interacted with hot meteoric water at temperatures between 325 and 400 °C and pressures around 2–3 kbar (Kay, 1983). Therefore, at least 6–9 km of subaerial arc crust, which corresponds to 1200–1800 km^3/km, has been removed over the past 34 m.y. If we take our best approximation for the current volume of arc material plus the amount lost to subduction and glacial erosion, the calculated average magma production rate over the past 46 m.y. is 182 km^3/km/m.y. (Table 2; Fig. 2). Assuming our volumetric estimates of existing and eroded crustal material are correct, the magma production rate for the Aleutian Island Arc is three to seven times higher than all existing estimates, and it exceeds that of the Sierra Nevada batholith (Ducea, 2001).

It has been proposed on the basis of recent marine and gravity data that the Izu-Bonin, Mariana, and Tonga Island Arcs grew rapidly (~60–180 km^3/km/m.y.) due to enhanced volcanic activity during the late Eocene to early Oligocene (Arculus, 2004; Dimalanta et al., 2002; Cosca et al., 1998). Interestingly, periods of intense middle Miocene and Pliocene-Holocene volcanism along the western Pacific island arcs also coincide with the pulses of magmatism in the Aleutians (Lee et al., 1995; Taylor, 1992). Determining whether extraordinarily high rates of arc magma production in the Eocene, Miocene, and Pliocene reflect increased plate velocities and subduction fluxes into the mantle, availability of exceptionally fertile mantle below these arcs, or other factors, is critical to understanding the past and present geodynamics of the entire Pacific region. Additional submarine sampling and geochronology is needed to further document the early growth histories of island arcs. Likewise, more seismic and gravity profiles will better constrain the crustal structure and depth of the Moho in island arcs, which will facilitate more accurate estimates of magma productivity.

ACKNOWLEDGMENTS

We thank Chris Wyatt for assistance with bathymetric data and figures, the captains and crews of the R/V *Roger Revelle,* R/V *Thomas G. Thompson,* and JASON II for support during sampling campaigns. Richard Arculus, Mihai Ducea, and an anonymous reviewer provided helpful reviews. Work was supported by NOAA's National Undersea Research Program in Fairbanks, Alaska, and National Science Foundation grants EAR-0114055, EAR-0337667 (Singer), and OCE-0242585 (Yogodzinski).

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Manuscript received 14 November 2005
Revised manuscript received 20 March 2006
Manuscript accepted 20 March 2006

Printed in USA

Geology

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Geology 2006;34;661-664
doi: 10.1130/G22433.1

Notes