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Intra-oceanic subduction systems: introduction

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Abstract: Intra-oceanic arcs are the simplest type of subduction systems in that they occur where overridding plates of subduction zones consist of oceanic rocks, contrasting with arcs built on continental margins. They comprise some 40% of the subduction margins of the Earth. The better-known examples include the Izu–Bonin–Mariana arc, the Tonga–Kermadec arc, the Vanuatu arc, the Solomon arc, the New Britain arc, the western part of the Aleutian arc, the South Sandwich arc and the Lesser Antilles arc. They are thought to represent the first stage in the generation of continental crust from oceanic materials. They are generally more inaccessible than continental arcs, but, for a variety of reasons, provide insights into processes in subduction zones that are impossible or difficult to glean from the better-studied continental arcs. Intra-oceanic arcs typically have a simpler crustal structure than arcs built on continental crust, although there are significant differences between examples. Geochemically, magmas erupted in intra-oceanic arcs are not contaminated by ancient sialic crust, and their compositions more accurately record partial melting processes in the mantle wedge. They are also the sites of generation of intermediate–silicic middle crust and volcanic rocks, probably representing the earliest stage of generation of andesitic continental crust by partial melting of basaltic lower crust. They are the best locations in which to study mantle flow in the vicinity of subducting slabs using both geophysical and geochemical methods. They are the sites of significant hydrothermal activity and metallogenesis. The fact that their hydrothermal discharges typically occur shallower in the ocean than those from mid-ocean ridge vents means that they have the potential for greater environmental impact.

Volcanic arcs form above subduction zones, where oceanic plate is recycled back into the Earth's interior, and are the most visible manifestations of plate tectonics – the convection mechanism by which the Earth loses heat. The total length of margins where oceanic crust is being subducted (approximately the same as the total length of volcanic arcs) on Earth is about 43 500 km (von Huene & Scholl 1991). Most of this length of arc is situated on continental crust and is marked by spectacular, large and, often, entirely subaerial volcanoes, as typified by the Andes, Japan, the Cascades and Central America. Much research on subduction zones has concentrated on such continental arcs because of their accessibility, their clear association with metalliferous mineralization, and their manifest relationship to volcanic and seismic hazards.

Some 17 000 km, or nearly 40%, of the global length of volcanic arc is not situated on the continental margins, but is instead situated on oceanic crust. These intra-oceanic arcs are the subject of this book. Intra-oceanic arcs are significantly less well studied than continental arcs. The main reason for this is that they are typically mostly submerged below sea level, sometimes with only the tops of the largest volcanoes forming islands. They also occur in some of the most remote places on Earth and it has proved difficult to persuade funding agencies to provide time for research ships to transit to many of the key localities.

Nevertheless, intra-oceanic arcs provide vital scientific information on how subduction zones work that is very difficult, or impossible, to obtain by studying continental arcs. Because they are situated on thin, dominantly mafic crust, significant contamination of magmas by easily fusible sialic crust cannot normally occur (Wilson 1989). It is therefore significantly more straightforward to understand magma-generation processes in the mantle in intra-oceanic arcs. They are also thought to represent the first stage in the poorly understood process by which basaltic, oceanic crust is modified to form continental crust, at least in post-Archaean times (Rudnick 1995; Taylor & McLennan 1995). Intra-oceanic arcs may also have a particular environmental importance in that they are the main locations where there is significant hydrothermal discharge in shallow oceans (de Ronde *et al.* 2001).

What exactly are intra-oceanic arcs? They are magmatic arcs within ocean basins, built on crust of oceanic derivation. Such crust might be ocean crust formed at either mid-ocean ridges or back-arc spreading centres, crust forming part of an

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oceanic plateau, crust formed by accretion of oceanic sediments in a subduction zone fore-arc or earlier intra-oceanic arc material. The variety of rocks that can form the basement to intra-oceanic arcs hints at the complexity that many of them show in detail. In fact, of the currently active intra-oceanic arcs only the central and western Aleutian arc overlies crust formed at a mid-ocean ridge. Perhaps it is better to define intra-oceanic arcs by what they are not – they do not overlie basement consisting of continental crust. Intra-oceanic arcs – as we define them – are equivalent to ensimatic arcs (Saunders & Tarney 1984) and are approximately equivalent to the 'oceanic island arcs' of Wilson (1989).

Over the last decade, there has been an enormous increase in knowledge of intra-oceanic arcs. New maps have become available, through the availability of Geosat and ERS 1 satellite altimetry data (Livermore *et al.* 1994; Sandwell & Smith 1997), and through greatly increased coverage by swath bathymetry mapping (Martinez *et al.* 1995; Deplus *et al.* 2001). The seismic velocity structure of arc crust has been determined in unprecedented detail using ray-tracing inversion in controlled-source seismology (Suyehiro *et al.* 1996; Holbrook *et al.* 1999). The seismic velocity structure of the upper mantle in the vicinity of arcs has been revealed using tomographic inversion in earthquake seismology (Zhao *et al.* 1992, 1997). Relocation of earthquake hypocentres using improved methods has provided better definition of Wadati–Benioff zones, showing the position of subducted slabs in the mantle (Engdahl *et al.* 1998). At the same time improvement in inductively coupled plasma-mass spectronomy (ICP-MS) techniques for high-precision determination of trace element abundances (e.g. Pearce *et al.* 1995; Eggins *et al.* 1997), and advances in radiogenic isotope analysis, have had a huge impact on the understanding of chemical fluxes in the mantle wedge and time constraints on magma ascent (Morris *et al.* 1990; Elliott *et al.* 1997; Hawkesworth *et al.* 1997).

Most previous special volumes or books on the subject have tended to deal with intra-oceanic arcs as a subset of convergent margins. Gill (1981), Thorpe (1982) and Tatsumi & Eggins (1995) provide excellent introductions to volcanic arcs, although the first two are now somewhat dated. The monograph *Subduction Top to Bottom* (Bebout *et al.* 1996) contains a wide range of recent papers on subduction zones. Other recent volumes concentrate on particular topics: *The Behaviour and Influence of Fluids in Subduction Zones* (Tarney *et al.* 1991), *Backarc Basins* (Taylor 1995) and *Active Margins and Marginal Basins of the Western Pacific* (Taylor & Natland 1995).

Characteristics of intra-oceanic arcs

The locations of the intra-oceanic arcs of the world are shown in Figure 1. All are in the western Pacific region, except three – the Aleutian arc in the north Pacific, and the Lesser Antilles and South Sandwich arcs, both in the Atlantic Ocean. The main physical characteristics of the arcs are compared in Table 1, and a schematic cross-section of an intra-oceanic subduction system is shown in Figure 2.

Convergence rates

Convergence rates vary from *c.* 20 mm a^{-1} in the Lesser Antilles arc to 240 mm a^{-1} in the northern part of the Tonga arc, the highest subduction rates on Earth (Bevis *et al.* 1995). Typical rates are in the range 50–130 mm a^{-1}. Note that intra-arc variations are almost as large as inter-arc ones. For example, in the Aleutian arc, convergence rates are about 66 mm a^{-1} beneath the eastern part of the arc where convergence is almost perpendicular to the trench (DeMets *et al.* 1990, 1994), and slightly higher in the western part of the arc, around 73 mm a^{-1}. However, because of the curvature of the arc, the convergence direction becomes increasingly oblique westwards to the point of becoming almost pure transform motion (Creager & Boyd 1991). Convergence rates vary along the Solomon arc mainly because two different plates are being subducted – the Solomon Sea and Australian plates, which are separated by an active spreading centre. Rates are significantly higher (135 mm a^{-1}) for the Solomon Sea–Pacific convergence to the north of the triple junction than for the Australian–Pacific convergence (97 mm a^{-1}) to the south (Mann *et al.* 1998). Most of the large variation in convergence rate along the Tonga–Kermadec arc is related to clockwise rotation of the arc accommodated by extension in the back-arc basin, which is spreading at a rate of 159 mm a^{-1} (full rate) at the northern end of the Lau Basin (Bevis *et al.* 1995).

In several cases, there are uncertainties about rates of convergence because of uncertainties in rates of back-arc extension, which preclude calculation of convergence rates from major plate motions (DeMets *et al.* 1990, 1994). Convergence rates at the Mariana Trench are poorly constrained, mainly for this reason. Estimates of opening rates for the central and southern parts of the Mariana Trough back-arc basin range

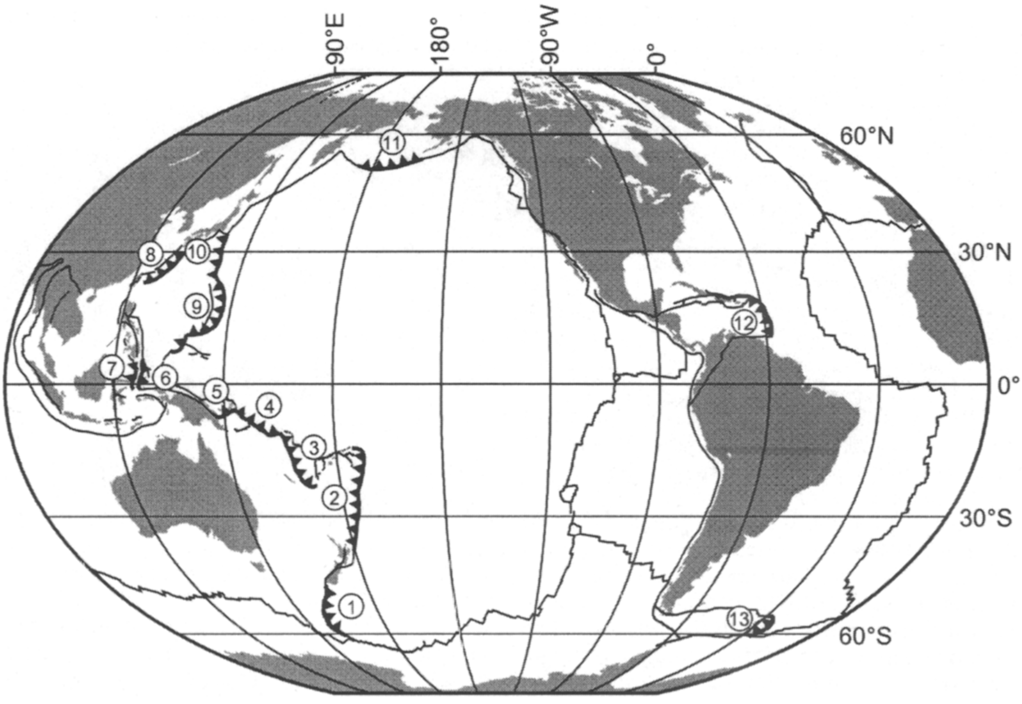

Fig. 1. Locations of modern intra-oceanic subduction systems (Mollweide projection). Trenches associated with these systems are marked by barbed lines. Other plate boundaries are shown as thin solid lines. Intra-oceanic subduction systems marked by numbers enclosed in circles are: 1, MacQuarie; 2, Tonga–Kermadec; 3, Vanuatu (New Hebrides); 4, Solomon; 5, New Britain; 6, Halmahera; 7, Sangihe; 8, Ryukyu; 9, Mariana; 10, Izu–Ogasawara (Bonin); 11, Aleutian; 12, Lesser Antilles; 13, South Sandwich. The Halmahera and Sangihe arcs are shown in their Neogene configuration; they are now in collision.

between 30 and 50 mm a^{-1} (Martinez & Taylor 2003). When combined with the plate kinematic model of Seno *et al.* (1993) these rates imply convergence rates >50 mm a^{-1} at the southern part of the Mariana Trench, increasing northward to >70 mm a^{-1} at the central part of the trench. Similar uncertainties exist for the Izu–Ogasawara arc along which convergence rates between the subducting Pacific and overriding Philippine Sea plates increase northwards from 47 to 61 mm a^{-1}, according to the plate kinematic model of Seno *et al.* (1993). The total convergence rates at the trench may be 1–3 mm a^{-1} faster than these rates as a consequence of intra-arc rifting (Taylor 1992). In several arcs accurate convergence rates have been accurately determined by geodetic Global Positioning System (GPS) measurements (Tonga–Kermadec, Bevis *et al.* 1995; Vanuatu, Taylor *et al.* 1995; Lesser Antilles, DeMets *et al.* 2000; Perez *et al.* 2001; Weber *et al.* 2001).

Ages of slabs

Ages of subducting slabs range from Late Jurassic (*c.* 152 Ma, Nakanishi *et al.* 1989) in the case of the Pacific Plate subducted beneath the Maraina arc, the oldest ocean floor currently being subducted anywhere in the world, to close to zero age along part of the Solomon arc (Mann *et al.* 1998). Along-arc variations in slab ages are not large. Of the arcs in Table 1, the age of the plate subducting beneath the Tonga–Kermadec arc is, perhaps, the most uncertain. The subducting slab is mid–Late Cretaceous in age, having formed by fast spreading at the Osbourn Trough, a fossil spreading centre that is now being subducted orthogonally to the trench. It has been suggested that the youngest crust generated at the Osbourn Trough may be as young as 70 Ma (Billen & Stock 2000), although others have argued that regional tectonic constraints preclude spreading at the Osbourn Trough more

Table 1. *Parameters of intra-oceanic subduction zones*

Arc	Convergence rate (mm a^{-1})	Age of subducting slab	Sediment thickness (m)	Sediment types	Accreting/ non-accreting	Back-arc rifting	Arc crustal thickness (km)	References
Tonga–Kermadec	60 (south) to 240 (north)	Mid–Late Cretaceous (probably >100 Ma)	70–157	Pelagic clay, chert, porcellanite, volcaniclastic deposits. Increasing terrigenous input to south	Non-accreting	Well-developed ocean spreading in Lau Basin with hydrothermal venting		Fouquet *et al.* (1991), Plank & Langmuir (1993), Bevis *et al.* (1995), Gamble *et al.* (1996), Larter *et al.* (2002)
Vanuatu	103–118	Eocene–Oligocene	650	Ash, volcaniclastic, deposits, calcareous ooze	Non-accreting	Well-developed oceanic spreading in the North Fiji Basin		Plank & Langmuir (1993), Taylor *et al.* (1995), Pelletier *et al.* (1998)
Solomon	135 (Solomon Sea–Pacific) and 97 (Australian–Pacific)	0–5 Ma		Clay, volcaniclastic, deposits, calcareous ooze	Non-accreting	None		Taylor & Exon (1987), Mann *et al.* (1998), Petterson *et al.* (1999)
New Britain	80–150	*c.* 45 Ma		Hemipelagic mud		Well-developed ocean spreading in the Manus Basin with hydrothermal venting		Binns & Scott (1993), Benes *et al.* (1994), Tregoning *et al.* (1998), Woodhead *et al.* (1998), Tregoning (2002), Sinton *et al.* (2003)
Mariana	>50 (south) to >70 (central)	*c.* 152 Ma	460	Siliceous ooze, volcaniclastic deposits, pelagic clay	Non-accreting	Complex history of rifting. Currently well-developed ocean spreading in Mariana Trough		Nakanishi *et al.* (1989), Taylor (1992), Plank & Langmuir (1993), Seno *et al.* (1993), Stern & Smoot (1998), Shipboard Scientific Party (2000), Martinez & Taylor (2003)
Izu–Ogasawara (Bonin)	>47 (south) to >61 (north)	127–144 Ma	410	Siliceous ooze, volcanic ash, calcareous ooze, pelagic clay	Non-accreting	Complex history of rifting. Recent formation of rift basins in the rear-arc	*c.* 20	Nakanishi *et al.* (1989), Taylor (1992), Seno *et al.* (1993), Suyehiro *et al.* (1996), Shipboard Scientific Party (2000)
Aleutian	66 (east) to 73 (west)	42–62 Ma	500	Siliceous ooze, clay, and tubiditic silts and sands	Accreting	None	*c.* 30	Lonsdale (1988), DeMets *et al.* (1990, 1994), Creager & Boyd (1991), Plank & Langmuir (1993), Fliedner & Klemperer (1999), Holbrook *et al.* (1999)
Lesser Antilles	*c.* 20	Jurassic–Early Cretaceous (south) to Late Cretaceous (> *c.* 75–85 Ma) (north)	Variable, from 410 m at DSDP Site 543 (north; 210 m subducted) to >6 km (south; perhaps 1 km subducted)	Subducted components: siliceous ooze, pelagic clay, carbonate ooze, turbiditic silts and sands	Accreting	The back-arc Grenada Trough is heavily sedimented and probably extinct	30–35	Boynton *et al.* (1979), Westbrook *et al.* (1984, 1988), Speed & Walker (1991), Plank & Langmuir (1993), Dixon *et al.* (1998), DeMets *et al.* (2000), McDonald *et al.* (2000), Perez *et al.* (2001), Weber *et al.* (2001)
South Sandwich	67–79	83 Ma (north) to 27 Ma (south)	<200 (south)	Siliceous mud (south)	Non-accreting	Well-developed ocean spreading along East Scotia Ridge with hydrothermal venting	<20	Ninkovich *et al.* (1964), Barker & Lawver (1988), Livermore & Woollett (1993), Vanneste & Larter (2002), Vanneste *et al.* (2002), German *et al.* (2000), Larter *et al.* (2003), Thomas *et al.* (2003)

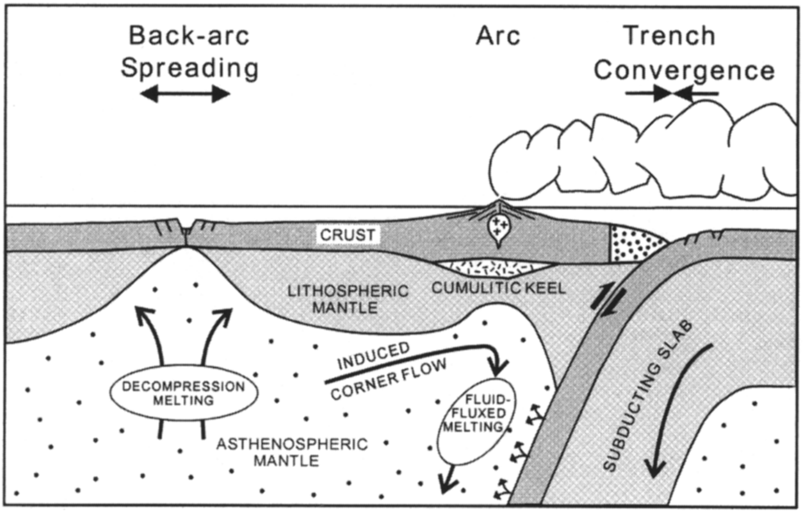

Fig. 2. Schematic cross-section of an intra-oceanic subduction zone, not to scale. The outer forearc (stippled) is the site of either sediment accretion or subduction erosion.

recently than 100 Ma (e.g. Larter *et al.* 2002), which gives a minimum age for the subducting slab. The Lesser Antilles and South Sandwich arcs show the greatest intra-arc variations in ages of subducting slabs (respectively, Jurassic or Early Cretaceous–Late Cretaceous, Westbrook *et al.* 1984, and 27–83 Ma, Barker & Lawver 1988; Livermore & Woollett 1993).

Topography of subducting plates

There are large variations in the topography of the subducting plates. Whereas some are relatively smooth, some contain ridges and seamounts that affect subduction and arc tectonics. The Jurassic ocean floor subducting at the Mariana arc is overlain by Cretaceous alkali basalts and numerous seamounts that continually collide with the trench. The Louisville Ridge hot-spot chain subducting at the Tonga–Kermadec Trench has caused indentation of the forearc. More dramatically, collision of the D'Entrecasteaux Ridge (an extinct arc) with the Vanuatu arc is causing uplift of the forearc, thrusting of the central part of the arc eastwards towards the rear-arc and development of a series of strike-slip faults approximately perpendicular to the arc (Maillet *et al.* 1995; Taylor *et al.* 1995). Similarly, recent uplift of the Solomon arc is probably a consequence of collision of the Coleman Seamount with the trench (Mann *et al.* 1998).

Sediment thickness

Sediment thicknesses are more variable than perhaps implied in Table 1, where several of the thicknesses are taken from Deep Sea Drilling Project (DSDP) or Ocean Drilling Program (ODP) cores. Sediment cover is commonly thinner over basement highs, and the resulting condensed sequences are sometimes targeted for drill sites. This tends to produce underestimates in subducted sediment thicknesses in compilations such as Table 1. Variations in thickness and composition of subducted sediments are probably greatest where arcs are close to, or cut across, ocean–continent boundaries. Thus, the sediment on the subducting plate arriving at the Lesser Antilles Trench increases dramatically southward toward the South American continental margin, where a >6 km-thick turbiditic fan is fed from the Orinoco River (Westbrook *et al.* 1984), of which 1 km is probably subducted and the rest added to an accretionary complex (Westbrook *et al.* 1988). By contrast, DSDP Site 543, near the northern part of the arc, showed just 410 m of sediment overlying basaltic basement on the subducting plate. Seismic reflection profiles here show that the upper 200 m of sediment is scrapped off and added to the accretionary complex, while the rest of the succession is subducted (Westbrook *et al.* 1984). There is a similar increase in terrigenous input derived from the New Zealand continent southward along the Tonga–Kermadec arc (Gamble *et al.* 1996).

Accretion v. non-accretion

Most modern intra-oceanic arcs are non-accreting, i.e. there is little or no net accumulation of off-scrapped sediment forming accretionary complexes. In other words, all the sediments arriving at the trenches are subducted (over a period) into the mantle. The two exceptions are the Lesser Antilles and Aleutian arcs, both of which have relatively high sediment inputs and where accretionary complexes have formed.

Back-arc spreading

Most of the arcs in Table 1 have closely associated back-arc rifts. Only the Solomon and Aleutian arcs are exceptions in having no apparent back-arc spreading. In most cases, the back-arc extension takes the form of well-organized seafloor spreading for at least part of the length of the back-arc. Such spreading appears to follow arc extension and rifting in at least some cases. The Mariana arc has had an especially complex history of arc and back-arc extension, starting with axial rifting of an Oligocene volcanic arc at about 29 Ma, beginning development of the back-arc Parece Vela Basin (Taylor 1992). A second episode of arc rifting started in Late Miocene–Pliocene times when the West Mariana Ridge rifted away from the active arc to form the Mariana Trough (Fryer 1996). The Mariana Trough is currently opening by seafloor spreading for most of its length, where mid-ocean ridge basalt (MORB)-like lavas are erupted, and by rifting of arc crust in its northern part (Martinez *et al.* 1995), where compositions are indistinguishable from those of the magmatic arc (Stolper & Newman 1994; Gribble *et al.* 1998).

The Izu–Ogasawara arc had similar early tectonic and magmatic histories to those of the Mariana arc (Taylor 1992; Macpherson & Hall 2001). An Oligocene arc rifted parallel to its length at *c.* 22 Ma to form the back-arc Shikoku Basin. However, a second episode of Late Pliocene–Recent arc-parallel rifting formed a series of rift basins in the present rear-arc that have not developed to ocean spreading centres (Taylor 1992). Ishizuka *et al.* (2003) present new Ar–Ar geochronological data to define the volcanic and extensional history of the arc and back-arc.

The East Scotia Ridge consists of nine mostly well-organized spreading segments (with a possible poorly defined tenth at the southern end of the ridge). The central segments are rift-like and erupt MORB (Livermore *et al.* 1997; Fretzdorff *et al.* 2002; Livermore 2003), but one segment in the south appears to have recently developed from arc extension to ocean spreading (Bruguier & Livermore 2001). Lavas tend to become compositionally more similar to the arc at the ends of the ridge, where it is close to the arc volcanic front (Fretzdorff *et al.* 2002). A similar relationship is observed in the Lau Basin back-arc to the Tonga arc, where water and other slab-derived chemical tracers increase as distance from the arc volcanic front decreases (Pearce *et al.* 1994; Peate *et al.* 2001). This in turn controls magma supply and crustal thickness in the back-arc (Martinez & Taylor 2002). Martinez & Taylor (2003) report similar variations related to distance from the arc volcanic front in the Manus Basin and Mariana Trough.

Arc crustal thickness and pre-arc basement

Figures for the thickness of the crust of arcs are only shown in Table 1, where high-quality wide-angle seismic and gravity data exist. Arc thicknesses depend on arc maturity, tectonic extension or shortening, and the thickness of pre-arc basement. Only approximately, therefore, is it true to say that the thin crusts of the South Sandwich (Larter *et al.* 2003) and Izu–Osgaswara (Suyehiro *et al.* 1996) arcs represent arcs in the relatively early stages of development, whereas the Lesser Antilles (Boynton *et al.* 1979) and Aleutian (Fliedner & Klemperer 1999; Holbrook *et al.* 1999) arcs with their thicker crusts are more mature.

Pre-arc basements of the arcs are very variable. The central and western parts of the Aleutian arc are built on Cretaceous oceanic plate that underlies the Bering Sea, and this is the only intra-oceanic arc built on normal ocean crust. The South Sandwich arc is a little more complex, being built on ocean plate formed since *c.* 10 Ma at the back-arc East Scotia Ridge spreading centre (Larter *et al.* 2003). Several of the arcs in Table 1 are built on earlier arc rocks. The present Izu–Ogasawara arc is built on stretched Eocene–Oligocene arc crust (Taylor 1992). The New Britain arc overlies a basement of Eocene–Miocene intra-oceanic arc rocks (Madsen & Lindley 1994; Woodhead *et al.* 1998) formed before a reversal in subduction polarity (Benes *et al.* 1994). Similarly, the Neogene Halmahera arc overlies ophiolitic basement and Early Tertiary arc volcanic rocks (Hall *et al.* 1991), and the basement to the Sangihe arc is also thought to consist of pre-Miocene ophiolitic or arc crust (Carlile *et al.* 1990).

Some of the arcs have more complex basement. The basement to the Solomon arc falls in to this category, and at present probably constitutes a zone of diffuse deformation at the edge of the Pacific Plate. It consists of several oceanic terrains, including parts of the Ontong Java Plateau, as well as MORB sequences (Petterson *et al.* 1999). The basement of the Lesser Antilles arc is poorly known. It probably consists of mid-Cretaceous–Palaeocene arc and accretionary complex crust, and possibly thick oceanic crust of the Caribbean Plateau (Macdonald *et al.* 2000). The volcanic rocks of this arc show evidence for widespread contamination by a sediment source during magma ascent. This contaminant increases to the south and is thought to be the old accretionary complex material forming basement to the arc (Davidson & Harmon 1989; Davidson 1996; van Soest *et al.* 2002). A parallel trend of southward-increasing sediment input to the mantle sources of the magmas is observed (Turner *et al.* 1996).

Exhumed intra-oceanic arcs

Structures of modern magmatic arcs inferred from geophysics and petrology can be 'ground-truthed' by studies of sections through arcs exposed by orogenic process. Slivers of arc crust are common, probably ubiquitous in collisional orogens. It is rare, however, for complete crustal sections through arcs from mantle to volcanic cover to be exposed. Well-documented examples include the Kohistan, Pakistan (Miller & Christensen 1994), Talkeetna, Alaska (DeBari & Sleep 1991) and Canyon Mountain, Oregon (Pearcy *et al.* 1990) arcs. All of these examples are thought to have been intra-oceanic. The Kohistan arc, in particular, has provided critical information on the seismic and petrological structure of arc crust (Chroston & Simmons 1989; Miller & Christensen 1994). DeBari & Sleep (1991) demonstrated that the Talkeetna arc can be used for mass-balance calculations to determine the composition of mantle-derived magma feeding the arc, and argued that it was high-Mg (and low-Al) basalt.

Current research themes

Mantle flow beneath arc and back-arc systems

Intra-oceanic arcs are the prime locations for geophysical and geochemical investigations into relationships between mantle flow and subduction. Intra-oceanic arcs lack the thick sialic crust that acts as a contaminant and density filter in continental arcs, and most magmas in them rise to the surface relatively unmodified from their original mantle-derived compositions.

It is now accepted that the majority of mafic magmas erupted in all volcanic arcs are derived by volatile-fluxed partial melting of peridotite in the mantle wedge, rather than by melting of the subducting slab (Tatsumi 1989; Pearce & Peate 1995; Tatsumi & Eggins 1995). Indeed, the characteristics of slab-melts are well known, and they form a distinctive, but relatively rare (at least in the post-Archaean record), type of subduction zone magma known as adakite (Defant & Drummond 1990).

Two-dimensional models for partial melting of mantle and the mantle 'corner' flow induced by the subducting plate in subduction zones are well developed (Davies & Stevenson 1992; Tatsumi & Eggins 1995; Winder & Peacock 2001). Extraction of a melt fraction from the mantle as it flows beneath back-arc spreading centres toward the arc is believed to cause the reduction in ratios of more incompatible, relative to less incompatible, trace elements (such as Nb/Yb and Nb/Ta) in arc basalts compared to MORBs (Woodhead *et al.* 1993, 1998; Pearce & Peate 1995). Such models of mantle flow have been adapted to explain variations in magma supply in back-arc basins by Martinez & Taylor (2002, 2003). Detailed seismic tomography images of the mantle beneath the NE Japan arc have been interpreted, together with other data, as evidence that mantle flow from back-arc to forearc is organized into 'hot fingers' (Tamura *et al.* 2002; Tamura 2003). However, measurement of seismic anisotropy beneath the Tonga arc and Lau Basin shows that mantle flow is locally parallel to the arc, and cannot be explained by coupling to the subducting slab (Smith *et al.* 2001). This is consistent with geochemical data indicating flow of mantle from the Samoan mantle plume around the north edge of the slab and into the back-arc (Turner & Hawkesworth 1998). Similar arc-parallel flow into a back-arc is thought to occur at the northern and southern ends of the slab beneath the South Sandwich arc (Livermore *et al.* 1997; Leat *et al.* 2000; Harrison *et al.* 2003; Livermore 2003). Questions remain as to what effect arc-parallel mantle flow has on magma compositions and supply in subduction zones.

Primary magmas and ultramafic keels

The major element composition of magmas feeding arcs from the mantle has been a subject of debate, particularly regarding the Mg and Al contents of primary magmas. Mafic compositions in arcs have variable MgO content, but with an abrupt cut-off at about 8 wt% MgO (less in the case of mature arcs), with very few, or zero, higher-Mg but non-cumulate compositions (Davidson 1996). One question is, therefore, whether this cut-off point represents the MgO content of the mantle-derived parental magmas, or whether the mantle-derived parental magmas are significantly more Mg-rich (>10% MgO), but are normally unable to reach the surface and erupt. Such high-Mg, primitive magmas have, in fact, been identified in many arcs, but are always volumetrically very minor. Their presence in many intra-oceanic and continental arcs indicates that they are, indeed, parental to arc magmatism (Ramsey *et al.* 1984; Heath *et al.* 1998; Macdonald *et al.* 2000). It has been argued that they have difficulty in traversing the crust because of their relatively high density (Smith *et al.* 1997) and the difficulty of traversing the crust without encountering magma chambers (Leat *et al.* 2002). Pichavant & Macdonald (2003) examine phase relationships of magnesian arc basalts and argue that only the most water-poor primitive magmas are able to traverse the crust without adiabatically freezing, explaining the rarity of primitive magmas in arcs. This raises further questions about the extent to which erupted and sampled primary magmas in arcs are typical of mantle-derived melts in arcs. There is a related debate about the origin of high-Al basalts, which have greater than *c.* 17 wt% Al_2O_3 and are characteristic of arcs. Crawford *et al.* (1987) reviewed the arguments and concluded that accumulation of plagioclase was the origin of the high Al abundances. These debates highlight the difficulty in modelling fractionation histories of arc magmas, even in intra-oceanic arcs, where primitive magmas are normally absent, and both addition and fractional removal of phenocrysts has occurred.

If the mantle-derived magmas are Mg-rich, the transition from primitive melts to low-Mg basalts by fractional crystallization must generate significant thicknesses of mafic and ultramafic cumulates. This is consistent with the presence of high-velocity (*P*-wave velocity = 6.9–7.5 km s^{-1}) layers several kilometres thick that have been seismically detected at the base of the crust in some intra-oceanic arcs (Suyehiro *et al.* 1996; Holbrook *et al.* 1999). Seismic velocity measurements on samples of exposed lower crust of the exhumed Kohistan arc strongly suggest that these high-velocity keels consist of ultramafic cumulates (Miller & Christensen 1994).

Slab-derived chemical components in intra-oceanic arcs

Subduction zones are the most important sites for fractionation of elements between different crustal and mantle reservoirs, and sites where crustal materials are returned to the mantle. They are therefore crucial for understanding the geochemical evolution of the Earth, at least since Archaean times (Hofmann & White 1982; Hart 1988; Dickin 1995; Tatsumi & Kogiso 2003). Geochemical studies of basalts from intra-oceanic arcs have been particularly important in determining how elements from different reservoirs are cycled through the mantle wedge, as contamination of magmas by ancient continental crust cannot have occurred. It has long been known that basalts of volcanic arcs are geochemically distinct from those erupted far from subduction zones. They normally have lower abundances of some incompatible trace elements (e.g. Nb, Ta, Zr, Hf, Ti and heavy rare earth elements) and higher abundances of others (e.g. K, Rb, Ba, Sr, Th, U and light rare earth elements), interpreted to be a result of addition of a 'subduction component' from the slab to the mantle wedge source of the basalts (Pearce 1983; Woodhead *et al.* 1993; Hawkesworth *et al.* 1994; Pearce & Peate 1995). Recent work has shown that the subduction component can be broken down into varying proportions of more fundamental components – the main ones are thought to be sediment and aqueous fluid. The sediment component (probably partial melt of sediment) varies in composition according to the type of sediments that are carried down the subduction zone with the slab. It is characterized by high light/heavy rare earth element, Th/Nb and Th/Tb ratios (Elliott *et al.* 1997; Woodhead *et al.* 1998). It sometimes has the continental isotopic signatures of high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ (Turner *et al.* 1996; Elliott *et al.* 1997; Class *et al.* 2000; Macpherson *et al.* 2003), and the cosmogenic signature of high ^{10}Be (Morris *et al.* 1990). The aqueous fluid component is derived by dehydration of basaltic slab and dewatering of sediments, and is characterized by high Ba/Th, Ba/Nb, B/Be and Cs/Rb ratios (Ryan *et al.* 1995; Elliott *et al.* 1997; Hawkesworth *et al.* 1997; Turner & Hawkesworth 1997; Peate & Pearce 1998). In other words, it is enriched in elements that experiments demonstrate are highly soluble in aqueous fluids at temperatures appropriate for the surface of the down-going slab (Brenan *et al.* 1995; Johnson & Plank 1999). Partial melts of the basaltic slab (adakites) may also be a minor component in some subduction zone magmas (Bédard 1999). However, much needs to be done in order to understand the nature of the element-transporting fluids, and methods of constraining the successive depletion and enrichment events in subduction environments.

The greater solubility of U than Th in aqueous fluids moving from the slab to the mantle wedge commonly results in a type of isotopic disequilibria between these elements in the erupted magmas, in which $^{238}U/^{230}Th$ is positively correlated with other tracers of the aqueous fluid component, such as Ba/Th. This type of disequilibrium is especially characteristic of intra-oceanic arcs (Elliott *et al.* 1997; Hawkesworth *et al.* 1997). The U–Th isotope disequilibria can be used to calculate the time lapse since fractionation of U from Th during slab dehydration, providing critical evidence for the timescales of melt migration (Hawkesworth *et al.* 1997). Results range from 90 ka for the Lesser Antilles (Turner *et al.* 1996) to 30–50 ka for the Tonga–Kermadec arc (Turner & Hawkesworth 1997) and *c.* 30 ka for the Mariana and Aleutian arcs (Elliott *et al.* 1997; Turner *et al.* 1998). However, the longer time for the Lesser Antilles probably includes 50 ka of magma residence in the crust, and the time for fluids and melt transport in the mantle seems to be consistently 30–50 ka. ^{226}Ra is a shorter-lived isotope (half-life of 1662 years) in the same chain as ^{230}Th. Some arc magmas have excess ^{226}Ra relative to ^{230}Th, but, because of the short half-life, these cannot result from the same slab dehydration processes as U–Th disequilibria and are assumed to reflect magma fractionation processes (Hawkesworth *et al.* 1997).

Formation of boninites

Boninites are rare, high-Mg, high-Si magmas of magmatic arcs. They dominantly occur in intra-oceanic arcs (Crawford *et al.* 1989). Their chemistry indicates that they were derived from depleted, harzburgitic sources in relatively shallow, lithospheric mantle that were subsequently enriched in incompatible elements. These incompatible elements were probably transported from subducting slabs as aqueous fluids derived from dehydration, as melts of sediment, and perhaps as partial melts of the slab crust (Crawford *et al.* 1989; Hickey-Vargas 1989; Taylor *et al.* 1994; Bédard 1999). The precise combination of circumstances that cause boninitic magmatism is debatable. Most authors appeal to processes in the evolution of subduction zones, whereas Macpherson & Hall (2001) suggested that heat convected by mantle plumes may have been critical in genesis of the Eocene Izu–Bonin–Mariana boninites. Deschamps & Lallamand (2003) describe the tectonic setting of boninites from Pacific arcs and show that intersection of a back-arc spreading centre with either an arc or a transform plate boundary are the most favourable sites for their generation.

Origin of silicic magmas

Intra-oceanic arcs dominantly erupt mafic magmas (basalt and basaltic andesite). Recently, however, there has been increasing recognition that silicic magmas form a significant proportion of their output. Tamura & Tatsumi (2002) showed that the Izu–Bonin arc is compositionally bimodal with maxima at both mafic and silicic compositions and a minimum at andesite, based on 1011 analyses from volcanic front volcanoes. This is in striking contrast to the traditional view of island arcs being dominated by andesite (e.g. Gill 1981). Analysis of ashes from cores from the Izu–Bonin and Mariana fore- and back-arcs provides further evidence for overall mafic–silicic bimodality in the arcs, or at least a high proportion of silicic magmas (Arculus *et al.* 1995; Straub 1995). Mafic–silicic bimodality is also becoming very evident in individual volcanoes of intra-oceanic arcs, and examples have been described from the Vanuatu arc (Robin *et al.* 1993; Monzier *et al.* 1994), the Tonga–Kermadec arc (Worthington *et al.* 1999; Smith *et al.* 2003) and the South Sandwich arc (Leat *et al.* 2003). Furthermore, it is becoming clear that there is a common, but possibly not ubiquitous, association of these silicic and bimodal basalt–silicic magmas with calderas. The calderas are typically 3–7 km in diameter and, because they are typically flooded, completely submerged or ice filled (in the South Sandwich Islands), many have only recently been discovered. Examples include the Raoul, Macauley and Brothers volcanoes in the Kermadec arc (Lloyd *et al.* 1996; Worthington *et al.* 1999; Wright & Gamble 1999), the Ambrym and Kuwar volcanoes, Vanuatu arc (Robin *et al.* 1993; Monzier *et al.* 1994), the South Sumisu and Myojin Knoll volcanoes, Izu–Bonin arc (Taylor *et al.* 1990; Fiske *et al.* 2001) and Southern Thule, South Sandwich arc (Smellie *et al.* 1998).

The traditional view on the origin of silicic magmas in intra-oceanic arcs is that they are generated by fractional crystallization of more mafic magmas (e.g. Ewart & Hawkesworth 1987; Woodhead 1988; Pearce *et al.* 1995). Recently, several authors have questioned this, and argued that the silicic rocks are generated by partial melting of andesitic (Tamura & Tatsumi 2002) or basaltic (Leat *et al.* 2003; Smith *et al.* 2003) igneous rocks within the crust. The debate is critical to understanding the way in which arc crust, and ultimately continental crust, is formed. The arguments are geochemical and also based on volume relationships. Suyehiro *et al.* (1996) identified a mid-crustal layer some 6 km thick in the Izu–Bonin arc that has a *P*-wave velocity of 6.0–6.3 km s^{-1}. Larter *et al.* (2001)

reported a similar, but thinner, layer in the South Sandwich arc. Suyehiro *et al.* (1996) and Larter *et al.* (2001) interpreted these layers as being intermediate–silicic plutonic rocks. The intermediate (tonalitic) to silicic Tanzawa plutonic complex, Honshu, Japan, is thought to be the lateral correlative of the 6.0–6.3 km s^{-1} layer in the Izu–Bonin arc. Geochemical and experimental results suggest that the tonalite was generated by *c.* 59% partial melting of hydrous basalt in the lower crust of the arc (Kawate & Arima 1998; Nakajima & Arima 1998), consistent with the experimental evidence for generation of silicic magmas by partial melting of amphibolites of Rapp & Watson (1995).

The role of subduction zones in the evolution of continental crust

Mechanisms for the evolution of continental crust are critical for understanding the evolution of Earth and its geochemical reservoirs. Volcanic arcs are traditionally thought to be the main sites of production of continental crust from mafic progenitors, particularly in post-Archaean times, with intra-oceanic arcs being the first stage of the process. This view has been encouraged by the fact that the dominant composition of lavas and pyroclastic deposits of many arcs (especially continental ones) is andesite (Gill 1981). Such andesite has a very similar major and trace element composition to bulk continental crust (Taylor & McLennan 1985; Rudnick 1995). However, in calculations of the composition of crust produced in volcanic arcs, the composition of volcanic products is largely irrelevant – what matters is the composition of magma added to the crust from the mantle, i.e. the composition of the magma flux across the Moho, and this is basaltic, not andesitic. Moreover, it is probably a high-Mg basalt containing some 12 wt% MgO (DeBari & Sleep 1991; Davidson 1996). If continental crust were derived from such basaltic magma generated from the mantle wedge, the crust would need to have been very significantly changed in composition. Continental crust has higher abundances of Si, alkalis and incompatible trace elements, lower abundances of Mg, and higher ratios of light rare earth elements to heavy rare earth elements than volcanic arc basalts (Pearcy *et al.* 1990; Rudnick 1995). Processes invoked to account for the change in composition from basaltic arc crust to continental crust include: (i) partial melting of basalt to generate intermediate and silicic material, which is added to the middle and upper crust as plutons and lavas; (ii) return to the mantle ('delamination') from the lower crust of mafic and ultramafic residue from such partial melting and ultramafic cumulates derived by fractional crystallization of mafic magmas; and (iii) injection of alkali- and trace-element-rich magmas into the crust after the lithosphere has been thickened to the garnet stability zone, presumably during arc–arc and arc–continent collisions (Pearcy *et al.* 1990; DeBari & Sleep 1991; Rudnick 1995; Taylor & McLennan 1995; Holbrook *et al.* 1999; Tatsumi & Kogiso 2003). Clift *et al.* (2003) describes crustal evolution of intra-oceanic arc material during arc–continent collisions in Taiwan and Ireland.

The detailed seismic velocity structure of the Izu–Bonin arc crust suggests that a 6 km-thick intermediate to silicic mid-crustal layer (*P*-wave velocity = 6.0–6.3 km s^{-1}) and 8 km-thick ultramafic lower crust (*P*-wave velocity = 7.1–7.3 km s^{-1}) are present (Suyehiro *et al.* 1996). These observations are consistent with some of the ideas about crustal modification mentioned above. However, in the central Aleutians mid-crustal material with velocities of 6.0–6.3 km s^{-1} is virtually absent, and velocities in the thick lower crust (up to 20 km) are generally slightly lower than in the Izu–Bonin arc (Holbrook *et al.* 1999). A mid-crustal layer with velocities of 6.0–6.3 km s^{-1} is present in the eastern Aleutian arc (Fliedner & Klemperer 1999) and the southern South Sandwich arc (Larter *et al.* 2001), but in both locations it is only about 2 km thick. The origin of such mid-crustal layers remains a matter of debate, and it has been suggested that the ultramafic lower crust to mantle transition is gradational in some places beneath arcs (Fliedner & Klemperer 2000). Jull & Kelemen (2001) have calculated that some arc lower crustal lithologies have densities similar to, or greater than, the underlying mantle at pressures >0.8 GPa and temperatures <800°C, possibly making lowermost arc crust prone to delamination. However, for crust comprising typical arc lithologies, 0.8 GPa is equivalent to a depth of about 28 km, which is deeper than the base of the crust in many modern intra-oceanic arcs.

Hydrothermal processes

Back-arc spreading centres of intra-oceanic arcs are well known as sites of hydrothermal activity. Hydrothermal phenomena include white and black smokers, and metallogenesis in both the Lau Basin and the Manus Basin (Fouquet *et al.* 1991; Ishibasi & Urabe 1995; Kamenetsky *et al.* 2001). Hydrothermal plumes have also been identified on the East Scotia Ridge (German *et* *al.* 2000). In these back-arc settings, the hydrothermal activity is associated with both basaltic and silicic volcanic centres (Ishibasi & Urabe 1995).

There is increasing evidence, however, that submerged volcanoes along the volcanic fronts of intra-oceanic arcs are sites of considerable hydrothermal activity. The first systematic survey of any submerged arc for hydrothermal activity revealed that seven out of the 13 submarine volcanoes in the southern Kermadec arc had hydrothermal plumes (de Ronde *et al.* 2001). Baker *et al.* (2003) present detailed observations of the distribution of these plumes and the composition of their particulate fraction. Massoth *et al.* (2003) characterize the chemistry of the gaseous and fluid components of the plumes and consider the evidence for a magmatic contribution. Projection of this frequency of hydrothermal activity to the global length of submerged arcs suggests that hydrothermal emissions from arcs may represent a significant part of the global budget. Moreover, hydrothermal vent sites of arcs are much shallower than those of mid-ocean and back-arc ridges, suggesting that hydrothermal emissions from arcs have a disproportionally high environmental impact (de Ronde *et al.* 2001). Several volcanic front volcanoes in the Mariana and Izu–Bonin arcs are also hydrothermally active and are producing metalliferous deposits (Stüben *et al.* 1992; Tsunogai *et al.* 1994; Iizasa *et al.* 1999; Fiske *et al.* 2001). Several of the hydrothermal vents in the Izu–Bonin arc (Myojin Knoll; Fiske *et al.* 2001) and the Kermadec arc (Brothers volcano; Wright & Gamble 1999; de Ronde *et al.* 2001) are within silicic calderas, and are associated with Au-rich metalliferous deposits. This raises the possibility that the calderas are formed by collapse into shallow magma chambers and that heat from the magma chambers drives the hydrothermal systems The metalliferous deposits may provide the closest analogues to Kuroko-type deposits (Iizasa *et al.* 1999).

Conclusions

- Nearly 40% of the global length of volcanic arc is situated on crust of oceanic derivation rather than continental crust, amounting to some 17 000 km of intra-oceanic arcs.
- Intra-oceanic arcs are prime locations for studies of mantle flow, elemental fluxes from subducting slabs and mantle partial melting processes in subduction systems, because such processes are not obscured by continental crust.
- There are very large variations in physical characteristics of intra-oceanic arcs, especially in convergence rates, ages, roughnesses and thicknesses of sediment cover of subducting slabs.
- Convergence rates range from *c.* 20 to 240 mm a^{-1}, and there are also large variations along the lengths of individual arcs. In the absence of geodetic GPS data, convergence rates are often poorly constrained because of uncertainties in rates of back-arc spreading.
- Only one intra-oceanic arc (the Aleutian arc) is built on normal ocean crust. The others are built on basements comprising a range of oceanic lithologies, including ocean crust formed at back-arc spreading centres, earlier intra-oceanic arcs, accretionary complexes and oceanic plateaux. It is, therefore, not possible to characterize typical intra-oceanic arc crust in terms of structure or thickness.
- It is becoming increasingly evident that silicic magmas are an important component of intra-oceanic arcs, often forming mafic–silicic bimodal series associated with calderas, and in some cases forming mid-crustal layers with *P*-wave velocities of *c.* 6.0–6.3 km s^{-1}. The silicic magmas may represent partial melts of the basaltic arc crust and, perhaps, the first stage in the development of continental crust.
- There is increasing evidence that intra-oceanic arc volcanoes are commonly sites of considerable hydrothermal venting that may form a significant part of the global hydrothermal venting budge into the oceans. Silicic calderas in intra-oceanic arcs are commonly sites of Au-rich metalliferous deposits.

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References

ARCULUS, R.J., GILL, J.B., CAMBRAY, H., CHEN, W. & STERN, R.J. 1995. Geochemical evidence of arc systems in the Western Pacific: an ash and turbidite record recovered by drilling. *In*: TAYLOR, B. & NATLAND, J. (eds) *Active Margins and Marginal Basins of the Western Pacific*. American Geophysical Union Monographs **88**, 45–65.

BAKER, E.T., FEELY, R.A., DE RONDE, C.E.J., MASSOTH, G.J. & WRIGHT, I.C. 2003. Submarine hydrothermal venting on the southern Kermadec volcanic arc front (offshore New Zealand): location and extent of particle plume signatures. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 141–161.

BARKER, P.F. & LAWVER, L.A. 1988. South American–Antarctic plate motion over the past 50 Myr, and the evolution of the South American–Antarctic ridge. *Geophysical Journal International*, **94**, 377–386.

BEBOUT, G.E., SCHOLL, D.W., KIRBY, S.H. & PLATT, J.P. (eds). 1996. *Subduction Top to Bottom.* American Geophysical Union, Monographs, **96**.

BÉDARD, J.H. 1999. Petrogenesis of boninites from the Betts Cove ophiolite, Newfoundland, Canada: identification of subducted source components. *Journal of Petrology*, **40**, 1853–1889.

BENES, V., SCOTT, S.D. & BINNS, R.A. 1994. Tectonics of rift propagation into a continental margin: western Woodlark Basin, Papua New Guinea. *Journal of Geophysical Research*, **99**, 4439–4455.

BEVIS, M., TAYLOR, F.W., SCHUTZ, B.E., RECY, J., ISACKS, B.L., HELU, S., SINGH, R., KENDRICK, E., STOWELL, J., TAYLOR, B. & CALMANT, S. 1995. Geodetic observations of very rapid convergence and back-arc extension at the Tonga arc. *Nature*, **374**, 249–251.

BILLEN, M.I. & STOCK, J. 2000. Morphology and origin of the Osbourn Trough. *Journal of Geophysical Research*, **105**, 13 481–13 489.

BINNS, R.A. & SCOTT, S.D. 1993. Actively forming polymetallic sulphide deposits associated with felsic volcanic rocks in the eastern Manus back-arc basin, Papua New Guinea. *Economic Geology*, **88**, 2226–2236.

BOYNTON, C.H., WESTBROOK, G.K., BOTT, M.H.P. & LONG, R.E. 1979. A seismic refraction investigation of crustal structure beneath the Lesser Antilles island arc. *Geophysical Journal of the Royal Astronomical Society*, **58**, 371–393.

BRENAN, J.M., SHAW, H.F., RYERSON, F.J. & PHINNEY, D.L. 1995. Mineral–aqueous fluid partitioning of trace elements at 900°C and 2.0 GPa – constraints on the trace element chemistry of mantle and deep crustal fluids. *Geochimica et Cosmochimica Acta*, **59**, 3331–3350.

BRUGUIER, N.J. & LIVERMORE, R.A. 2001. Enhanced magma supply at the southern East Scotia ridge: evidence for mantle flow around the subducting slab? *Earth and Planetary Science Letters*, **191**, 129–144.

CARLILE, J.C., DIGDOWIROGO, S. & DARIUS, K. 1990. Geological setting, characteristics and regional exploration for gold in the volcanic arcs of North Sulawesi, Indonesia. *Journal of Geochemical Exploration*, **35**, 105–140.

CHROSTON, P.N. & SIMMONS, G. 1989. Seismic velocities from the Kohistan volcanic arc, northern Pakistan. *Journal of the Geological Society, London*, **146**, 971–979.

CLASS, C., MILLER, D.M., GOLDSTEIN, S.L. & LANGMUIR, C.H. 2000. Distinguishing melt and fluid subduction components in Umnak volcanics, Aleutian arc. *Geochemistry Geophysics Geosystems*, **1**, 1999GC000010.

CLIFT, P.D., SCHOUTEN, H. & DRAUT, A.E. 2003. A general model of arc–continent collision and subduction polarity reversal from Taiwan and the Irish Caledonides. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 81–98.

CRAWFORD, A.J., FALLOON, T.J. & EGGINS, S. 1987. The origin of island arc high-alumina basalts. *Contributions to Mineralogy and Petrology*, **97**, 417–430.

CRAWFORD, A.J., FALLON, T.J. & GREEN, D.H. 1989. Classification, petrogenesis and tectonic setting of boninites. *In*: CRAWFORD, A.J. (ed.) *Boninites.* Unwin Hyman, London, 1–49.

CREAGER, K.C. & BOYD, T.M. 1991. The geometry of Aleutian subduction: three-dimensional kinematic flow model. *Journal of Geophysical Research*, **96**, 2293–2307.

DAVIDSON, J.P. 1996. Deciphering mantle and crustal signatures in subduction zone magmatism. *In*: BEBOUT, G.E., SCHOLL, D.W., KIRBY, S.H. & PLATT, J.P. (eds) *Subduction Top to Bottom.* American Geophysical Union Monographs, **96**, 251–262.

DAVIDSON, J.P. & HARMON, R.S. 1989. Oxygen isotope constraints on the petrogenesis of volcanic arc magmas from Martinique, Lesser Antilles. *Earth and Planetary Science Letters*, **95**, 255–270.

DAVIES, J.H. & STEVENSON, D.J. 1992. Physical model of source region of subduction zone volcanics. *Journal of Geophysical Research*, **97**, 2037–2070.

DEBARI, S.M. & SLEEP, N.H. 1991. High-Mg, low-Al bulk composition for the Talkeetna island arc, Alaska: implications for primary magmas and the nature of arc crust. *Geological Society of America Bulletin*, **103**, 37–47.

DEFANT, M.J. & DRUMMOND, M.S. 1990. Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature*, **347**, 662–665.

DEMETS, C., GORDON, R.G., ARGUS, D.F. & STEIN, S. 1990. Current plate motions. *Geophysical Journal International*, **101**, 425–478.

DEMETS, C., GORDON, R.G., ARGUS, D.F. & STEIN, S. 1994. Effects of recent revisions of the geomagnetic reversal time-scale on estimates of current plate motions. *Geophysical Research Letters*, **21**, 2191–2194.

DEMETS, C., JANSMA, P.E., MATTIOLI, G.S., DIXON, T.H., FARINA, F., BILHAM, R., CALAIS, E. & MANN, P. 2000. GPS geodetic constraints on Caribbean-North American plate motions. *Geophysical Research Letters*, **27**, 437–440.

DEPLUS, C., LE FRIANT, A., BOUDON, G., KOMOROWSKI, J.-C., VILLEMANT, B., HARFORD, C., SÉGOUFIN, J. & CHEMINÉE, J.-L. 2001. Submarine evidence for large-scale debris avalanches in the Lesser Antilles arc. *Earth and Planetary Science Letters*, **192**, 145–157.

DE RONDE, C.E.J., BAKER, E.T., MASSOTH, G.J., LUTON, J.E., WRIGHT, I.C., FEELEY, R.A. & GREENE, R.R. 2001. Intra-oceanic subduction-related hydrothermal venting, Kermadec arc, New Zealand. *Earth and Planetary Science Letters*, **193**, 359–369.

DESCHAMPS, A. & LALLEMAND, S. 2003. Geodynamic setting of Izu–Bonin–Mariana boninites. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 163–185.

DICKIN, A.P. 1995. *Radiogenic Isotope Geology*. Cambridge University Press, Cambridge.

DIXON, T.H., FARINA, F., DEMETS, C., JANSMA, P., MANN, P. & CALAIS, E. 1998. Relative motion between the Caribbean and North American plates and related boundary zone deformation from a decade of GPS observations. *Journal of Geophysical Research*, **103**, 15157–15182.

EGGINS, S.M., WOODHEAD, J.D., KINSLEY, L.P.J, MORTIMER, G.E., SYLVESTER, P. MCCULLOCH, M.T., HERGT, J.M. & HANDLER, M.R. 1997. A simple method for the precise determination of ≥40 trace elements in geological samples by ICPMS using enriched isotope international standardisation. *Chemical Geology*, **134**, 311–326.

ELLIOTT, T., PLANK, T., ZINDLER, A., WHITE, W. & BOURDON, B. 1997. Element transport from slab to volcanic front at the Mariana arc. *Journal of Geophysical Research*, **102**, 14 991–15 019.

ENGDAHL, E.R., VAN DER HILST, R. & BULAND, R. 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bulletin of the Seismological Society of America*, **88**, 722–743.

EWART, A. & HAWKESWORTH, C.J. 1987. The Pliocene–Recent Tonga–Kermadec arc lavas: interpretation of new isotopic and rare earth data in terms of a depleted mantle source model. *Journal of Petrology*, **28**, 495–530.

FISKE, R.S., NAKA, J., IIZASA, K., YUASA, M. & KLAUS, A. 2001. Submarine silicic caldera at the front of the Izu-Bonin arc, Japan: voluminous seafloor eruptions of rhyolite pumice. *Geological Society of America Bulletin*, **113**, 813–824.

FLIEDNER, M.M. & KLEMPERER, S.L. 1999. Structure of an island arc: wide-angle seismic studies in the eastern Aleutian Islands, Alaska. *Journal of Geophysical Research*, **104**, 10 667–10 694.

FLIEDNER, M.M. & KLEMPERER, S.L. 2000. Crustal structure transition from oceanic arc to continental arc, eastern Aleutian Islands and Alaska Peninsula. *Earth and Planetary Science Letters*, **179**, 567–579.

FOUQUET, Y., VON STACKELBERG, U., CHARLOU, J.L., DONVAL, J.P., ERZINGER, J., FOUCHER, J.P., HERZIG, P., MÜHE, R., SOAKAI, S., WIEDICKE, M. & WHITECHURCH, H. 1991. Hydrothermal activity and metallogenesis in the Lau back-arc basin. *Nature*, **349**, 778–781.

FRETZDORFF, S., LIVERMORE, R.A., DEVEY, C.W., LEAT, P.T. & STOFFERS, P. 2002. Petrogenesis of the back-arc East Scotia Ridge, South Atlantic Ocean. *Journal of Petrology*, **43**, 1435–1467.

FRYER, P. 1996. Evolution of the Mariana convergent plate margin system. *Reviews of Geophysics*, **34**, 89–125.

GAMBLE, J., WOODHEAD, J., WRIGHT, I. & SMITH, I. 1996. Basalt and sediment geochemistry and magma petrogenesis in a transect from oceanic island arc to rifted continental margin arc: the Kermadec–Hikurangi margin, SW Pacific. *Journal of Petrology*, **37**, 1523–1546.

GERMAN, C.R., LIVERMORE, R.A., BAKER, E.T., BRUGUIER, N.I., CONNELLY, D.P., CUNNINGHAM, A.P., MORRIS, P., ROUSE, I.P., STRATHAM, P.J. & TYLER, P.A. 2000. Hydrothermal plumes above the East Scotia Ridge: an isolated high-latitude back-arc spreading centre. *Earth and Planetary Science Letters*, **184**, 241–250.

GILL, J.B. 1981. *Orogenic Andesites and Plate Tectonics*. Springer, New York.

GRIBBLE, R.F., STERN, R.J., NEWMAN, S., BLOOMER, S.H. & O'HEARN, T. 1998. Chemical and isotopic composition of lavas from the northern Mariana Trough: implications for magmagenesis in back-arc basins. *Journal of Petrology*, **39**, 125–154.

HALL, R., NICHOLS, G., BALLANTYNE, P., CHARLTON, T. & ALI, J. 1991. The character and significance of basement rocks of the southern Molucca Sea region. *Journal of Southeast Asian Earth Sciences*, **6**, 249–258.

HARRISON, D., LEAT, P.T., BURNARD, P.G., TURNER, C., FRETZDORFF, S. & MILLAR, I.L. 2003. Resolving mantle components in oceanic lavas from segment E2 of the East Scotia back-arc ridge, South Sandwich Islands. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 333–344.

HART, S.R. 1988. Heterogeneous mantle domains: signatures, genesis and mixing chronologies. *Earth and Planetary Science Letters*, **90**, 273–296.

HAWKESWORTH, C.J., GALLAGHER, K., HERGT, J.M. & MCDERMOTT, F. 1994. Destructive plate margin magmatism: geochemistry and melt generation. *Lithos*, **33**, 169–188.

HAWKESWORTH, C.J., TURNER, S.P., MCDERMOTT, F., PEATE, D.W. & VAN CALSTEREN, P. 1997. U–Th isotopes in arc magmas: implications for element transfer from the subducted crust. *Science*, **276**, 551–555.

HEATH, E., MACDONALD, R., BELKIN, H., HAWKESWORTH, C. & SIGURDSSON, H. 1998. Magmagenesis at Soufriere Volcano, St Vincent, Lesser Antilles. *Journal of Petrology*, **39**, 1721–1764.

HICKEY-VARGAS, R. 1989. Boninites and tholeiites from DSDP Site 458, Mariana forearc. *In*: CRAWFORD, A.J. (ed.) *Boninites*. Unwin Hyman, London, 339–356.

HOFMANN, A.W. & WHITE, W.M. 1982. Mantle plumes from ancient oceanic crust. *Earth and Planetary Science Letters*, **57**, 421–436.

HOLBROOK, W.S., LIZARRALDE, D., MCGEARY, S., BANGS, N. & DIEBOLD, J. 1999. Structure and composition of the Aleutian island arc and implications for continental crustal growth. *Geology*, **27**, 31–34.

IIZASA, K., FISKE, R.S., ISHIZUKA, O., YUASA, M., HASHIMOTO, J., ISHIBASHI, J., NAKA, J., HORII, Y., FUJIWARA, Y., IMAI, A. & KOYAMA, S. 1999. A Kuroko-type polymetallic sulfide deposit in a submarine caldera. *Science*, **283**, 975–977.

ISHIBASHI, J. & URABE, T. 1995. Hydrothermal activity related to arc–backarc magmatism in the Western Pacific. *In*: TAYLOR, B. (ed.) *Backarc Basins: Tectonics and Magmatism*. Plenum Press, New York, 451–495.

ISHIZUKA, O., UTO, K. & YUASA, M. 2003. Volcanic history of the back-arc region of the Izu–Bonin (Ogasawara) arc. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 187–205.

JOHNSON, M.C. & PLANK, T. 1999. Dehydration and melting experiments constrain the fate of subducted sediments. *Geochemistry Geophysics Geosystems*, **1**, 1999GC000014.

JULL, M. & KELEMEN, P.B. 2001. On the conditions for lower crustal convective instability. *Journal of Geophysical Research*, **106**, 6423–6446.

KAMENETSKY, V.S., BINNS, R.A., GEMMELL, J.B., CRAWFORD, A.J., MERNAGH, T.P., MAAS, R. & STEELE, D. 2001. Parental basaltic melts and fluids in eastern Manus backarc basin: implications for hydrothermal mineralisation. *Earth and Planetary Science Letters*, **184**, 685–702.

KAWATE, S. & ARIMA, M. 1998. Petrogenesis of the Tanzawa plutonic complex, central Japan: exposed felsic middle crust of the Izu–Bonin–Mariana arc. *The Island Arc*, **7**, 342–358.

LARTER, R.D., CUNNINGHAM, A.P., BARKER, P.F., GOHL, K. & NITSCHE, F.O. 2002. Tectonic evolution of the Pacific margin of Antarctica 1. Late Cretaceous tectonic reconstructions. *Journal of Geophysical Research,* **107** (B12), EPMS, 1–19, 2345, 10.1029/2000JB000052.

LARTER, R.D., VANNESTE, L.E. & BRUGUIER, N.J. 2001. Structure, composition and evolution of the South Sandwich island arc: implications for rates of arc magmatic growth and subduction erosion. *Eos, Transactions, American Geophysical Union,* **82**(47), Fall Meeting Supplement, T32D-10.

LARTER, R.D., VANNESTE, L.E., MORRIS, P. & SMYTHE, D.K. 2003. Structure and tectonic evolution of the South Sandwich arc. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 255–284.

LEAT, P.T., LIVERMORE, R.A., MILLAR, I.L. & PEARCE, J.A. 2000. Magma supply in back-arc spreading centre segment E2, East Scotia Ridge. *Journal of Petrology*, **41**, 845–866.

LEAT, P.T., RILEY, T.R., WAREHAM, C.D., MILLAR, I.L., KELLEY, S.P. & STOREY, B.C. 2002. Tectonic setting of primitive magmas in volcanic arcs: an example from the Antarctic Peninsula. *Journal of the Geological Society, London*, **159**, 31–44.

LEAT, P.T., SMELLIE, J.L., MILLAR, I.L. & LARTER, R.D. 2003. Magmatism in the South Sandwich arc. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 285–313.

LIVERMORE, R.A. 2003. Back-arc spreading and mantle flow in the east Scotia Sea. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 315–331.

LIVERMORE, R.A. & WOOLLETT, R.W. 1993. Seafloor spreading in the Weddell Sea and southwest Atlantic since the Late Cretaceous. *Earth and Planetary Science Letters*, **117**, 475–495.

LIVERMORE, R., CUNNINGHAM, A., VANNESTE, L. & LARTER, R. 1997. Subduction influence on magma supply at the east Scotia Ridge. *Earth and Planetary Science Letters*, **150**, 261–275.

LIVERMORE, R., MCADOO, D. & MARKS, K. 1994. Scotia Sea tectonics from high-resolution satellite gravity. *Earth and Planetary Science Letters*, **123**, 255–268.

LLOYD, E.F., NATHAN, S., SMITH, I.E.M. & STEWART, R.B. 1996. Volcanic history of Macauley Island, Kermadec Ridge, New Zealand. *New Zealand Journal of Geology and Geophysics,* **39**, 295–308.

LONSDALE, P. 1988. Paleogene history of the Kula plate – offshore evidence and onshore implications. *Geological Society of America Bulletin*, **100**, 733–754.

MACDONALD, R., HAWKESWORTH, C.J. & HEATH, E. 2000. The Lesser Antilles volcanic chain: a study in arc magmatism. *Earth Science Reviews,* **49,** 1–76.

MACPHERSON, C.G. & HALL, R. 2001. Tectonic setting of Eocene boninitic magmatism in the Izu-Bonin–Mariana forearc. *Earth and Planetary Science Letters*, **186**, 215–230.

MACPHERSON, C.G., FORDE, E.J., HALL, R. & THIRLWALL, M.F. 2003. Geochemical evolution of magmatism in an arc-arc collision: the Halmahera and Sangihe arcs, eastern Indonesia. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 207–220.

MADSEN, J.A. & LINDLEY, I.D. 1994. Large-scale structures on Gazelle Peninsula, New Britain: implications for the evolution of the New Britain arc. *Australian Journal of Earth Sciences*, **41**, 561–569.

MAILLET, P., RUELLAN, E., GÉRARD, M., PERSON, A., BELLON, H., COTTEN, J., JORON, J.-L., NAKADA, S. & PRICE, R.C. 1995. Tectonics, magmatism, and evolution of the New Hebrides backarc troughs (Southwest Pacific). *In*: TAYLOR, B. (ed.) *Backarc Basins: Tectonics and Magmatism*. Plenum Press, New York, 177–235.

MANN, P., TAYLOR, F.W., LAGOE, M.B., QUARLES, A. & BURR, G. 1998. Accelerating late Quaternary uplift of the New Georgia island group (Solomon island arc) in response to subduction of the recently active Woodlark spreading center and Coleman Seamount. *Tectonophysics*, **295,** 259–306.

MARTINEZ, F. & TAYLOR, B. 2002. Mantle wedge control on back-arc crustal accretion *Nature*, **416**, 417–420.

MARTINEZ, F. & TAYLOR, B. 2003. Controls on back-arc crustal accretion: insights from the Lau, Manus and Mariana basins. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 19–54.

MARTINEZ, F., FRYER, P., BAKER, N.A. & YAMAZAKI, T. 1995. Evolution of backarc rifting: Mariana Trough, 20°–24°N. *Journal of Geophysical Research*, **100**, 3807–3827.

MASSOTH, G.J., DE RONDE, C.E.J., LUPTON, J.E., FEELY, R.A., BAKER, E.T., LEBON, G.T. & MAENNER, S.M. 2003. Chemically rich and diverse submarine hydrothermal plumes of the southern Kermadec volcanic arc (New Zealand). *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 119–139.

MILLER, D.J. & CHRISTENSEN, N.I. 1994. Seismic signature and geochemistry of an island arc: a multidisciplinary study of the Kohistan accreted terrane, northern Pakistan. *Journal of Geophysical Research*, **99**, 11 623–11 642.

MONZIER, M., ROBIN, C. & EISSEN, J.-P. 1994. Kuwae (≈1425 A. D.): the forgotten caldera. *Journal of Volcanology and Geothermal Research*, **59**, 207–218.

MORRIS, J.D., LEEMAN, W.P. & TERA, F. 1990. The subducted component in island arc lavas: constraints from Be isotopes and B–Be systematics. *Nature*, **344**, 31–36.

NAKAJIMA, K & ARIMA, M. 1998. Melting experiments on hydrous low-K tholeiite: implications for the genesis of tonalitic crust in the Izu–Bonin–Mariana arc. *The Island Arc*, **7**, 359–373.

NAKANISHI, M., TAMAKI, K. & KOBAYASHI, K. 1989. Mesozoic magnetic anomaly lineations and seafloor spreading history of the northwest Pacific. *Journal of Geophysical Research*, **94**, 15 437–15 462.

NINKOVICH, D., HEEZEN, B.C., CONOLLY, J.R. & BURCKLE, L.H. 1964. South Sandwich tephra in deep-sea sediments. *Deep Sea Research*, **11**, 605–619.

PEARCE, J.A. 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. *In*: HAWKESWORTH, C.J. & NORRY, M.J. (eds) *Continental Basalts and Mantle Xenoliths*. Shiva, Nantwich, 230–249.

PEARCE, J.A. & PEATE, D.W. 1995. Tectonic implications of the composition of volcanic arc magmas. *Annual Reviews of Earth and Planetary Science*, **23**, 251–285.

PEARCE, J.A., BAKER, P.E., HARVEY, P.K. & LUFF, I.W. 1995. Geochemical evidence for subduction fluxes, mantle melting and fractional crystallization beneath the South Sandwich arc. *Journal of Petrology*, **36**, 1073–1109.

PEARCE, J.A., ERNEWEIN, M., BLOOMER, S.H., PARSON, L.M., MURTON, B.J. & JOHNSON, L.E. 1994. Geochemistry of Lau Basin volcanic rocks: influence of ridge segmentation and arc proximity. *In*: SMELLIE, J.L. (ed.) *Volcanism Associated with Extension at Consuming Plate Margins*. Geological Society, London, Special Publications, **81**, 53–75.

PEARCY, L.G., DEBARI, S.M. & SLEEP, N.H. 1990. Mass balance calculations for two sections of island arc crust and implications for the formation of continents. *Earth and Planetary Science Letters*, **96**, 427–442.

PEATE, D.W. & PEARCE, J.A. 1998. Causes of spatial compositional variations in Mariana arc lavas: trace element evidence. *The Island Arc*, **7**, 479–495.

PEATE, D.W., KOKFELT, T.F., HAWKESWORTH, C.J., VAN CALSTEREN, P.W., HERGT, J.M. & PEARCE, J.A. 2001. U-series isotope data on Lau Basin glasses: the role of subduction-related fluids during melt generation in back-arc basins. *Journal of Petrology*, **42**, 1449–1470.

PELLETIER, B., CALMANT, S. & PILLET, R. 1998. Current tectonics of the Tonga–New Hebrides region. *Earth and Planetary Science Letters*, **164**, 263–276.

PEREZ, O.J., BILHAM, R., BENDICK, R., VELANDIA, J.R., HERNANDEZ, N., MONCAYO, C., HOYER, M. & KOZUCH, M. 2001. Velocity field across the southern Caribbean plate boundary and estimates of Caribbean/South American plate motion using GPS geodesy 1994–2000. *Geophysical Research Letters*, **28**, 2987–2990.

PETTERSON, M.G., BABBS, T., NEAL, C.R., MAHONEY, J.J., SAUNDERS, A.D., DUNCAN, R.A., TOLIA, D., MAGU, R., QOPOTO, C., MAHOA, H. & NATOGGA, D. 1999. Geological–tectonic framework of Solomon Islands, SW Pacific: crustal accretion and growth within an intra-oceanic setting. *Tectonophysics*, **301**, 35–60.

PICHAVANT, & MACDONALD, R. 2003. Mantle genesis and crustal evolution of primitive calc-alkaline basaltic liquids from the Lesser Antilles arc. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 239–254.

PLANK, T. & LANGMUIR, C.H. 1993. Tracing trace elements from sediment input to volcanic output at subduction zones. *Nature*, **362**, 739–743.

RAMSAY, W.R.H., CRAWFORD, A.J. & FODEN, J.D. 1984. Field setting, mineralogy, chemistry, and genesis of arc picrites, New Georgia, Solomon Islands. *Contributions to Mineralogy and Petrology*, **88**, 386–402.

RAPP, R.P. & WATSON, E.B. 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust–mantle recycling. *Journal of Petrology*, **36**, 891–931.

ROBIN, C., EISSEN, J.-P. & MONZIER, M. 1993. Giant tuff cone and 12 km-wide associated caldera at Ambrym Volcano (Vanuatu, New Hebrides arc). *Journal of Volcanology and Geothermal Research*, **55**, 225–238.

RUDNICK, R.L. 1995. Making continental crust. *Nature*, **378**, 571–578.

RYAN, J.G., MORRIS, J., TERA, F., LEEMAN, W.P. & TSVETKOV, A. 1995. Cross-arc geochemical variations in the Kurile arc as a function of slab depth. *Science*, **270**, 625–627.

SANDWELL, D.T. & SMITH, W.H.F. 1997. Marine gravity anomaly from Geosat and ERS 1 satellite altimetry. *Journal of Geophysical Research*, **102**, 10 039–10 954.

SAUNDERS, A.D. & TARNEY, J. 1984. Geochemical characteristics of basaltic volcanism within back-arc basins. *In*: KOKELAAR, B.P. & HOWELLS, M.F. (eds) *Marginal Basin Geology*. Geological Society, London, Special Publications, **16**, 59–76.

SENO, T., STEIN, S. & GRIPP, A.E. 1993. A model for the motion of the Philipine Sea plate consistent with NUVEL-1 and geological data. *Journal of Geophysical Research*, **98**, 17 941–17 948.

SHIPBOARD SCIENTIFIC PARTY 2000. Leg 185 summary: inputs to the Izu–Mariana subduction system. *In*: PLANK, T., LUDDEN, J.N., ESCUTIA, C. *et al. Proceedings of the Ocean Drilling Program, Initial Reports*, **185**, 1–63.

SINTON, J.M., FORD, L.F., CHAPPELL, B. & MCCULLOCH, M.T. 2003. Magma genesis and mantle heterogeneity in the Manus back-arc basin, Papua New Guinea. *Journal of Petrology*, **44**, 159–195.

SMELLIE, J.L., MORRIS, P., LEAT, P.T., TURNER, D.B. & HOUGHTON, D. 1998. Submarine caldera and other volcanic observations in Southern Thule, South Sandwich Islands. *Antarctic Science*, **10**, 171–172.

SMITH, G.P., WIENS, D.A., FISHER, K.M., DORMAN, L.M., WEBB, S.C. & HILDEBRAND, J.A. 2001. A complex pattern of mantle flow in the Lau backarc. *Science*, **292**, 713–716.

SMITH, I.E.M., WORTHINGTON, T.J., PRICE, R.C. & GAMBLE, J.A. 1997. Primitive magmas in arc-type volcanic associations: examples from the southwest Pacific. *The Canadian Mineralogist*, **35**, 257–273.

SMITH, I.E.M., WORTHINGTON, T.J., STEWART, R.B., PRICE, R.C. & GAMBLE, J.A. 2003. Felsic volcanism in the Kermadec arc, SW Pacific: crustal recycling in an oceanic setting. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 99–118.

SPEED, R.C. & WALKER, J.A. 1991. Oceanic crust of the Grenada Basin in the southern Lesser Antilles arc platform. *Journal of Geophysical Research*, **96**, 3835–3851.

STERN, R.J. & SMOOT, N.C. 1998. A bathymetric overview of the Mariana forearc. *The Island Arc*, **7**, 525–540.

STOLPER, E. & NEWMAN, S. 1994. The role of water in the petrogenesis of Mariana trough magmas. *Earth and Planetary Science Letters*, **121**, 293–325.

STRAUB, S.M. 1995. Contrasting compositions of Mariana Trough fallout tephra and Mariana Island arc volcanics: a fractional crystallization link. *Bulletin of Volcanology*, **57**, 403–421.

STÜBEN, D., BLOOMER, S.H., TAÏBI, N.E., NEUMANN, T., BENDEL, V., PÜSCEL, U., BARONE, A., LANGE, A., SHIYING, WU, CUIZHONG, LI & DEYU, Z. 1992. First results of study of sulphur-rich hydrothermal activity from and island-arc environment: Esmeralda Bank in the Mariana arc. *Marine Geology*, **103**, 521–528.

SUYEHIRO, K., TAKAHASHI, N., ARIIE, Y., YOKOI, Y., HINO, R., SHINOHARA, M., KANAZAWA, T., HIRATA, N., TOKUYAMA, H. & TAIRA, A. 1996. Continental crust, crustal underplating, and low-Q upper mantle beneath an ocean island arc. *Science*, **272**, 390–392.

TAMURA, Y. 2003. Some geochemical constraints on hot fingers in the mantle wedge: evidence from NE Japan. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 221–237.

TAMURA, Y. & TATSUMI, Y. 2002. Remelting of an andesitic crust as a possible origin for rhyolitic magma in oceanic arcs: an example from the Izu–Bonin arc. *Journal of Petrology*, **43**, 1029–1047.

TAMURA, Y., TATSUMI, Y., ZHAO, D., KIDO, Y. & SHUKUNO, H. 2002. Hot fingers in the mantle wedge: new insights into magma genesis in subduction zones. *Earth and Planetary Science Letters*, **197**, 105–116.

TARNEY, J., PICKERING, K.T., KNIPE, R.J. & DEWEY, J.F. (eds). 1991. *The Behaviour and Influence of Fluids in Subduction Zones*. Royal Society, London. (*Philiosophical Transactions of the Royal Society of London, Series A*, **335**, 225–418.)

TATSUMI, Y. 1989. Migration of fluid phases and genesis of basalt magmas in subduction zones. *Journal of Geophysical Research*, **94**, 4697–4707.

TATSUMI, Y. & EGGINS, S. 1995. *Subduction Zone Magmatism*. Blackwell Science, Cambridge, MA.

TATSUMI, T. & KOGISO, T. 2003. The subduction factory: its role in the evolution of the Earth's crust and mantle. *In*: LARTER, R.D. & LEAT, P.T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 55–80.

TAYLOR, B. 1992. Rifting and the volcanic-tectonic evolution of the Izu-Bonin–Mariana arc. *In*: TAYLOR, B., FUJIOKA, K. *et al. Proceedings of the Ocean Drilling Program, Scientific Results*, **126**, 627–651.

TAYLOR, B. (ed.). 1995. *Backarc Basins: Tectonics and Magmatism*. Plenum, New York.

TAYLOR, B. & EXON, N.F. 1987. An investigation of ridge subduction in the Woodlark–Solomons region: introduction and overview. *In*: TAYLOR, B. & EXON, N.F. (eds) *Marine Geology, Geophysics, and Geochemistry of the Woodlark Basin–Solomon Islands*. Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, **7**, 24–235.

TAYLOR, B. & NATLAND, J. (eds). 1995. *Active Margins and Marginal Basins of the Western Pacific*. American Geophysical Union Monographs, **88**.

TAYLOR, B., BROWN, G., GILL, J.B., HOCHSTAEDTER, A.G., HOTTA, H., LANGMUIR, C.H., LEINEN, M., NISHIMURA, A. & URABE, T. 1990. ALVIN-SeaBeam studies of the Sumisu rift, Izu–Bonin arc. *Earth and Planetary Science Letters*, **100**, 127–147.

TAYLOR, F.W., BEVIS, M.G., SCHUTZ, B.E., KUANG, D., RECY, J., CALMANT, S., CHARLEY, D., REGNIER, M., PERIN, B., JACKSON, M. & REICHENFELD, C. 1995. Geodetic measurements of convergence at the New Hebrides island arc indicate arc fragmentation caused by an impinging aseismic ridge. *Geology*, **23**, 1011–1014.

TAYLOR, R.N., NESBITT, R.W., VIDAL, P., HARMON, R.S., AUVRAY, B. & CROUDACE, I.W. 1994. Mineralogy, chemistry and genesis of the boninite series volcanics, Chichijima, Bonin Islands, Japan. *Journal of Petrology*, **35**, 577–617.

TAYLOR, S.R. & MCLENNAN, S.M. 1985. *The Continental Crust: its Composition and Evolution*. Blackwell Scientific, Oxford.

TAYLOR, S.R. & MCLENNAN, S.M. 1995. The chemical evolution of the continental crust. *Reviews of Geophysics*, **33**, 241–265.

THOMAS, C., LIVERMORE, R.A. & POLLITZ, F.F. 2003. Motion of the Scotia Sea plates. *Geophysical Journal International*, in press.

THORPE, R.S. (ed.). 1982. *Andesites: Orogenic Andesites and Related Rocks*. John Wiley, Chichester.

TREGONING, P. 2002. Plate kinematics in the western Pacific derived from geodetic observations. *Journal of Geophysical Research*, **107**(B1), 2020, DOI: 10.1029/2001JB000406.

TREGONING, P., LAMBECK, K., STOLZ, A., MORGAN, P., MCCLUSKY, S.C., VAN DER BEEK, P., MCQUEEN, H., JACKSON, R.J., LITTLE, R.P., LAING, A. & MURPHY, B. 1998. Estimation of current plate motions in Papua New Guinea from Global Positioning System observations. *Journal of Geophysical Research*, **103**, 12 181–12 203.

TSUNOGAI, U., ISHIBASHI, J., WAKITA, H., GAMO, T., WATANABE, K., KAJIMURA, T., KANAYAMA, S. & SAKI, H. 1994. Peculiar features of Suiyo Seamount hydrothermal fluids, Izu-Bonin arc: differences from subaerial volcanism. *Earth and Planetary Science Letters*, **126**, 289–301.

TURNER, S. & HAWKESWORTH, C. 1997. Constraints on flux rates and mantle dynamics beneath island arcs from Tonga-Kermadec lava geochemistry. *Nature*, **389**, 568–573.

TURNER, S. & HAWKESWORTH, C. 1998. Using geochemistry to map mantle flow beneath the Lau Basin. *Geology*, **26**, 1019–1022.

TURNER, S., HAWKESWORTH, C., VAN CALSTEREN, P., HEATH, E., MACDONALD, R. & BLACK, S. 1996. U-series isotopes and destructive plate margin magma genesis in the Lesser Antilles. *Earth and Planetary Science Letters*, **142**, 191–207.

TURNER, S., MCDERMOTT, F., HAWKESWORTH, C. & KEPEZHINSKAS, P. 1998. A U-series study of lavas from Kamchatka and the Aleutians: constraints on source composition and melting process. *Contributions to Mineralogy and Petrology*, **133**, 217–234.

VAN SOEST, M.C., HILTON, D.R., MACPHERSON, C.G. & MATTEY, D.P. 2002. Resolving sediment subduction and crustal contamination in the Lesser Antilles island arc: a combined He–O–Sr isotope approach. *Journal of Petrology*, **43**, 143–170.

VANNESTE, L. & LARTER, R.D. 2002. Sediment subduction, subduction erosion and strain regime in the northern South Sandwich forearc. *Journal of Geophysical Research*, **107** (B7), EMPS, 1–24, 2149, 10.1029/2001JB000396.

VANNESTE, L.E., LARTER, R.D. & SMYTHE, D.K. 2002. A slice of intraoceanic arc: insights from the first multichannel seismic reflection profile across the South Sandwich arc. *Geology*, **30**, 819–822.

VON HUENE, R. & SCHOLL, D.W. 1991. Observations at convergent margins concerning sediment subduction, subduction erosion, and growth of the continental crust. *Reviews of Geophysics*, **29**, 279–316.

WEBER, J.C., DIXON, T.H., DEMETS, C., AMBEH, W.B., JANSMA, P., MATTIOLI, G., SALEH, J., SELLA, G., BILHAM, R. & PEREZ, O. 2001. GPS estimate of relative motion between the Caribbean and South American plates, and geologic implications for Trinidad and Venezuela. *Geology*, **29**, 75–78.

WESTBROOK, G.K., LADD, J.W., BUHL, P., BANGS, N. & TILEY, G.J. 1988. Cross section of an accretionary wedge: Barbados Ridge complex. *Geology*, **16**, 631–635.

WESTBROOK, G.K., MASCLE, A. & BIJU-DUVAL, B. 1984. Geophysics and the structure of the Lesser Antilles forearc. *In*: BIJU-DUVAL, B., MOORE, J.C. *et al. Initial Reports of the Deep Sea Drilling Project*, **78A**, 23–38.

WINDER, R.O. & PEACOCK, S.M. 2001. Viscous forces acting on subducting lithosphere. *Journal of Geophysical Research*, **106**, 21 937–21 951.

WILSON, M. 1989. *Igneous Petrogenesis*. Unwin Hyman, London.

WOODHEAD, J.D. 1988. The origin of geochemical variations in Mariana lavas: a general model for petrogenesis in intraoceanic island arcs? *Journal of Petrology*, **29**, 805–830.

WOODHEAD, J., EGGINS, S. & GAMBLE, J. 1993. High field strength and transition element systematics in island arc and back-arc basin basalts: evidence for multi-phase melt extraction and a depleted mantle wedge. *Earth and Planetary Science Letters*, **114**, 491–504.

WOODHEAD, J.D., EGGINS, S.M. & JOHNSON, R.W. 1998. Magma genesis in the New Britain island arc: further insights into melting and mass transfer processes. *Journal of Petrology*, **39**, 1641–1668.

WORTHINGTON, T.J., GREGORY, M.R. & BONDARENKO, V. 1999. The Denham caldera on Raoul Volcano: dacitic volcanism in the Tonga–Kermadec arc. *Journal of Volcanology and Geothermal Research*, **90**, 29–48.

WRIGHT, I.C. & GAMBLE, J.A. 1999. Southern Kermadec submarine caldera arc volcanoes (SW Pacific); caldera formation by effusive and pyroclastic eruption. *Marine Geology*, **161**, 207–227.

ZHAO, D., HASEGAWA, A. & HORIUCHI, S. 1992. Tomographic imaging of P and S wave velocity structure beneath northeastern Japan. *Journal of Geophysical Research*, **97**, 19 909–19 928.

ZHAO, D., XU, Y., WIENS, D.A., DORMAN, L., HILDEBRAND, J. & WEBB, S. 1997. Depth extent of the Lau back-arc spreading center and its relation to subduction processes. *Science*, **278**, 254–257.