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Earth and Planetary Science Letters 202 (2002) 105–115

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New rates of western Pacific island arc magmatism from seismic and gravity data

C. Dimalanta [a,b,*], A. Taira [a], G.P. Yumul Jr. [b], H. Tokuyama [a], K. Mochizuki [c]

[a] *Ocean Research Institute, University of Tokyo, 1-15-1 Minami-dai, Nakano-ku, Tokyo 164-8639, Japan*
[b] *Rushurgent Working Group, National Institute of Geological Sciences, University of the Philippines, Diliman, Quezon City 1101, Philippines*
[c] *Earthquake Research Institute, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*

Received 29 January 2002; received in revised form 23 May 2002; accepted 10 June 2002

Abstract

Numerous studies have been conducted in order to look into the evolution of the continental crust. Some suggest that one of the mechanisms which contribute to the growth of continental crust is arc magmatism. It is in this context that Reymer and Schubert (Tectonics 3 (1984) 63) estimated arc magmatic addition rates to the continental crust. Their results suggest that island arc magmatism was producing material at an average rate of 20–40 km^3/km/Myr (volume per unit width along the strike direction of arc). The present work utilizes the most recent worldwide marine gravity data, together with improved seismic data from some oceanic island arcs in the western Pacific region. The combined gravity and seismic data allow a more accurate image of the subsurface configuration beneath the oceanic island arcs and yield better estimates of crustal volumes created during arc magmatic processes. Oceanic island arcs investigated in this study show a crustal thickness ranging from 20 to 30 km. Utilizing this thickness, the relevant crustal volume for each island arc is then estimated. Dividing the crustal volume by the age of initiation of subduction of the arc gives arc magmatic addition rates of 30–95 km^3/km/Myr. The estimates presented here are nearly twice as high as the previous estimates of arc magmatic addition rates.

Keywords: continental crust; magmatism; island arcs; gravity anomalies; velocity; models

1. Introduction

Arc magmatism has long been recognized to be one of the mechanisms whereby new crustal material is created along subduction zones. Attempts to quantify the volume of crustal material generated in this manner have been made previously. However, the results of recent work in some island arcs (e.g. Izu-Bonin, Aleutians) give arc magmatic addition rates which are higher compared to previous estimates. This paper, therefore, re-evaluates these earlier estimates of arc magmatic addition to come up with values which might be more representative of arc magmatism in the

* Corresponding author. Tel.: +63-2-436-8840; Fax: +63-2-436-8840; +63-2-929-6047.
E-mail address: rwg@i-next.net (C. Dimalanta).

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PII: S0012-821X(02)00761-6

western Pacific region. The availability of recent geophysical data for some of these island arcs makes a re-evaluation possible.

It was Reymer and Schubert [1] who first came up with addition rates to the continental crust and estimated an arc magmatic addition rate of 20–40 km^3/km/Myr. This estimate, which was determined using seismically derived crustal profiles and occasionally supplemented by gravity data, has been challenged by some investigators. In the study made by Taira et al. [2] using seismic data from the Izu-Bonin island arc, the growth rate of the northern Izu-Bonin arc is estimated to be 80 km^3/km/Myr. For that matter, Holbrook et al. [3] obtained a magma production rate of 82 km^3/km/Myr utilizing new seismic data from the Aleutian island arc.

In view of these recent results, questions have been raised with regard to the previous estimates, which are significantly lower compared to these new values. It has also been pointed out that the earlier authors overestimated the age of initiation of subduction of some island arcs (e.g. 75 Ma for the Aleutians, 60 Ma for Tonga, 60 Ma for the New Hebrides), which led to their low crustal addition rate values. Overestimation of the age of initiation of subduction resulted from the fact that the oldest volcanic rocks, which have later been found to be non-subduction related, have previously been included in the computation of the crustal thickness. Compared with mature continental or island arcs, oceanic island arcs in the western and southern Pacific show simpler and better-constrained tectonic and magmatic evolution [4–6]. Furthermore, new seismic and gravity data provide better constraints in configuring the structure of the subsurface beneath these oceanic island arcs, which allows more appropriate estimates of crustal thickness and relevant crustal volumes.

This study is an attempt to re-evaluate the arc magmatic addition rates given by Reymer and Schubert [1] by taking advantage of the availability of recent geophysical and other relevant data. It will, hence, be possible to come up with better-constrained estimates of western Pacific arc magmatic addition rates. The results obtained from this study will hopefully foster an understanding of the role of arc systems in the evolution of continental crust.

2. Methodology

The methodology utilized by Reymer and Schubert [1] to estimate arc magmatic addition rates for non-accreted oceanic island arcs is adopted in this study. Gravity and seismic data are used to determine the thickness of the crust beneath the island arcs. The area corresponding to a 6-km thick oceanic crustal basement is subtracted from the measured thickness. The normal oceanic crust, which consists of crustal material generated along spreading ridges, has a mean thickness of 6–7 km [7–8]. It is therefore necessary to remove this amount of material, which was produced by processes other than arc magmatism. The remaining amount is believed to correspond to crustal material created by arc magmatism. Dividing this volume of material by the age of the arc, i.e. age corresponding to the onset of subduction, provides the corresponding arc magmatic addition rate.

Free-air gravity anomaly profiles for the different oceanic island arcs (Fig. 1) were obtained from the worldwide marine gravity data of Sandwell and Smith [9]. Available seismic velocity data were used to constrain the modeling of gravity data by defining the configuration and thickness of the oceanic island arcs and depths to Moho [10].

Two-dimensional modeling of the free-air gravity anomalies was done in order to simulate the configuration and thickness of the crust. Based on the available seismic velocity data, density models consisting of polygons to simulate the forearc, main arc, back-arc, subducting slab and mantle were constructed [11]. During gravity modeling, the configurations of the polygons were kept fixed while the density contrasts were constantly changed until a good fit between the observed and calculated gravity values was achieved (Fig. 2). The densities obtained during modeling are simply nominal values and do not correspond to real densities.

Modeling the free-air gravity anomalies of the

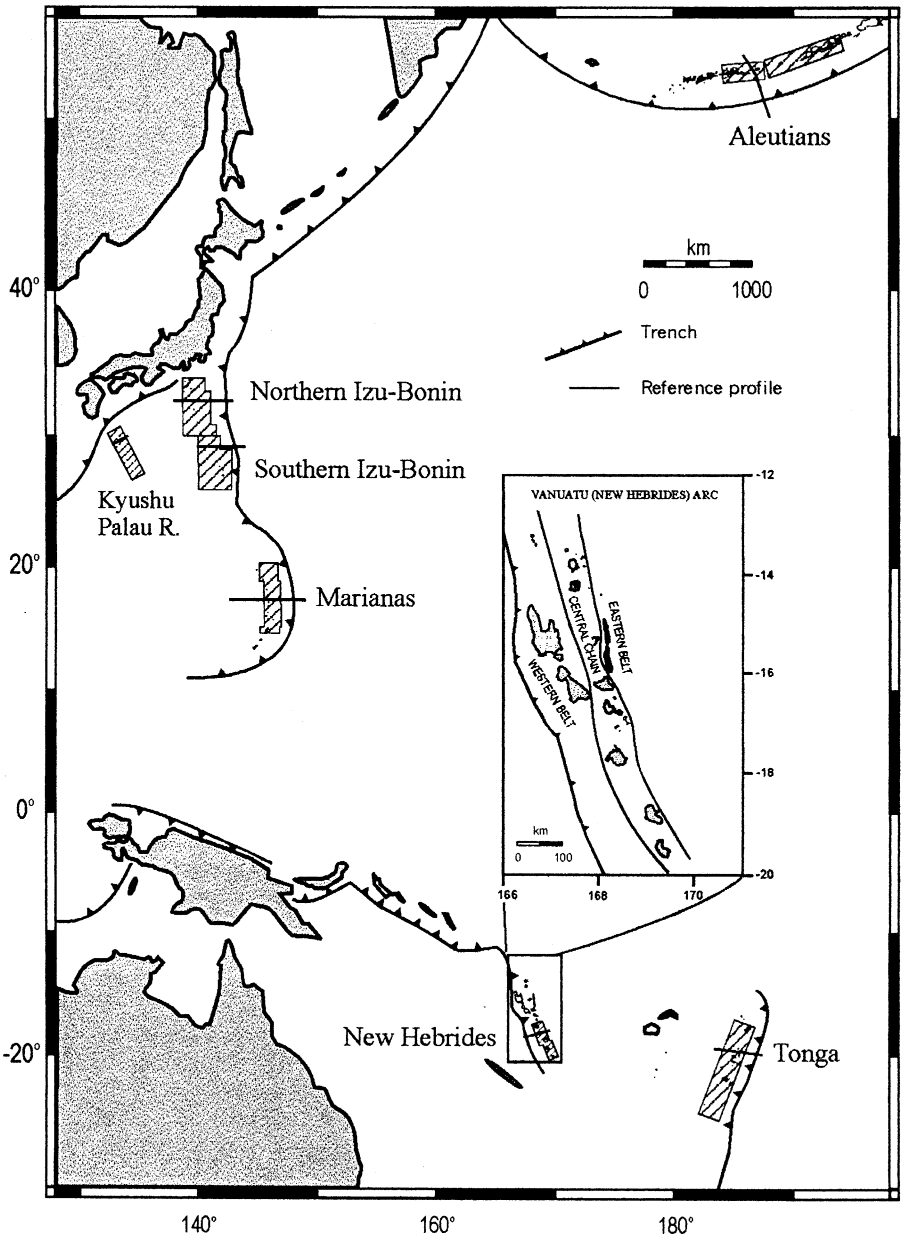


Fig. 1. Map showing the arc-trench systems of the western Pacific region which were investigated in this study: (1) Aleutians, (2) Izu-Bonin, (3) Marianas, (4) New Hebrides, and (5) Tonga. Inset shows the New Hebrides island arc which is divided into the Western Belt, the Central Chain and the Eastern Belt. Lines indicate the seismic velocity profiles which were used as reference to constrain the modeling of gravity data. Diagonally lined boxes represent areas of the island arc from which volumes were estimated.

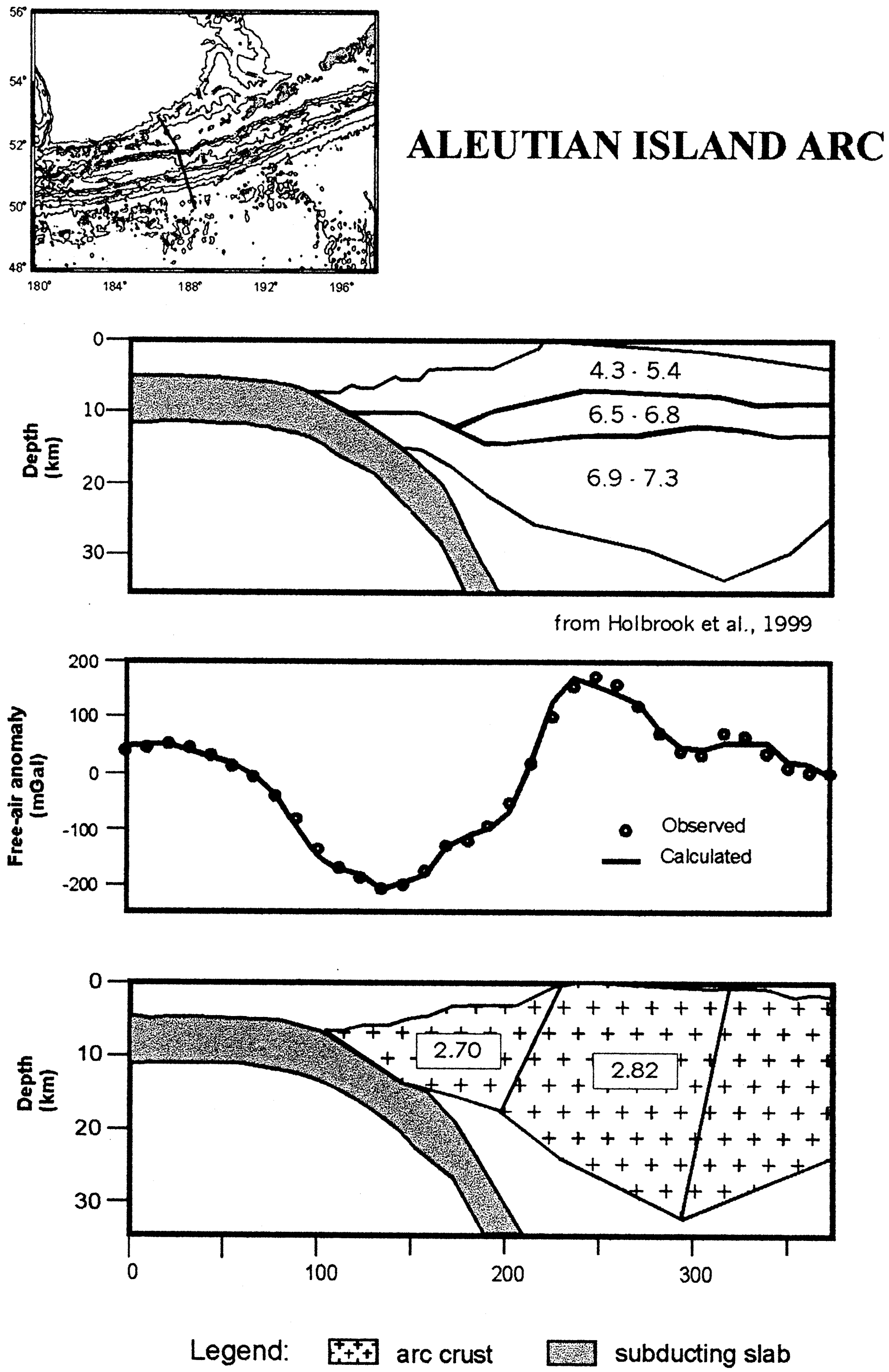


Fig. 2. Seismic velocity model (from Holbrook et al. [3]), calculated and observed gravity values and the density model used during the gravity modeling of one of the profiles for the Aleutian island arc.

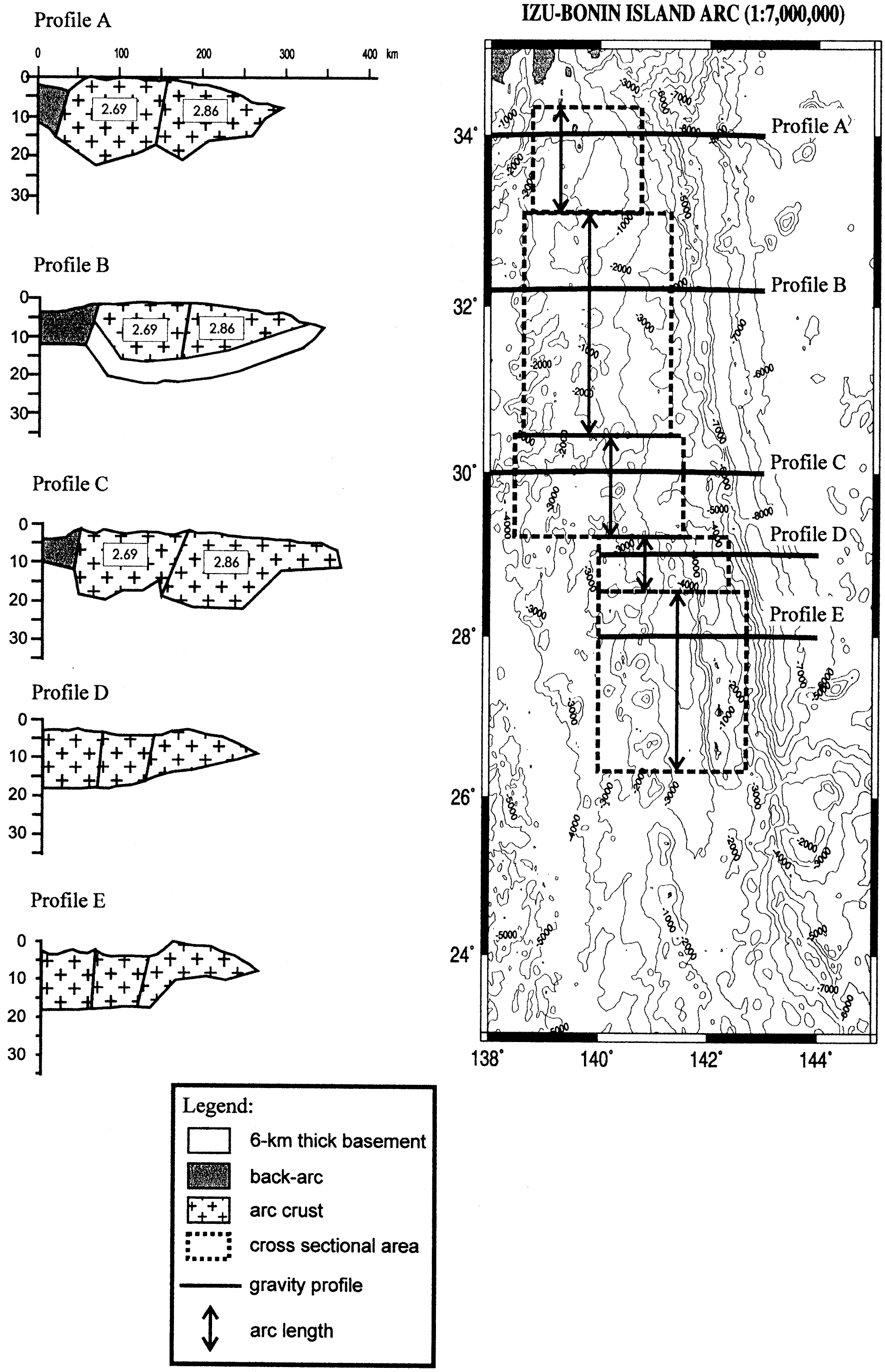


Fig. 3. Profiles in the northern and southern Izu-Bonin island arc that were utilized in the gravity modeling to determine crustal thickness. The relevant crustal volumes were estimated from cross-sectional areas along certain lengths of the arc.

Table 1
Estimates of crustal volumes for certain lengths of the arc

Arc	Volume (km^3)	Arc length (km)	Vol./arc length (km^3/km)
Izu-Bonin (northern)			
Profile A	390 000	134	2 910
Profile B	840 000	285	2 947
Profile C	158 000	58	2 724
Kyushu-Palau Ridge			
Profile A	45 000	141	319
Profile B	130 000	335	388
Izu-Bonin (southern)			
Profile A	205 000	140	1 464
Profile B	430 000	290	1 483
Marianas			
Profile A	320 000	163	1 963
Profile B	970 000	431	2 250
Profile C	165 000	81	2 037
Aleutians			
Profile A	710 000	219	3 242
Profile B	1 380 000	414	333
Tonga			
Profile A	590 000	393	501
Profile B	550 000	367	1 499
New Hebrides			
Profile A	485 000	205	2 366
Profile B	490 000	225	2 178

Summary of the results of this study showing the volume of crustal material estimated for each profile along certain lengths of each arc system.

island arcs in terms of the densities of the forearc, main arc and back-arc allows us to use these average densities in order to create profiles along other portions of the arc from which crustal thickness can be estimated. The resulting density values for the profile constrained by seismic data (B) are used to model gravity data in other profiles (A and C) in order to obtain the crustal thickness along these new profiles (A and C). This procedure is repeated for several profiles constructed for each arc system (Fig. 3), and this subsequently allowed an estimate of the relevant crustal volumes along a certain arc length to be made (Table 1).

3. New estimates of arc magmatic addition

Suyehiro et al. [12] produced an image of the northern portion of the Izu-Bonin island arc from ocean bottom seismometer (OBS) data. The seismic velocity model reveals an arc crust composed of an upper crust, middle crust and lower crust. This model was used to constrain the modeling of free-air gravity anomalies. The combined seismic and gravity data show a maximum crustal thickness of around 22 km. Several profiles which were constructed show that the arc has an almost constant thickness of ∼22 km along the entire length of the northern portion of the Izu-Bonin island arc.

The crustal structure of the southern part of the Izu-Bonin island arc is different from the northern portion in that no middle crust can be observed in the southern Izu-Bonin island arc. The seismic velocity model of Hino et al. [13] is used to construct a density model. Results of the gravity modeling show that the southern Izu-Bonin island arc is thinner compared to the northern part and that it has a crustal thickness of around 16 km. Modeling of the gravity profiles from the Maria-

Table 2
New estimates of arc magmatic addition rates

Arc	Crustal thickness (km)	Volume (km^3/km)	Age of initiation of subduction (Myr)	References	ARC magmatic addition rate ($km^3/km/Myr$)
Izu-Bonin	22	2720–2950	49	[17]	63–68 (northern+KPR)
	16	1460–1480			30 (southern)
Marianas	22	1960–2250	45	[17]	44–50
Aleutians	30	3240–3330	55	[25]	59–61
Tonga	20	1500	27	[4]	56
New Hebrides	26	2180–2365	25	[26]	87–95

Summary of the crustal thickness, crustal volume and arc magmatic addition rates for the island arcs that were investigated in this study. The table also shows the age of initiation of subduction (with the corresponding references) that was used in calculating arc magmatic addition rates.

nas island arc reveals a crustal thickness of about 22 km [14].

Recent seismic reflection and refraction data from the Aleutian island arc were used to produce a new image of its crustal structure [3]. Among the main features of the new velocity structure is the presence of a mid-crustal layer with velocities higher than those indicated for the middle crustal layer of the northern Izu-Bonin island arc. The velocity and density models show that the arc has a crustal thickness of approximately 30 km.

Seismic and gravity data from the New Hebrides (Vanuatu) island arc show that the island arc has a thickness of around 26 km. The seismic velocity data do not suggest the presence of a middle crust layer [15], and a crustal thickness of roughly 20 km is suggested by seismic data from the Tonga island arc [16].

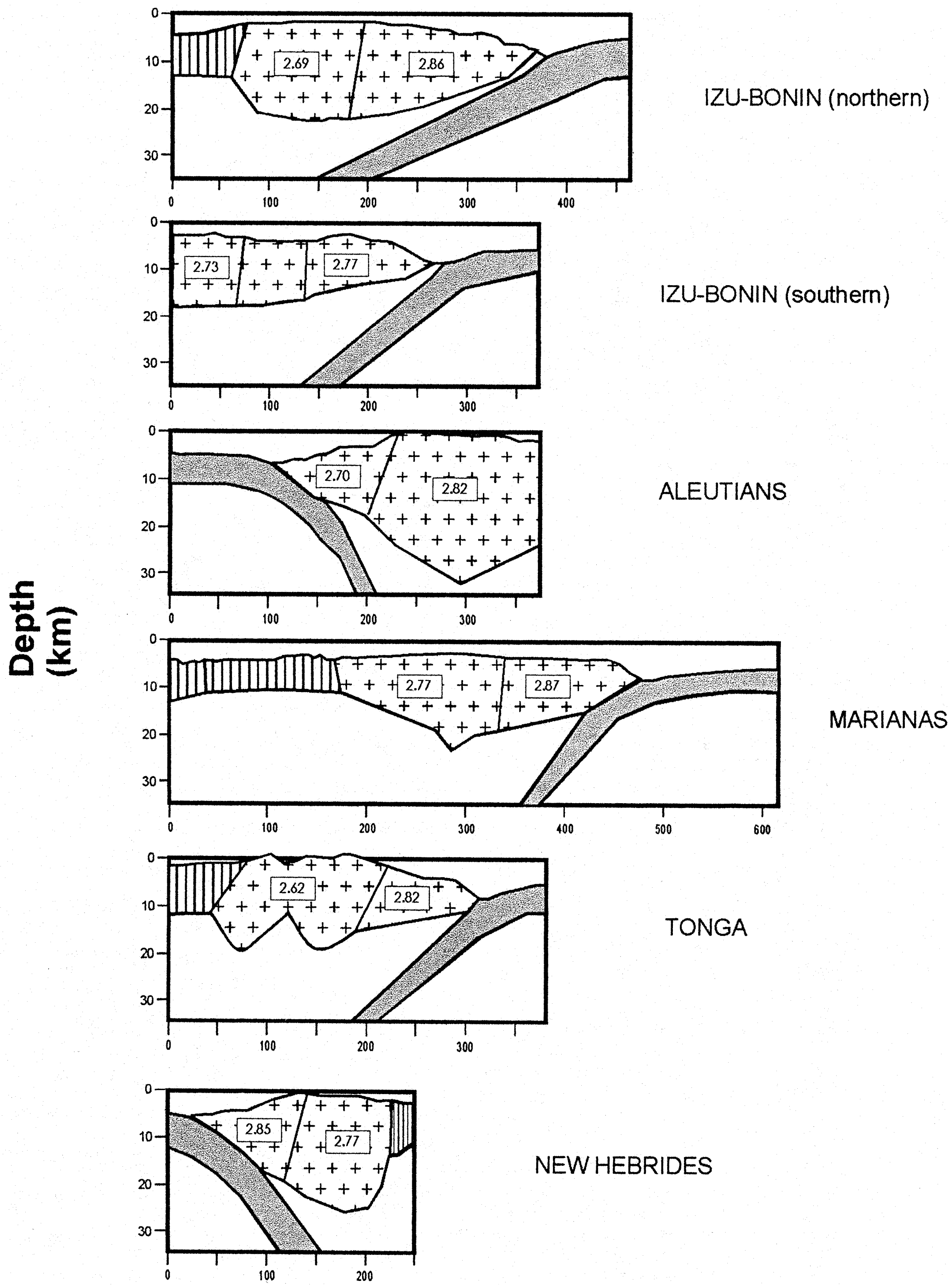
Table 3
Comparison of the volume, age and arc magmatic addition rates between Reymer and Schubert's study [1] and the present study

Arc	Volume (km^3/km)	Age (Myr)	Addition rate ($km^3/km/Myr$)
	Reymer and Schubert (1984)		
Izu-Bonin	1250	45	28
Marianas	1300–1750	45	29–39
Aleutians	1725–2500	75	23–33
Tonga	1400–1950	60	24–33
New Hebrides	1700	60	28
	This study		
Izu-Bonin	2720–2950	49	56–60
Marianas	1960–2250	45	44–50
Aleutians	3240–3330	55	59–61
Tonga	1500	27	56
New Hebrides	2180–2365	25	87–95

The combined seismic and gravity data reveal that the island arcs studied have crustal thicknesses ranging from as thin as ∼16 km (e.g. southern Izu-Bonin) to ∼30 km (e.g. Aleutians) (Fig. 4). Dividing the relevant crustal volumes by the age of initiation of subduction of the arcs yields new estimates of arc magmatic addition rates.

The present study shows that magmatic addition rates vary from 30 to 95 $km^3/km/Myr$ for some island arcs in the western Pacific region (Table 2). The small volume of crustal material estimated for the Tonga island arc can be attributed to size reduction as a result of the rifting undergone by the arc. Thus, the arc magmatic addition rate given for the Tonga island arc may be considered a minimum estimate since it does not incorporate the crustal material beneath the Lau Ridge. The same is true in the case of the Marianas island arc where only the crustal material beneath the volcanic arc and forearc are measured. The crustal material beneath the entire remnant arc (West Mariana Ridge) is not considered in the calculations. Crustal thickness estimates were not possible for some of the remnant arcs due to the absence of seismic data which can be used to constrain the modeling of gravity data.

The arc magmatic addition rates for the northern Izu-Bonin island arc are expected to become higher (i.e. range from 63 to 68 $km^3/km/Myr$) if the rates for its remnant arc, the northern Kyushu Palau Ridge, are added to these values.


IZU-BONIN (northern)
2.69
2.86
IZU-BONIN (southern)
2.73
2.77
ALEUTIANS
2.70
2.82
MARIANAS
2.77
2.87
TONGA
2.62
2.82
NEW HEBRIDES
2.85
2.77
Depth (km)
0
10
20
30
100
200
300
400
500
600

So why are these present estimates higher than the arc magmatic addition rates previously suggested by Reymer and Schubert [1]? For one, these authors overestimated the age of initiation of subduction of some island arcs utilized in their measurements (e.g. New Hebrides, Tonga, Aleutians). Recently available data, especially those from the DSDP and ODP results, were used to constrain the tectonic and magmatic evolution of the western and southern Pacific region.

The age of initiation of subduction which led to the development of the Izu-Bonin–Marianas island arc is well constrained by fossil and radiometric ages [17]. In the southwestern Pacific region, ODP results utilizing tephrochronological data and plate reconstructions based on hotspot tracks provide us the most recent age controls on the initiation of subduction of island arcs in this region (Table 3) [4–5].

Secondly, improved seismic data and the availability of worldwide marine gravity data give a better image of the crustal configuration of these island arcs. Hence, more accurate estimates of the relevant crustal volumes are obtained. The estimates obtained here may be deemed to be representative of arc magmatism in the western Pacific region.

4. Discussion

The western Pacific region is characterized by continuous subduction, arc magmatism and episodes of rifting which produced the oceanic island arcs, arcuate trenches and marginal basins that mark the region. Various investigations have been carried out in order to look into the crustal structure, and tectonic evolution of these trench-arc–back-arc basin systems. However, in spite of the different evolutionary histories which these island arcs have undergone, some similarities become apparent especially with regard to arc magmatism. Although the process of magma generation varies from place to place, the recent data on arc magmatic addition rates, including this study, indicate that arc magmatism is taking place at a relatively higher rate compared to the estimates made previously. For that matter, aside from the recognition that arc volcanism is episodic, one must never forget that arc volcanism is not active during back-arc basin opening. This places another complexity in the computation of crustal thickness of island arcs.

The range of values given in Table 2 might be representative of Cenozoic arc magmatic addition rates in the western Pacific region. These high arc magmatic addition rates are not only true for the western Pacific region but also for the Atlantic. New seismic data from the South Sandwich island arc gave an arc magmatic addition rate of ~ 60 $km^3/km/yr$ [18]. The results presented here show that arc magmatism is a significant mechanism which contributes to the growth of continental crust.

However, crustal growth has been defined as the net gain in volume or mass of continental crust. Hence, the addition to and subtraction of materials from the crust both need to be factored in any crustal growth computation [19].

Numerous studies have identified other mechanisms which lead to crustal addition and subtraction. Crustal addition processes consist of the magmatic additions through the formation of thick oceanic plateaus, intraplate volcanism, crustal underplating and ophiolite accretion [20–22]. On the other hand, subtraction processes include sediment subduction, subduction or tectonic erosion and delamination [23,24]. However, it has been difficult to arrive at estimates of subtraction processes. This is true in the case of tectonic erosion since some convergent margins are not characterized by well-developed accretionary prisms

←
Fig. 4. Summary of the variations in the crustal thickness of some island arcs as configured by the combined seismic and gravity data. The seismically derived crustal data that were used to constrain modeling of the gravity data are taken from: Suyehiro et al. [12] (northern Izu-Bonin), Hino et al. [13] (southern Izu-Bonin), Holbrook et al. [3] (Aleutians), La Traille and Hussong [14] (Marianas), Shor et al. [16] (Tonga), and Ibrahim et al. [15] (New Hebrides). The density values given are nominal values and do not represent real densities.

or have accretionary complexes which have already been eroded.

Therefore, even if it has been pointed out several times in this study that arc magmatism contributes significantly to the growth of continental crust, an understanding of the contributions from plume magmatism and other arc addition processes as well as the role of crustal recycling is necessary before a complete picture of crustal growth can be achieved.

As a matter of fact, numerous studies continue to be carried out in order to find answers to questions such as: How much 'new crust' is juvenile? What proportion of the crust created by processes such as arc magmatism is accreted to continental crust and how much of this is destroyed? What proportion of crust is recycled through sediment subduction, tectonic erosion and delamination? Are the present growth rates similar to growth rates in the past? Have various processes (e.g. crustal formation, accretion, rifting, etc.) been the same throughout geological history?

In the light of these uncertainties and the lack of definite answers to the above questions it is apparent that more investigations need to be carried out before we can come up with accurate crustal growth models and to enable us to fully understand the concept of continental growth. Nevertheless, the results obtained from the present work emphasize the significant contribution of arc magmatism to crustal growth within the upper crustal level.

5. Summary

Various uncertainties still remain when it comes to the question of continental crustal growth. It has long been established that one of the major mechanisms which contribute to the growth of continental crust is arc magmatism. Hence, this paper presents new estimates of arc magmatic addition rates in the western Pacific region.

Recent seismic data and marine gravity data are used in this study to determine the crustal thickness and structure of some island arcs in the western Pacific region. In spite of obvious differences among the different arc-trench systems, it is necessary to calibrate arc magmatic addition rates along some of these subduction zones.

These island arcs are shown to have a crustal thickness ranging from 15 to 30 km. Modeling of gravity data from several profiles constructed along the length of the arc provided estimates of the relevant crustal volumes. The results show that arc magmatic addition rates vary from 30 to 95 km^3/km/Myr. The majority of these values are higher than previous estimates of arc magmatic addition rates, suggesting that arc magmatism must have played an important role in continental crustal growth.

Acknowledgements

This paper is part of the doctoral thesis of C.B.D. at the Ocean Research Institute, the University of Tokyo under a scholarship grant from the Japanese Ministry of Education and Culture (Monbusho). Comments made by E.J. Marquez on the first draft of this paper are acknowledged. The assistance and advice offered by Y. Kido of JAMSTEC during the initial stage of this study are appreciated. This paper benefited from the comments given by D. Abbott, J. Milsom and M. Coffin on an earlier version. Constructive reviews by Prof. S.C. Lee and Prof. E. Honza are appreciated.***[AC]***

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