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# Silicic magmas of Protector Shoal, South Sandwich arc: indicators of generation of primitive continental crust in an island arc

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**Abstract –** Protector Shoal, the northernmost and most silicic volcano of the South Sandwich arc, erupted dacite–rhyolite pumice in 1962. We report geochemical data for a new suite of samples dredged from the volcano. Geochemically, the dredge and 1962 samples form four distinct magma groups that cannot have been related to each other, and are unlikely to have been related to a single basaltic parent, by fractional crystallization. Instead, the silicic rocks are more likely to have been generated by partial melting of basaltic lower crust within the arc. Trace element and Sr–Nd isotope data indicate that the silicic volcanics have compositions that are more similar to the volcanic arc than the oceanic basement formed at a back-arc spreading centre, and volcanic arc basalts are considered to be the likely source for the silicic magmas. The South Sandwich Islands are one of several intra-oceanic arcs (Tonga–Kermadec, Izu–Bonin) that have: (1) significant amounts of compositionally bimodal mafic–silicic volcanic products and (2) 6.0–6.5 km $s^{-1}$ *P*-wave velocity layers in their mid-crusts that have been imaged by wide-angle seismic surveys and interpreted as intermediate-silicic plutons. Geochemical and volume considerations indicate that both the silicic volcanics and plutonic layers were generated by partial melting of basaltic arc crust, representing an early stage in the fractionation of oceanic basalt to form continental crust.

Keywords: geochemistry, island arcs, pumice, South Atlantic, submarine volcanoes.

## 1. Introduction

The separation of continental crust from the mantle is one of the most fundamental processes in Earth evolution, yet it is still incompletely understood. The key to the process is the generation of large volumes of silicic magmas (e.g. rhyolites, dacites, andesites) from basaltic parents. Most such silicic magmas are generated within the framework of already-existing continental material, and their origin has been extensively investigated in this continental setting. There is increasing evidence that the voluminous post-Archaean tonalite–granodiorite batholiths characteristic of active continental margins were formed mainly by a process of partial melting of basaltic crust. The evidence for this has accumulated from experiments (Rushmer, 1991; Rapp & Watson, 1995; Beard, 1995; Nakajima & Arima, 1998), geochemical studies (Atherton & Petford, 1993; Muir *et al.* 1995; Millar *et al.* 2001; Kawate & Arima, 1998) and modelling (Petford & Gallagher, 2001; Annen & Sparks, 2002; Jackson *et al.* 2005). Experiments have indicated that the tonalitic–granodioritic (basaltic andesite–dacite) magmas can be formed by fluid-absent partial melting of hydrous, amphibolitic, lower crustal basaltic lithologies, generating 25–40 % partial melts at *c.* 1050–1100 °C and at a range of crustal pressures (Rushmer, 1991; Rapp & Watson, 1995). Such temperatures suggest that the lower crust source rocks are heated by addition of basaltic magmas, consistent with the active margin setting of most tonalite–granodiorite batholiths (Petford & Gallagher, 2001; Annen & Sparks, 2002).

Such partial melting of basaltic crust to form silicic magmas, as seen in the generation of continental margin tonalite–granodiorite suites, is thought to be a critical part of the process of generation of continental crust of andesitic bulk composition (Weaver & Tarney, 1984; Rudnick, 1995) from basalt (the composition of magma flux across the Moho). Other factors are supra-subduction environments and possible recycling of the mafic residue of the partial melting of basalt into the mantle (Arndt & Goldstein, 1989; Pearcy, DeBari & Sleep, 1990). While the generation of silicic batholiths by a process of partial melting of basaltic crust is widely accepted in the case of continental margin arcs, silicic magmas in intra-oceanic arcs have been thought by most workers to have formed by a process of fractional crystallization from basaltic parent magmas (e.g. Ewart, Bryan & Gill, 1973; Woodhead, 1988; Pearce *et al.* 1995). Intra-oceanic arcs are volumetrically dominated by basaltic volcanic products. However, there is increasing recognition that locally abundant silicic magmas are a widespread feature of intra-oceanic arcs, often forming compositionally bimodal mafic–silicic suites, and often associated with calderas, implying generation of significant volumes of the silicic magmas over short timescales (Lloyd *et al.* 1996; Smellie *et al.*

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1998; Worthington, Gregory & Bondarenko, 1999; Wright & Gamble, 1999; Tamura & Tatsumi, 2002; Leat *et al.* 2003; Smith, Stewart & Price, 2003; Smith *et al.* 2003; Wright, Worthington & Gamble, 2006). Plutonic intermediate-silicic rocks locally form significant volumes within intra-oceanic arcs. They are known mostly from seismic experiments, which image silicic plutons as *c.* 6.0–6.5 km $s^{-1}$ ($P$-wave) mid-crustal layers, identified in the Izu–Bonin (Suyehiro *et al.* 1996; Takahashi, Suyehiro & Shinohara, 1998), Tonga (Crawford *et al.* 2003), Aleutian (Fliedner & Klemperer, 1999), South Sandwich (Leat *et al.* 2003), and probably the Lesser Antilles (Boynton *et al.* 1979) arcs.

Similar temperatures presumably exist in the lower crusts of both oceanic and continental arcs, and similar hydrous mafic lower crust, the sources for silicic–intermediate partial melts, probably exists in both. It is therefore likely that, if partial melting of hydrous basalt occurs within continental arcs, it also occurs in intra-oceanic arcs. At least some silicic magmas of intra-oceanic arcs thus probably formed by partial melting of basaltic lower crust. This paper examines the origin of a suite of silicic volcanic rocks from the South Sandwich intra-oceanic arc.

## 2. The South Sandwich arc

The South Sandwich arc, South Atlantic, is a tectonically primitive intra-oceanic island arc situated on the small Sandwich plate, below which the South American plate is subducting (Fig. 1). The arc is built on oceanic crust formed at the back-arc spreading centre at *c.* 8–10 Ma (Larter *et al.* 2003). The arc is remote from pre-existing continental crust, there is no significant influx of continent-derived sediment to the arc–trench system, and virtually all of the relatively thin sediment cover on the subducting plate is subducted (Barker, 1995; Larter *et al.* 1998; Vanneste & Larter, 2002). The only evidence of crust pre-dating the *c.* 10 Ma age of the oceanic basement is the existence of a fragment of presumed volcanic arc terrane in the southern fore-arc, that has yielded K–Ar ages of 28.5–32.8 Ma (Barker, 1995). The arc therefore has an exceptionally simple structure, and the present arc crust can be assumed to have developed on pre-existing oceanic plate during the last 10 My. Seismic and gravity data suggest that the arc crust is 16–20 km thick (Larter *et al.* 2003), at the thin end of the range for island arcs.

The arc consists of seven main volcanic islands, and a number of smaller volcanic islands and seamounts. The main volcanoes rise some 3 km from the sea floor and their effusive products are dominated by basalts (Baker, 1968, 1978; Holdgate & Baker, 1979; Pearce *et al.* 1995; Leat *et al.* 2003). The volcanic rocks are divided into three main series: with increasing incompatible trace elements contents, low-K tholeiitic, tholeiitic and calc-alkaline (Pearce *et al.* 1995; Leat *et al.* 2003). In addition to the dominant basalts and basaltic andesites (<57 wt % $SiO_2$), silicic rocks are reported to occur in the main volcanic arc at, from north to south: Protector Shoal (dacites and rhyolites); Visokoi Island (andesite); Candlemas Island (andesites and dacites); Bristol Island (including Freezland Rock) (andesite); Southern Thule (Cook, Thule and Bellingshausen islands) (andesites and dacites) (Baker, 1978, 1990; Pearce *et al.* 1995; Leat *et al.* 2003). In addition, andesites occur on the rear-arc Leskov Island (Baker, 1990; Pearce *et al.* 1995) and dacites on Nelson Seamount, whose unusual compositions have been linked to melting of subducting sediment (Leat *et al.* 2004). In this paper we describe the silicic volcanic rocks of Protector Shoal and compare these with the other volumetrically significant occurrences of silicic rocks in the main part of the arc (Leat *et al.* 2003).

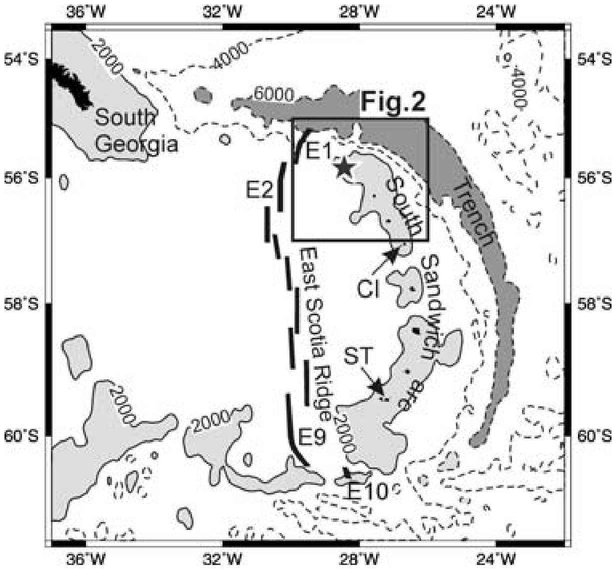

Figure 1. Bathymetric sketch map of the South Sandwich arc, showing the location of Protector Shoal (star) and Figure 2. Bathymetric contours are at 2000 m intervals, with the 2000 m contour as a solid line, and the 4000 and 6000 m contours as dashed lines. E1–E10 are segments of the back-arc East Scotia Ridge spreading centre. CI – Candlemas Island; ST – Southern Thule island group.

## 3. Protector Shoal

Protector Shoal (Gass, Harris & Holdgate, 1963; Holdgate & Baker, 1979; Baker, 1990) is the northernmost known volcanic edifice of the South Sandwich arc, being situated 50 km northwest of Zavodovski Island, the northernmost island of the arc. It is entirely submerged and, according the Admiralty chart (Hydrographic Office, 1989), rises to within 27 m of sea level. The map of predicted bathymetry derived from satellite altimetry (Sandwell & Smith, 1997) shows that this summit of the Shoal is situated at the western end of an E–W-trending ridge (27°30′ to

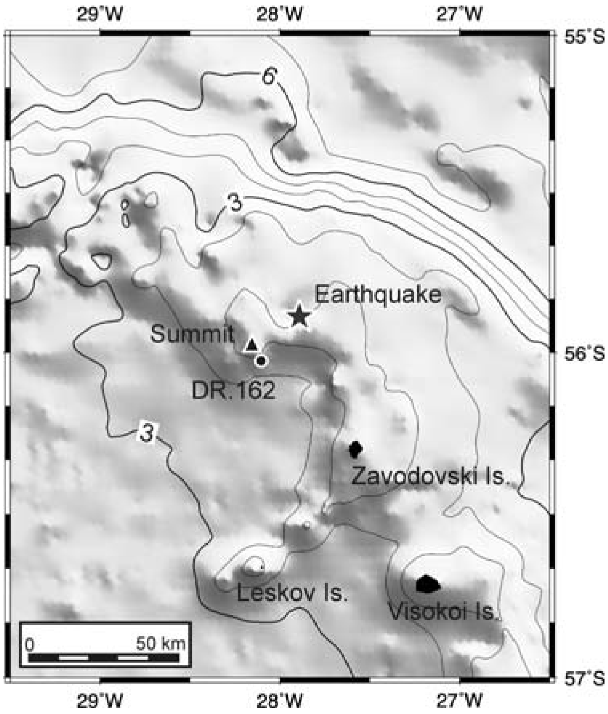

Figure 2. Shaded relief showing predicted bathymetry of Protector Shoal area from satellite altimetry (Sandwell & Smith, 1997). Zavodovski and Visokoi islands are volcanoes of the main volcanic front, and Leskov Island is in a rear-arc position. The topographic summit of Protector Shoal is shown by the triangle. The epicentre of the 10.15 UT earthquake of 14 March 1962 is shown by the star. The contour interval is 3 km, with relief highlighted by light from the northeast.

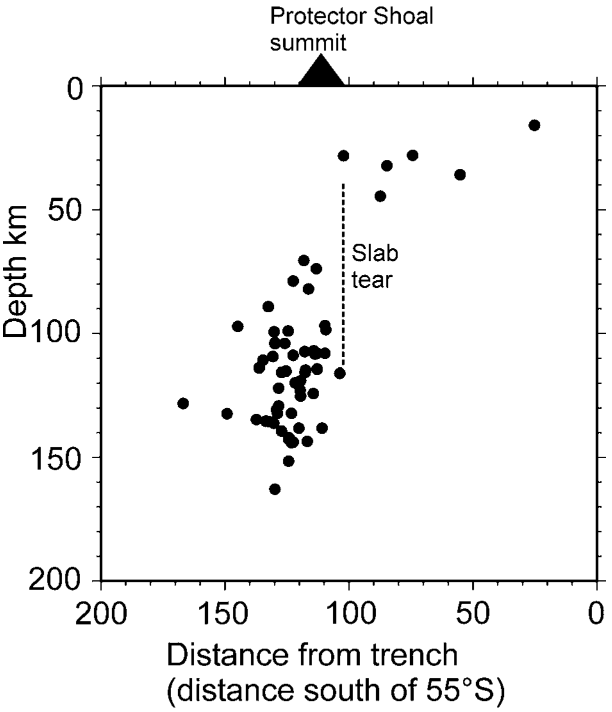

Figure 3. North–South earthquake hypocentre section (27.5–28° W) from the database of Engdahl (1998). Selected events are from 1964 to 2002 with these criteria: azimuthal gap < 180°; depth phases ≥ 3.

28°20′ ) at latitude 55°57′ S, which forms a prominent feature of the edifice (Fig. 2). The steep S-facing slopes contrast with the more gentle N-facing slopes. The latter are cut by what appears to be an embayment some 20 km across. It is possible that this embayment is a caldera or lateral collapse structure.

The E–W-trending ridge overlies a tear in the South American plate (Forsyth, 1975). The tearing is caused by the geometry of the northern edge of the subduction system, with the South American plate subducting south of the tear, but remaining in a strike-slip relationship to the Sandwich plate north of the tear. The position of the tear is imaged by the abrupt change in depth of well-located earthquakes (Engdahl, van der Hilst & Bulland, 1998) and directly underlies Protector Shoal (Fig. 3). It is possible that the slab edge is a zone of enhanced fluid flow from the slab, as seen at the south end of the South Sandwich arc (Leat *et al.* 2004), and that this fluid flow enhanced mantle melting to produce the E–W feature.

### 3.a. The 1962 eruption

Protector Shoal is believed to have erupted in March 1962. An extensive pumice raft was encountered by the ship HMS *Protector* on 14 March 1962 in the vicinity of Zavodovski Island, with the most concentrated distribution between 55°55′ and 56°15′ (Gass, Harris & Holdgate, 1963). The pumice clasts were reported to be up to 1.5 m across, and formed into elongate rafts trending in an E–W direction (downstream from Protector Shoal in the prevailing eastward-flowing ocean current and winds). The distribution of the pumice raft is consistent with the eruption having occurred in the vicinity of Protector Shoal a few days before 14 March 1962. Gass, Harris & Holdgate (1963) suggested that the eruption may have been linked to an earthquake centred on 55.9° S, 27.9° W which occurred at 10.15 UT on 5 March 1962. The epicentre location, if accurate, was along the E–W ridge, at the southern end of the N-facing embayment (Fig. 2). Subsequently, pumice samples were dredged from the sea floor near the summit by HMS *Protector*, and this was taken as a strong indication that the vent had been in the summit region of the Shoal (Gass, Harris & Holdgate, 1963). However, the earthquake was calculated to have been relatively deep (25 km, although this is subject to large error, and may not mean much more than the earthquake was within the crust) (Advanced National Seismic System, 2005, http://quake.geo.berkeley.edu/anss/); there is no certainty that earthquake and eruption were directly linked. Nevertheless, the evidence that the eruption took place within the Protector Shoal edifice is regarded as conclusive (Baker, 1990). Gass, Harris & Holdgate (1963) calculated that the volume of erupted pumice was at least 0.6 km$^3$, based on the minimum area covered, raft depth of 4.5 m, and a 2.5 % pumice content of the rafts. This corresponds to a volume of *c.* 0.2 km$^3$ of magma, although it should be emphasized that large errors are possible in all parameters. This volume is unlikely to have been sufficiently large to have been associated with caldera collapse.

### 3.b. Samples

Protector Shoal was dredged in 1997 from RRS *James Clark Ross* during British Antarctic Survey Cruise JR18. The dredge site (56°01.91′; 28°07.84’ W to 56°01.53′, 28°08.51’ W) was a steep, SE-facing slope immediately southeast of the summit. The site was at 1370–1570 m water depth. Most of the samples described in this study are from the JR18 dredge, augmented by data from pumices collected in 1962 from the sea surface by HMS *Protector* (Gass, Harris & Holdgate, 1963; Pearce *et al.* 1995) and pumice samples collected from beaches in Tierra del Fuego and the South Shetland Islands (Risso, Scasso & Aparicio, 2002).

The JR18 samples include two main types: white, highly vesicular pumice and grey, significantly less vesicular (*c.* 30 % vesicles), lava-like fragments. Both types occur as sub-angular fragments up to 23 cm in maximum dimension. It addition, there were a small number of angular lava-like fragments, presumed to be accidental xenoliths. No drop stones were collected by the dredge; this is unusual for dredges from in the area, and is a strong indication of the extreme youth (< 10000 years) of the volcanic cover of the Shoal.

Petrographically, all the samples are unaltered, with fresh phenocrysts and matrices, and none of the samples contain secondary minerals within vesicles. There is no significant petrographic variation within chemically defined groups (Section 4.a). The petrography of one sample from each group of dredged rocks was verified on a CAMECA SX100 microprobe at the Department of Earth Sciences, University of Cambridge, UK, using normal operating conditions. The lava-like fragments (sample DR.162.1 was analysed by microprobe), which form one of the distinct chemical groups (Section 4.a), consist of phenocrysts of plagioclase, orthopyroxene, augite, Ti-magnetite and rare ilmenite in a hypocrystalline matrix consisting of flow-aligned microcrystals enclosed in glass. The chemically defined type A pumices (sample DR.162.10 was analysed) have the same phenocryst assemblage as the lava-like fragments, with the addition of quartz. The matrix is a completely fresh, clear glass. The type B pumice (DR.121.23) consists of plagioclase, quartz, augite, orthopyroxene, diopside, ilmenite and rare amphibole in a clear glass matrix. Pumices from the 1962 eruption are reported as having plagioclase, magnetite and orthopyroxene phenocrysts (Gass, Harris & Holdgate, 1963). No accessory minerals were identified in the rocks, consistent with their low abundances of trace elements.

An compositions of plagioclase rims are restricted for each sample, but distinct from those of other groups (DR.162.1, $An_{50–54}$: DR.162.10, $An_{58–62}$; DR.162.23, $An_{54–56}$), while cores of the same phenocrysts are more variable, but again different from group to group (DR.162.1, $An_{35–58}$: DR.162.10, $An_{53–68}$; DR.162.23, $An_{50–56}$). This suggests separate evolutions for the groups. Orthopyroxenes are similar in all groups ($En_{48–65}$), with DR.162.1, ($En_{57–62}$) being distinct from DR.162.10, ($En_{48–55}$) in both rims and cores. Fairly homogeneous augite ($En_{36–39}Wo_{42–43}$) occurs in all analysed groups, but apparently stable diopside ($En_{45}Wo_{47}$) and one crystal of hornblendic amphibole were found only in DR.162.23.

## 4. Geochemistry

The samples from JR18 were analysed by standard XRF methods at the University of Keele, UK, for major elements and by ICP-MS at Durham University, UK, for trace elements. Sr and Nd isotopes were analysed on a Finnegan-MAT 262 machine at the NERC Isotope Geosciences Laboratory, UK, using the same methods as Riley *et al.* (2005). These new data (Tables 1, 2) are compared to pumice samples analysed by ICP-MS from the pumice raft of the 1962 eruption, and pumice samples collected from beaches in Tierra del Fuego and the South Shetland Islands.

All the samples are rhyolites and dacites, with the exception of one andesitic lithic inclusion (Gass, Harris & Holdgate, 1963). It is likely that some of the samples from JR18 have been slightly altered by interaction with seawater. The samples have LOI values that range from 0.47 to 5.71 wt %, with LOI values of 2.76 to 2.96 wt % for most of the pumices (Table 1). As there is no petrographic evidence for devitrification or other alteration of phenocrysts or matrices in the samples, these LOI values indicate that the glasses are variably hydrated. Pre-eruption water contents of the magmas are unknown, but are likely to have been in the range 4 to 6 wt % by comparison with measurements on fluid inclusions in silicic magmas from other volcanic arcs, with water dominating the volatile budget (e.g. Macdonald, Hawkesworth & Heath, 2000; Liu *et al.* 2006). The depths of the vents for the Protector eruptions could have ranged from the summit at 27 m to about the start of the dredge at 1570 m, equivalent to a pressure range of 0.37 to 15.5 MPa. Solubilities of water in silicic glasses at 700 °C at these pressures are *c.* 0.2 % at the lower pressure to *c.* 1.7 % at the higher (Liu, Zhang & Behrens, 2005). Ascent of pumices within a submarine eruption column (Cashman & Fiske, 1991) could result in further volatile loss. Most of the original volatile content of the magmas must therefore have

Table 1. Major and trace element analyses of samples dredged from Protector Shoal

| Sample | DR.162.1 | DR.162.2 | DR.162.3 | DR.162.14 | DR.162.15 | DR.162.16 | DR.162.8 | DR.162.9 | DR.162.10 | DR.162.19 | DR.162.20 | DR.162.21 | DR.162.22 | DR.162.23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | L | L | L | L | L | L | A | A | A | A | A | A | A | B |
| Major elements by XRF (wt %) | | | | | | | | | | | | | | |
| $SiO_2$ | 72.18 | 72.16 | 71.67 | 71.99 | 71.86 | 70.98 | 67.49 | 68.08 | 68.71 | 67.69 | 68.60 | 68.29 | 69.90 | 67.41 |
| $TiO_2$ | 0.43 | 0.43 | 0.46 | 0.44 | 0.44 | 0.44 | 0.43 | 0.39 | 0.40 | 0.44 | 0.39 | 0.40 | 0.39 | 0.31 |
| $Al_2O_3$ | 13.85 | 13.58 | 13.83 | 13.87 | 13.66 | 13.59 | 13.74 | 13.41 | 13.55 | 13.50 | 13.54 | 13.70 | 14.03 | 12.12 |
| $Fe_2O_3$(T)* | 2.85 | 2.70 | 2.59 | 2.55 | 3.05 | 2.89 | 4.10 | 3.68 | 3.61 | 4.35 | 3.55 | 3.60 | 3.62 | 2.67 |
| MnO | 0.07 | 0.08 | 0.06 | 0.07 | 0.08 | 0.07 | 0.16 | 0.09 | 0.08 | 0.09 | 0.08 | 0.08 | 0.08 | 0.06 |
| MgO | 0.69 | 0.88 | 1.02 | 0.89 | 0.70 | 1.18 | 1.20 | 0.92 | 0.91 | 1.19 | 0.96 | 0.97 | 0.94 | 1.21 |
| CaO | 2.87 | 2.82 | 2.84 | 2.83 | 2.92 | 3.12 | 3.77 | 3.63 | 3.53 | 3.75 | 3.47 | 3.58 | 3.54 | 2.97 |
| $Na_2O$ | 4.70 | 4.88 | 5.21 | 5.19 | 4.88 | 5.63 | 4.64 | 5.16 | 4.77 | 4.32 | 4.81 | 4.80 | 4.38 | 6.16 |
| $K_2O$ | 1.14 | 0.96 | 0.64 | 0.62 | 1.28 | 0.66 | 1.12 | 1.18 | 1.14 | 1.12 | 1.11 | 1.13 | 1.10 | 1.14 |
| $P_2O_5$ | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.08 | 0.06 | 0.06 | 0.08 | 0.07 | 0.07 | 0.06 | 0.05 |
| LOI | 0.66 | 0.94 | 0.96 | 0.98 | 0.47 | 0.88 | 2.84 | 2.99 | 2.78 | 2.76 | 2.92 | 2.88 | 2.18 | 5.71 |
| Total | 99.50 | 99.49 | 99.34 | 99.48 | 99.40 | 99.50 | 99.57 | 99.59 | 99.54 | 99.29 | 99.50 | 99.50 | 100.22 | 99.81 |
| Trace elements by ICP-MS (ppm) | | | | | | | | | | | | | | |
| Sc | 14.2 | 14.5 | 15.5 | 12.6 | 14.3 | 15.0 | 13.7 | 14.7 | 12.2 | 14.4 | 12.0 | 11.5 | 10.8 | 13.6 |
| V | 15.8 | 16.3 | 18.5 | 16.5 | 16.5 | 17.3 | 57.7 | 43.5 | 44.6 | 59.3 | 46.3 | 41.8 | 44.1 | 31.6 |
| Cr | 0.2 | 0.2 | 0.0 | 0.5 | 0.2 | 0.3 | 4.0 | 1.2 | 1.3 | 4.1 | 1.0 | 1.1 | 1.9 | 20.6 |
| Co | 2.0 | 2.3 | 2.3 | 2.2 | 2.3 | 2.7 | 15.6 | 7.1 | 7.7 | 8.3 | 7.4 | 5.6 | 5.8 | 4.1 |
| Ni | 2.1 | 5.3 | 1.6 | 2.5 | 3.7 | 4.2 | 15.7 | 4.3 | 1.7 | 4.7 | 2.0 | 1.3 | 2.6 | 4.5 |
| Cu | 5.2 | 9.3 | 8.1 | 5.8 | 6.8 | 8.8 | 43.9 | 41.2 | 23.8 | 29.1 | 18.6 | 19.3 | 26.9 | 15.8 |
| Zn | 24.4 | 30.0 | 27.6 | 28.5 | 30.9 | 34.2 | 37.4 | 33.9 | 34.1 | 39.8 | 32.3 | 31.1 | 38.6 | 28.4 |
| Ga | 14.0 | 14.0 | 14.3 | 13.9 | 13.9 | 14.2 | 12.6 | 12.7 | 12.7 | 12.7 | 12.3 | 12.5 | 12.7 | 11.0 |
| Rb | 10.54 | 8.52 | 6.01 | 5.84 | 11.33 | 5.82 | 19.50 | 20.14 | 19.94 | 19.73 | 19.75 | 19.61 | 20.57 | 20.79 |
| Sr | 116.0 | 115.2 | 118.1 | 117.4 | 115.0 | 116.0 | 111.9 | 111.1 | 108.8 | 113.3 | 107.5 | 111.4 | 108.9 | 99.6 |
| Y | 30.9 | 30.1 | 31.2 | 30.4 | 30.6 | 29.0 | 26.2 | 26.9 | 26.9 | 26.2 | 26.7 | 26.6 | 26.7 | 24.0 |
| Zr | 119.6 | 117.5 | 119.5 | 118.4 | 117.4 | 114.4 | 94.0 | 98.5 | 99.1 | 94.4 | 98.4 | 97.9 | 98.3 | 117.3 |
| Nb | 1.96 | 1.94 | 1.98 | 1.93 | 1.94 | 1.96 | 2.08 | 2.17 | 2.12 | 2.10 | 2.10 | 2.11 | 2.14 | 1.84 |
| Cs | 0.151 | 0.216 | 0.151 | 0.142 | 0.151 | 0.184 | 0.587 | 0.584 | 0.572 | 0.616 | 0.583 | 0.568 | 0.611 | 0.557 |
| Ba | 188.3 | 183.3 | 181.6 | 181.4 | 187.0 | 176.4 | 245.4 | 227.9 | 232.2 | 252.4 | 228.1 | 225.5 | 242.0 | 228.9 |
| La | 6.67 | 6.67 | 7.03 | 6.85 | 6.62 | 6.84 | 7.15 | 7.21 | 7.35 | 7.15 | 7.25 | 7.19 | 7.45 | 6.99 |
| Ce | 17.53 | 17.49 | 18.58 | 18.05 | 17.44 | 18.13 | 17.80 | 18.14 | 18.46 | 17.84 | 18.20 | 18.00 | 18.54 | 17.17 |
| Pr | 2.60 | 2.59 | 2.75 | 2.65 | 2.62 | 2.68 | 2.54 | 2.58 | 2.60 | 2.56 | 2.58 | 2.58 | 2.64 | 2.40 |
| Nd | 12.37 | 12.22 | 13.15 | 12.54 | 12.54 | 12.60 | 11.49 | 11.54 | 11.72 | 11.55 | 11.69 | 11.70 | 11.97 | 10.69 |
| Sm | 3.46 | 3.45 | 3.62 | 3.44 | 3.52 | 3.49 | 3.03 | 3.10 | 3.14 | 3.08 | 3.14 | 3.12 | 3.15 | 2.76 |
| Eu | 1.03 | 1.04 | 1.05 | 1.06 | 1.05 | 1.04 | 0.82 | 0.81 | 0.82 | 0.82 | 0.82 | 0.80 | 0.83 | 0.68 |
| Gd | 4.40 | 4.25 | 4.44 | 4.26 | 4.37 | 4.15 | 3.63 | 3.61 | 3.69 | 3.66 | 3.66 | 3.67 | 3.74 | 3.20 |
| Tb | 0.77 | 0.75 | 0.78 | 0.75 | 0.78 | 0.73 | 0.64 | 0.66 | 0.66 | 0.65 | 0.66 | 0.66 | 0.66 | 0.57 |
| Dy | 4.82 | 4.72 | 4.89 | 4.77 | 4.89 | 4.57 | 4.10 | 4.12 | 4.15 | 4.07 | 4.20 | 4.12 | 4.16 | 3.58 |
| Ho | 1.08 | 1.04 | 1.08 | 1.03 | 1.09 | 1.02 | 0.89 | 0.90 | 0.91 | 0.91 | 0.91 | 0.90 | 0.92 | 0.81 |
| Er | 3.07 | 3.01 | 3.09 | 3.00 | 3.09 | 2.90 | 2.58 | 2.61 | 2.67 | 2.60 | 2.60 | 2.61 | 2.68 | 2.34 |
| Tm | 0.540 | 0.533 | 0.540 | 0.528 | 0.544 | 0.506 | 0.457 | 0.457 | 0.466 | 0.462 | 0.459 | 0.466 | 0.471 | 0.415 |
| Yb | 3.38 | 3.31 | 3.34 | 3.30 | 3.42 | 3.14 | 2.84 | 2.87 | 2.92 | 2.86 | 2.92 | 2.89 | 2.95 | 2.66 |
| Lu | 0.57 | 0.56 | 0.58 | 0.56 | 0.58 | 0.54 | 0.48 | 0.48 | 0.50 | 0.48 | 0.49 | 0.49 | 0.50 | 0.46 |
| Hf | 3.40 | 3.31 | 3.41 | 3.37 | 3.42 | 3.32 | 2.91 | 3.01 | 3.04 | 2.90 | 3.03 | 3.02 | 3.10 | 3.34 |
| Ta | 0.146 | 0.142 | 0.142 | 0.138 | 0.146 | 0.140 | 0.168 | 0.174 | 0.172 | 0.168 | 0.170 | 0.169 | 0.178 | 0.165 |
| Pb | 1.62 | 1.73 | 1.68 | 1.66 | 1.75 | 1.64 | 2.67 | 2.61 | 2.40 | 2.72 | 2.36 | 2.38 | 2.69 | 2.23 |
| Th | 1.51 | 1.50 | 1.51 | 1.47 | 1.50 | 1.42 | 1.81 | 1.83 | 1.86 | 1.80 | 1.83 | 1.82 | 1.90 | 1.92 |
| U | 0.428 | 0.443 | 0.455 | 0.429 | 0.458 | 0.436 | 0.539 | 0.492 | 0.489 | 0.846 | 0.526 | 0.497 | 0.507 | 0.522 |

Type: L–lava-like clasts; A–type A; B–type B.
*Total Fe as $Fe_2O_3$.

Table 2. Sr and Nd isotope data for dredged silicic rocks from Protector Shoal

| Sample | Type | $^{87}Sr/^{86}Sr$ | Sr ± | Sm (ppm) | Nd (ppm) | $^{143}Nd/^{144}Nd$ | Nd ± |
|---|---|---|---|---|---|---|---|
| DR.162.14 | Lava-like clast | 0.703759 | 3 | 3.151 | 13.035 | 0.513003 | 4 |
| DR.162.15 | Lava-like clast | 0.703715 | 3 | 3.370 | 12.031 | 0.512993 | 3 |
| DR.162.19 | Type A pumice | 0.703961 | 4 | 3.112 | 11.362 | 0.512974 | 4 |
| DR.162.22 | Type A pumice | 0.703755 | 4 | 3.114 | 11.437 | 0.512993 | 4 |
| DR.162.23 | Type B pumice | 0.704121 | 3 | 2.762 | 10.353 | 0.513011 | 6 |

degassed during the eruptions, and measured LOI values must represent post-eruptive addition of water during hydration of the glasses.

Hydration of silicic glass is commonly associated with mobility of Na, K and other alkalis (e.g. Stewart, 1979; Acosta-Vigil, London & Morgan, 2005), and evidence for such mobility has to be assessed. There are negative correlations between LOI and $K_2O$ abundances in the lava-like clasts (Table 1), indicating loss of K during progressive hydration from least-altered values of 0.47 % LOI and 1.28 % $K_2O$. $Na_2O$ is slightly positively correlated with LOI in the same samples, increasing from 4.88 % to 5.19 % from the least to most hydrated samples, indicating minor possible Na

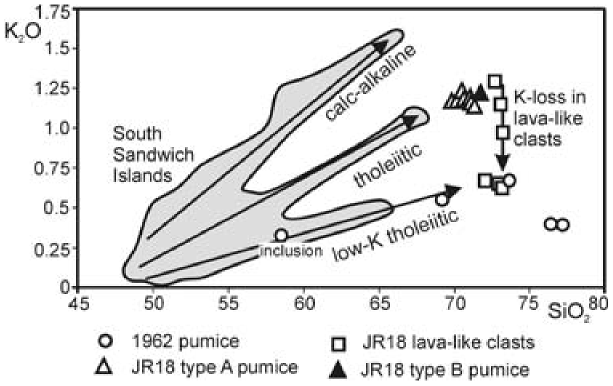

Figure 4. $K_2O$ v. $SiO_2$ plot (anhydrous basis) showing the relationship of Protector Shoal samples to the South Sandwich arc (Leat *et al.* 2003). JR18 dredge samples are compared to the 1962 pumice (Gass, Harris & Holdgate, 1963; Pearce *et al.* 1995; Risso, Scasso & Aparico, 2002).

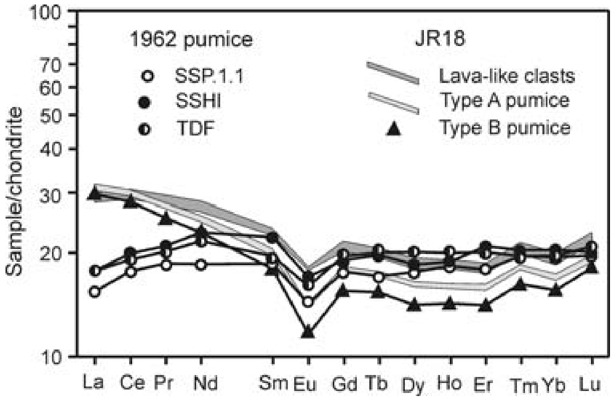

Figure 5. Chondrite-normalized rare-earth element plot showing the four distinct Protector Shoal groups. The 1962 pumice data are from the pumice raft (SSP.1.1: Pearce *et al.* 1995), and South Shetland Islands and Tierra del Fuego (SSHI and TDF respectively: Risso, Scasso & Aparico, 2002).

addition during hydration. Rb shows similar behaviour to K, falling from 11.33 to 5.84 ppm from the least to most hydrated sample. All other elements, including Cs, Ba and Sr show minor variation and no correlation with LOI in the same samples, indicating that they were immobile. There is weak positive correlation of Na and K with LOI in type A pumices, indicating that both may have been added during hydration of these samples, but no evidence of mobility of any other elements (Rb, Cs, Ba and Sr are almost constant; Table 1).

K, Na and Rb were evidently mobilized during hydration, and abundances of these elements should be used with caution. Other elements show no evidence for mobility during hydration. Despite the selective K-loss, the samples clearly belong to both the low-K tholeiitic and tholeiitic chemical series of the South Sandwich Islands (Pearce *et al.* 1995; Leat *et al.* 2003).

### 4.a. Chemical types

We divide the samples into four distinct chemical groups defined by major and trace element abundances:

(1) 1962 pumices. This group forms an andesite–dacite–rhyolite series (Gass, Harris & Holdgate, 1963; Pearce *et al.* 1995; Risso, Scasso & Aparicio, 2002) that plots along the low-K tholeiitic trend of the South Sandwich arc (Fig. 4). The Tierra del Fuego and South Shetland samples plot below this trend and may have lost K during prolonged exposure to seawater. In trace elements, as we shall detail below, there is a strong similarity between these far-travelled clasts and those recovered from the 1962 pumice rafts.

(2) Lava-like clasts from the JR18 dredge. This group consists of six relatively dense rhyolite samples. K abundances are variable and they are considered to form a tholeiitic group that have variably lost K (Fig. 4). Fe abundances are low (total Fe as $Fe_2O_3$, volatile free = 2.59–3.08 wt %) relative to type A pumices.

(3) Type A pumice clasts from the JR18 dredge. The seven samples are dacitic and plot within the tholeiitic trend of the South Sandwich Islands (Fig. 4).

(4) Type B pumice clast from the JR18 dredge. This is a single tholeiitic rhyolite sample. It has a distinctive low $Al_2O_3$ content at relatively high MgO (12.88 wt % and 1.29 wt % respectively, volatile-free).

The groups are easily distinguished using trace elements. In the rare earth element (REE) plot (Fig. 5), the three 1962 pumice samples are sub-parallel and have distinctive light REE-depleted patterns that peak at Nd–Sm and have chondrite-normalized La/Yb ($La/Yb_N$) ratios of $< 1$ (0.79–0.9). In contrast, all the samples from the JR18 dredge are enriched in light REE relative to middle and heavy REE. They have concave-up middle–heavy REE patterns (Gd–Lu). The six lava-like clasts from the JR18 dredge plot as a tight group with middle–heavy REE patterns similar to the 1962 pumices and are LREE-enriched ($La/Yb_N = 1.39$–$1.56$), with convex-up middle–light REE patterns, peaking at Ce. The seven type A pumices from the JR18 dredge form a different, even tighter grouping with relatively low middle–heavy REE and stronger light REE-enrichment ($La/Yb_N = 1.78$–$1.81$). The single type B pumice has distinctive low middle–heavy REE, and the most concave-up middle–heavy REE pattern. It has the lowest Eu and the highest $La/Yb_N$ (1.89).

The REE data show that the three JR18 groups are different from one another and from the 1962 pumice. This is further confirmed by using other trace element ratios. The Ba/Yb and Th/Yb v. Nb/Yb plots have been

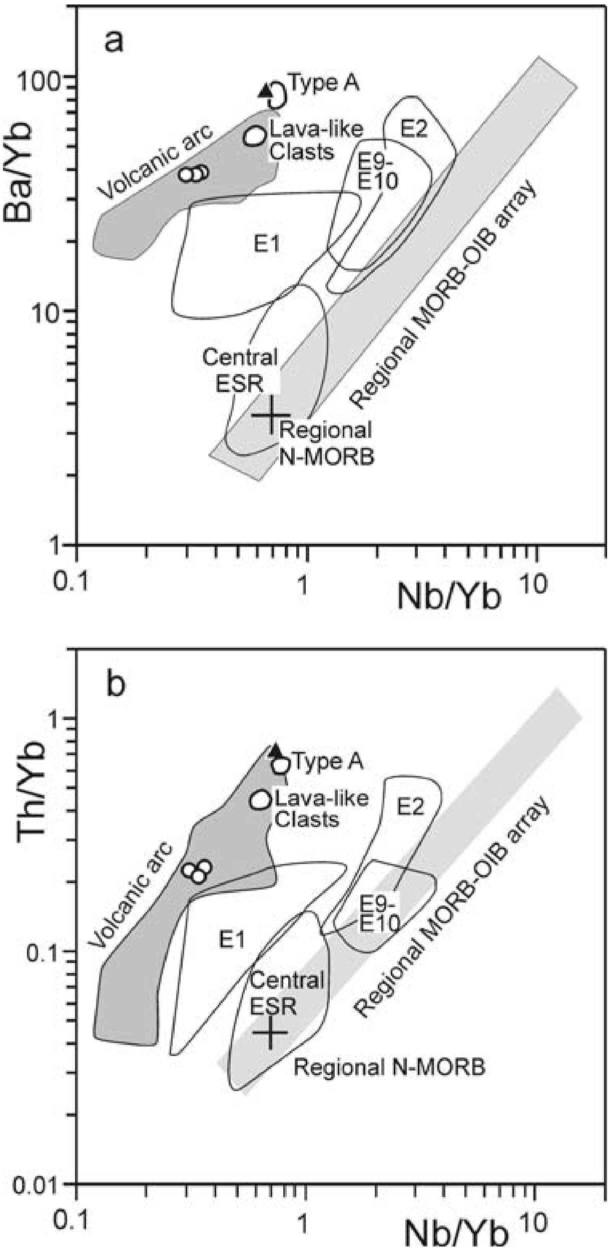

Figure 6. Plots of Ba/Yb and Th/Yb v. Nb/Yb showing the composition of Protector Shoal samples relative to the regional MORB-OIB array, the main South Sandwich Islands volcanic arc and the back-arc basin spreading centre (fields after Leat *et al*. 2004). The lava-like clasts and type A pumice clasts are shown as fields; symbols for 1962 eruption and type B pumices as in Figure 4. ESR – East Scotia Ridge.

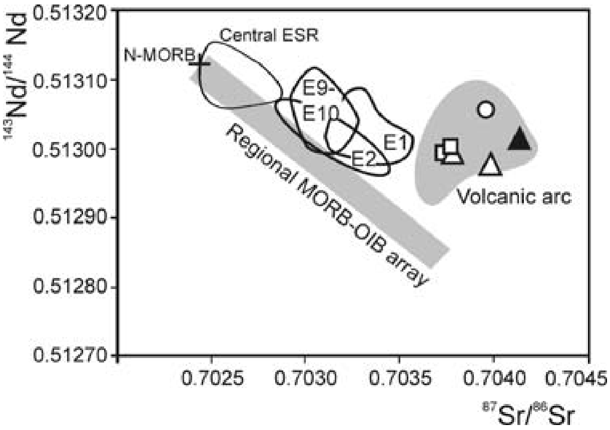

Figure 7. $^{143}$Nd/$^{144}$Nd v. $^{87}$Sr/$^{86}$Sr plot showing that the Protector Shoal samples plot as groupings within the field of the South Sandwich Islands volcanic arc, and distinct from the back-arc spreading centre. Data for 1962 eruption pumice from Pearce *et al*. (1995). Fields after Leat *et al*. (2004); symbols as in Figure 4. ESR – East Scotia Ridge. Errors in ratios are smaller than symbol sizes.

used to illustrate and model the origin of arc and back-arc magmas in the South Sandwich system (Pearce *et al*. 1995; Leat *et al*. 2004). In these diagrams (Fig. 6), the four magma types plot as distinct groups. All plot within or close to the field of the South Sandwich arc, rather than the back-arc basin, indicating that they were derived via partial melting or fractional crystallization from arc rather than back-arc basalts. Other trace element differences between the groups are summarized in Table 3. In nearly all ratios, the four groups are distinct, and, when all the ratios are considered, the four groups are clearly different magma batches. The trace element variation within groups is very small. Interestingly, while the 1962 pumice group had the most depleted sources in terms of ratios of Zr, Nb, Ba and Th to Yb (the lowest ratios), type B pumices had an even more depleted source in terms of Nb/Ta (all the samples have subchondritic Nb/Ta ratios, a feature of the South Sandwich arc, with the most depleted sources having the lowest Nb/Ta ratios: Leat *et al*. 2003). The elements Th, Nb and Ba have similar, low compatibilities in South Sandwich magmas, and ratios between them reflect additions of different Th- or Ba-bearing fluids from the slab into the arc magmas (Elliott *et al*. 1997; Leat *et al*. 2003, 2004). Th/Nb and Ba/Th show an approximately reversely correlated relationship between the groups (Table 3), consistent with distinct sources for each group having been dominated by either a Ba- or Th-rich subduction component, but inconsistent with any genetic link between the four magma groups.

### 4.b. Sr and Nd isotopes

Sr–Nd isotope ratios of a subset of samples plot as distinct groups, although there is little distinction between the lava-like clasts and type A pumices. The 1962 pumice sample and the type B pumice sample have distinctive high $^{143}$Nd/$^{144}$Nd and high $^{87}$Sr/$^{86}$Sr ratios, respectively, that differ from the other groups by significantly more than their errors. All the samples plot within the known field for the island arc and have higher $^{87}$Sr/$^{86}$Sr ratios than any known back-arc sample (Fig. 7). This again suggests that the silicic rocks were derived via partial melting or fractional crystallization from arc rather than back-arc basalts.

Table 3. Trace element characteristics of the silicic groups of Protector Shoal

| | 1962 pumice[1] | Lava-like clasts | Type A pumice | Type B pumice |
|---|---|---|---|---|
| $SiO_2$ (%) | 69.1–76.3 | 72.6–73.2 | 69.8–71.3 | 71.6 |
| K-series[2] | Low–K tholeiite | tholeiite | tholeiite | tholeiite |
| $La/Yb_N$ | 0.79–0.90 | 1.39–1.56 | 1.78–1.81 | 1.89 |
| Zr/Yb | 24.9–28.8 | 34.3–36.4 | 33.0–34.4 | 44.1 |
| Nb/Yb | 0.30–0.34 | 0.57–0.62 | 0.72–0.76 | 0.69 |
| Ba/Yb | 38.0–38.7 | 54.4–56.2 | 77.9–88.8 | 86.1 |
| Th/Yb | 0.21–0.23 | 0.44–0.45 | 0.63–0.64 | 0.72 |
| Nb/Ta | 12.4 | 13.3–14.0 | 12.0–12.5 | 11.2 |
| Th/Nb | 0.64–0.75 | 0.73–0.77 | 0.84–0.89 | 1.04 |
| Ba/Th | 169–183 | 121–125 | 124–141 | 120 |

$SiO_2$ recalculated to 100% volatile-free. [1] 1962 pumice excludes the andesite inclusion of Gass, Harris & Holdgate (1963). [2] K-series after Pearce *et al.* (1995).

### 4.c. Interpretation

The four groups of silicic samples from Protector Shoal are distinct one from another in terms of their bulk major and trace element chemistry and Sr and Nd isotope ratios. This result precludes the groups having been directly related one to another by fractional crystallization. Possible interpretations are that the silicic magmas were derived from separate basaltic magmas via fractional crystallization, or were derived from separate mafic sources via partial melting. In the absence of basaltic samples from Protector Shoal, it is impossible to model possible basalt–rhyolite fractionation trends. Nevertheless, the balance of probabilities has to be that the silicic magmas were generated by partial melting. Experience of basalt magmatism in the South Sandwich Islands has shown that compositions of basalts erupted on individual volcanoes tend to be highly homogeneous for long periods. Examples of this are the recent tholeiitic basaltic andesite magmatism on Bellingshausen Island, and the older low-K tholeiitic basaltic lava sequence on Candlemas and Vindication islands (Pearce *et al.* 1995; Leat *et al.* 2003). It is therefore unlikely that four basaltic magma types were simultaneously available for fractionation to silicic magmas within the Protector Shoal volcano. However, if the silicic magmas were generated by partial melting of the crust beneath Protector Shoal, basaltic parts of the crust with different origins and compositions may well partially melt at the same time to produce several distinct silicic magma batches. Our interpretation is therefore that the Protector Shoal silicic magmas are likely to have been generated by partial melting of discrete mafic parts of the sub-arc crust.

What parts of the sub-arc crust partially melted? The sub-arc crust is thought to consist of pre-existing basaltic ocean crust that formed at the East Scotia Ridge spreading centre, and intrusions and volcanic rocks of the arc (Leat *et al.* 2003; Larter *et al.* 2003). In principle, it is possible for both the crust formed at the spreading centre and the arc to have partially melted. The basalts of the spreading centre and the arc are normally sufficiently different from each other in terms of trace element and isotopic ratios for an easy distinction to be made. The silicic rocks clearly fall within the arc, rather than the spreading centre, fields in geochemical plots (Figs 6, 7), implying that the arc, rather than the back-arc crust, is the source. However, some caution is required because Protector Shoal is adjacent to Segment E1 of the spreading centre. Segment E1 is an unusual segment and is characterized by variable geochemical composition, but it is generally very similar to the arc in composition. The high subduction component in the source of segment E1 is related to the proximity of the spreading axis of this segment to the arc (Leat *et al.* 2004). If the conditions that generated the present Segment E1 are a long-standing feature of that part of the back-arc, Protector Shoal may be built on crust similar to that of the present-day Segment E1. However, geochemical plots (Figs 6, 7) indicate that the silicic magmas plot further toward the arc field in all respects (high Ba/Nb, Th/Nb and $^{87}Sr/^{86}Sr$) than any known composition from Segment E1. If the sampled compositional range from the active spreading centre of Segment E1 is representative of the oceanic crust of this segment below the arc, the silicic rocks are unlikely to have been derived from this source. However, given that the composition of Segment E1 beneath the arc is unknown, there must remain a possibility that crust formed at the spreading centre was a source for the silicic magmas.

## 5. Other silicic magmas in the South Sandwich arc: geochemical and seismic evidence

Significant amounts of silicic rocks crop out on two other major volcanoes of the South Sandwich arc (Candlemas and Southern Thule), and silicic rocks are inferred from seismic imaging to occur in the mid-crust beneath Southern Thule. The geochemistry of the outcropping silicic rocks has not provided an unequivocal answer as to whether they were produced by fractional crystallization or partial melting. However, it has been argued for the strongly bimodal mafic–silicic sequence on Candlemas Island (Leat *et al.* 2003) that the higher Zr, Hf/Sm ratios of the silicic rocks relative to the basalts indicates involvement of amphibole in their genesis. Since amphibole is an observed phenocryst phase in neither the basalts nor the Candlemas silicic rocks, this was taken to indicate that the silicic rocks were derived by partial melting of an amphibole-bearing mafic source within the arc crust.

The silicic rocks occurring in the mid-crust beneath Southern Thule were imaged by a wide-angle seismic experiment (Larter *et al.* 1998). They form a 2 km thick mid-crustal layer which has a $P$-wave velocity of 6.0–6.5 km $s^{-1}$. The layer is interpreted as consisting of intermediate-silicic igneous intrusions (tonalite–granodiorite–granite), following interpretations of seismically imaged mid-crustal layers having the same seismic velocity in the Izu–Bonin arc (Suyehiro *et al.* 1996; Takahashi, Suyehiro & Shinohara, 1998). If this interpretation is correct, the 6.0–6.5 km $s^{-1}$ layer, at 2 km thick, is some 18 times too thick to represent tonalitic cumulate resulting from generation of erupted silicic magmas, and some 4–5 times too thick to represent non-erupted silicic magma in relation to the thickness of mafic cumulate in the seismic profile (Leat *et al.* 2003). However, the volume relationships are permissive of the 6.0–6.5 km $s^{-1}$ layer representing an intermediate composition partial melt of the basaltic crust. At 40 % partial melting, 33 % of the lower crust would be a residue from this partial melting event, a thickness that can readily be accommodated with the seismic evidence (Leat *et al.* 2003). The volume relationships derived from seismic evidence are therefore strongly indicative of formation of significant volumes of intermediate-silicic magma within the South Sandwich arc by crustal partial melting.

## 6. Discussion

All intra-oceanic arcs are dominated by basaltic effusive products, but one of the surprises of recent studies of subaerial and submarine parts of several intra-oceanic arcs is the local abundance of silicic volcanics that form a part of distinctly bimodal mafic–silicic series. The association is well documented in the Tonga–Kermadec arc (Lloyd *et al.* 1996; Worthington, Gregory & Bondarenko, 1999; Wright & Gamble, 1999; Smith, Stewart & Price, 2003; Smith *et al.* 2003), where 11 of 30 petrologically described volcanoes have silicic products (Smith *et al.* 2003). The silicic magmas of the arc form many internally homogeneous chemical groups, which are distinct from each other, even within products of the same caldera volcano (Smith, Stewart & Price, 2003; Smith *et al.* 2003). This feature of their chemistry, strikingly similar to that of the Protector Shoal suite, was taken, along with compositional features and volume relationships, as evidence that the Tonga–Kermadec silicic magmas were not derived from mafic magmas by fractional crystallization, but are products of partial melting (Smith, Stewart & Price, 2003; Smith *et al.* 2003; Wright, Worthington & Gamble, 2006).

Tamura & Tatsumi (2002) showed that 1011 analyses from the volcanic front of the Izu–Bonin arc form a basalt–rhyolite bimodal association, with a minimum at andesite. They interpreted the rhyolites to have been formed by partial melting of andesitic crust of the arc. Bimodal associations are also present in the central part of the Vanuatu arc (Robin, Eissen & Monzier, 1993; Monzier, Robin & Eissen, 1994).

The South Sandwich, Tonga–Kermadec and Izu–Bonin arcs, all of which have locally abundant silicic magmas, also have 6.0–6.5 km $s^{-1}$ $P$-wave velocity layers within the middle crusts of the arc that have been imaged by wide-angle seismic experiments (Suyehiro *et al.* 1996; Takahashi, Suyehiro & Shinohara, 1998; Crawford *et al.* 2003; Leat *et al.* 2003). These middle crust layers are interpreted as intermediate-silicic plutons, an interpretation that is reinforced by exposure of the Izu–Bonin tonalitic unit as the Tanzawa Complex formed where the Izu–Bonin arc intersects the Japan arc (Taira *et al.* 1998). Geochemical and experimental results suggest that this tonalite was generated by ∼ 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 (Rapp & Watson, 1995). Similar 6.0–6.5 km $s^{-1}$ $P$-wave velocity mid-crustal layers have been imaged locally beneath the eastern Aleutian arc (Fliedner & Klemeperer, 1999) and may occur in the central Lesser Antilles arc (Boynton *et al.* 1979). However, it is uncertain whether such mid-crustal layers occur in all intra-oceanic arcs, being absent, for example, in the central Aleutian arc (Holbrook *et al.* 1999).

The silicic volcanic rocks and silicic-intermediate mid-crustal plutons of intra-oceanic arcs are not representative of continental crust (Taira *et al.* 1998), as they lack the critical enrichments in alkali, LREE and other incompatible elements that are characteristic of continental crust (Weaver & Tarney, 1984; Rudnick & Fountain, 1995). Such enrichment is only likely be imparted within lithosphere thickened by collision or magma accumulation (Pearcy, DeBari & Sleep, 1990; Clift, Schouten & Draut, 2003). However, the partial melting process we propose for the Protector Shoal silicic rocks must differentiate the basaltic lower crust into the intermediate-silicic part and a dense, Mg-rich, Si-poor residue within the lower crust. The dense residue may more readily detach from the crust and recycle into the mantle during collision of intra-oceanic arcs than during the evolution of continental arcs. It is therefore likely that generation of the widespread intermediate-silicic magmas represents an early stage in the formation of continental crust.

## 7. Conclusions

Dredged samples from Protector Shoal, the northernmost known volcano of the South Sandwich arc, are entirely silicic in composition.

None of the dredged samples are similar to the pumice products of the 1962 eruption of the shoal. Taken together, the silicic sample suite comprises four distinct groups that do not appear to be related to each other, or to a common basaltic parent, by fractional crystallization.

The silicic magmas are interpreted to be a result of partial melting of basaltic crust within the arc. The partial melting conditions are similar to those assumed when basaltic continental crust partially melts to form active margin batholiths.

The Protector Shoal silicic rocks have compositions more similar to the South Sandwich arc than the back-arc, and basaltic rocks formed within the arc, rather than its oceanic basement, are likely to have been the magma source.

Volume considerations indicate that a seismically imaged 6.0–6.5 km $s^{-1}$ *P*-wave velocity (compositionally silicic-intermediate) mid-crustal layer further south in the South Sandwich arc was also the product of partial melting of basaltic arc crust. The South Sandwich arc is one of several intra-oceanic arcs that have both significant amounts of silicic volcanic rocks, often in compositionally bimodal associations, and a 6.0–6.5 km $s^{-1}$ mid-crustal layer. Such silicic rocks in intra-oceanic arcs represent the formation of the most primitive known continental crust.

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