Combined Sr, Nd, Pb and Li isotope geochemistry of alkaline lavas from northern James Ross Island (Antarctic Peninsula) and implications for back-arc magma formation

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A B S T R A C T

We present a comprehensive geochemical data set for a suite of back-arc alkaline volcanic rocks from James Ross Island Volcanic Group (JRIVG), Antarctic Peninsula. The elemental and isotopic (Sr, Nd, Pb and Li) composition of these Cenozoic basaltic melts emplaced east of the Antarctic Peninsula is different from the compositions of the fore-arc alkaline volcanic rocks in Southern Shetlands and nearby Bransfield Strait. The variability in elemental and isotopic composition is not consistent with the JRIVG derivation from a single mantle source but rather it suggests that the magma was mainly derived from a depleted mantle with subordinate OIB-like enriched mantle component (EM II). The isotopic data are consistent with mantle melting during extension and possible rollback of the subducted lithosphere of the Antarctic plate. Magma contamination by Triassic–Early Tertiary elastic sediments deposited in the back-arc basin was only localized and affected Li isotopic composition in two of the samples, while most of the basaltshow very little variation in δ7Li values, as anticipated for “mantle-driven” Li isotopic composition. These variations are difficult to resolve with radiogenic isotope systems but Li isotopes may prove sensitive in tracking complex geochemical processes acting through the oceanic crust pile, including hydrothermal leaching and seawater equilibration.

1. Introduction

Partial melting of mantle rocks, fractional crystallization of the melts and magma contamination with crustal rocks, and especially with sediments in the back-arc basin, are the main factors that control the chemical and isotopic composition of magmas that form in the back-arc spreading centres (e.g., Woodhead et al., 1993). Many back-arc basaltic rocks also have geochemical signatures that suggest involvement of subduction processes in their petrogenesis (e.g., Woodhead et al., 1993; Gribble et al., 1998; Turner and Hawkesworth, 1998; Peate et al., 2001). Such signatures are typically linked to prior depletion of mantle source and enrichment of magmas with elements that are thought to be transported from subducted lithosphere to the mantle wedge (e.g., water and large ion lithophile elements). In addition, thermal and mechanical properties of lithosphere that underlies the magmatic arc and the slope of subducted slabs are also expected to control the composition of back-arc magmas (Jarrard, 1986).

Intrusions of Cenozoic volcanic rocks that occur east of the Antarctic Peninsula in Western Antarctica are often referred to as James Ross Island Volcanic Group (JRIVG, Nelson, 1966). They intrude Triassic and younger sediments deposited in the back-arc basin of the Antarctic Peninsula in the western part of the Weddell Sea in the Larsen basin (Fig. 1). The post-Gondwanan tectonic evolution of this region includes a south-east subduction of the Phoenix plate (now part of the Antarctic plate) under the continental margin of Antarctic Peninsula, collision of the Phoenix plate spreading centre with the continental margin and subsequent slowing of the plate convergence in the Tertiary and progressive diachronous migration of the subduction towards the north-east (McCarron and Larter, 1998). During the accretion and build-up of a thick accretionary wedge on the lithospheric crust, the subduction migrated north-west, away from the Antarctic Peninsula and it probably continues till today at a very slow rate (Larter, 1991). The compression due to the lithospheric convergence was later replaced by extension across the fore-arc and magmatic arc regions and it was associated with
rift and alkaline to calc-alkaline volcanism (McCarron and Smellie, 1998; Keller et al., 2002).

In contrast to the noticeable petrological and volcanological research in the JRIVG (Bibby, 1966; Nelson, 1966; Smellie, 1981; Sykes, 1988a; Smellie, 1999) and several dating campaigns that helped to establish the age of volcanism in the region (Sykes, 1988b; Jonkers and Kelley, 1998; Kristjánsson et al., 2005; Smellie et al., 2006a,b; Williams et al., 2006), surprisingly little is known about the chemical (Smellie, 1987; Smellie et al., 2006a) and isotopic composition of the JRIVG lavas. The available geochemical data suggest that magmas erupted in the region follow two alkaline differentiation trends: a sodium-rich and potassium-rich trend (Smellie, 1987; Smellie et al., 2006a). Lack of geochemical and, in particular, isotopic data has so far precluded a direct comparison of the JRIVG lavas with magmatic products from the other parts of the Antarctic Peninsula subduction system (cf. Hole et al., 1993; Keller et al., 2002; Fretzdorff et al., 2004).

In this paper we present new major and trace element as well as Sr – Nd – Pb – Li isotopic data for the back-arc basalts from the Antarctic Peninsula subduction system (James Ross Island Volcanic Group) to discuss the petrogenesis and magma sources and to document the differences in magma composition between arc and back-arc settings.

2. Geological setting and samples

James Ross Island (Fig. 2) is the largest single outcrop of the JRIVG, but in present-day most of the exposure of the volcanic rocks, including the island’s major volcano Mt. Haddington (1638 m), is covered by an ice cap. The Ulu Peninsula in the northern part of the island represents the largest deglaciated area, with exposures of Cretaceous marine sediments (Crame et al., 1991) that were overlain by lava-fed deltas built of hyaloclastic breccias, pillow-lavas and subaerial lava flows at the top, less common tuff cones with subordinate pillow lavas, and locally penetrated by basaltic dykes and subvolcanic plugs. The age of basaltic lava-fed deltas in the Ulu Peninsula (Brandy Bay area) has been recently dated by the 40Ar–39Ar technique at 6.16 – 3.95 Ma (Kristjánsson et al., 2005; Smellie et al., 2006b). This range, however, does not include the volcanic rocks on Cape Lachman (JR1) and the tuff cone of Bibby Point (dyke JR16).

The emplacement of alkaline volcanic rocks of the JRIVG near the northern tip of the Antarctic Peninsula along a system of block faults probably started as early as 10 Ma ago (Dingle and Lavelle, 1998; Smellie, 1999) and continued until relatively recently with the youngest recorded intrusions at ca. 130 ka (Smellie et al., 2006a).
The JRIVG consists of voluminous intrusions of lavas and other volcanic products that correspond in composition to tholeiites, alkali basalts, hawaiites and rarely also to basanites and mugearites (Smellie, 1999). Volcanism in JRIVG was both subaerial and submarine, with development of features typical of lava–sea water interaction, such as pillow lavas and voluminous hyaloclastic breccias. In addition, marine fossils in some of the volcanoclastic products also suggest that some of the eruptions occurred in the marine environment while other show features indicative of magma intrusion under the inland ice cap (Smellie 2006).

Samples for this study were collected from lava flows, dykes and magma feeding channels in different parts of the Ulu Peninsula in the Brandy Bay area (Fig. 2; Cape Lachman, Lachman Crags, Bibby Point and Davis Dome). The samples comprise 14 alkaline olivine basalts and olivine dolerites (Table 1). They all have similar mineral composition but differ significantly in the mineral grain size. The olivine basalts contain phenocrysts of automorphic olivine with inclusions of Cr-rich spinel. Olivine is also present in the matrix, often together with plagioclase, clinopyroxene, magnetite and ilmenite and variable proportion of glass. Olivine dolerites are free of glass and typically contain much larger laths of plagioclase partially enclosed in clinopyroxene within the ophitic texture. Secondary constituents that are present in some JRIVG basalts include various alteration products of olivine (serpentine, bowlingite), zeolite minerals in amygdules and vugs, and palagonitic alteration of glass in hyaloclastic breccias and tuffs. The samples were thoroughly checked for presence of alteration products using optical microscopy and results of major element analysis (see below). Only non-altered samples without detectable amounts of alteration products were used for petrogenetic interpretations in this study.

3. Analytical techniques

Major element composition of the basalts was determined by wet chemistry techniques in the Czech Geological Survey in Prague; basaltic standard reference materials NIST-688 and BM (ZGI Berlin) were analyzed for quality control of the measurements. The contents of Ni were measured using an ARL 9400 Advant XP X-ray fluorescence spectrometer in the Czech Geological Survey, using the BM and JB-2 basaltic SRMs for quality control. Other trace elements and isotope analyses were carried out in the Department of Earth Science at the University of Bergen. Concentrations of trace elements and REEs were determined by solution measurements on a Thermo Finnigan Element 2 ICP-MS instrument following dissolution of sample powders in a PicoTrace pressure digestion system using a mixture of HF–HNO₃ purified previously by sub-boiling distillation. Basaltic reference material BCR-2 was periodically analyzed for quality control. Results for standard reference materials analyzed for major and trace elements during the course of this study are given in the Appendix.

Powdered samples for isotope analysis were dissolved in a mixture of purified concentrated HF and HNO₃, and ion-exchange chromatography was employed to isolate Sr, Nd, Pb and Li from the sample matrix. Strontium, Pb and REE were separated by specific extraction chromatography using the technique described by Pin et al. (1994), and Nd was subsequently separated using a modified version of the method described by Richard et al. (1976). Strontium and Nd isotopes were measured on a Finnigan MAT 262 thermal ionization mass-spectrometer in static mode by double Re-filament technique. Strontium isotopic ratios were corrected for mass-dependent fractionation using 86Sr/88Sr=0.1194 and exponential law; Nd isotopic ratios were corrected in the same way using 146Nd/144Nd=0.7219. Repeat measurements of the NBS-987 and La Jolla standards in the course of this study gave average 86Sr/88Sr and 143Nd/144Nd values of 0.710267±24 and 0.511841±10 (2 s.d.), respectively. Long term precision for measurements of Sr and Nd isotopic composition in NBS-987 and La Jolla standards was 0.04 and 0.02‰, respectively. The total procedural blanks for Sr and Nd were lower than 50 and 10 pg, respectively and were negligible for the present study. Isotopic composition of Pb was determined by solution multi-collector ICP-MS (Thermo Finnigan Neptune) technique in static mode. Correction of Pb isotopic ratios for mass discrimination utilized exponential law and natural isotopic composition of 205TI/204TI=2.3871 that was added to the samples prior to the analysis. Repeat measurements of the NBS-981 standard in the course of this study gave mean 206Pb/204Pb, 207Pb/204Pb and 208Pb/204Pb ratios of 16.934±12, 15.484±12 and 36.677±29 (2 s.d.), respectively. Total procedural blank for Pb was lower than 130 pg and was always negligible.

Sample preparation and ion exchange separation of Li followed the procedure described in Magna et al. (2004). Lithium isotopic composition was determined by solution multi-collector ICP-MS in static mode and the measured isotopic ratios were corrected for instrumental mass discrimination by applying standard-sample bracketing technique. Lithium isotopic compositions of samples are expressed as δ²⁷Li (‰) with reference to the L-SVEC Li-carbonate standard (7Li/6Li=12.02±0.03; Flesch et al., 1973) that was used to bracket the samples during the analysis. Replica (including full chemical separation of Li from the matrix) measurements of basaltic reference rocks JB-2, BHVO-2 and BCR-2 analyzed during the course of this study yielded δ²⁷Li=4.78±0.53‰ (2 s.d., n=3), 4.58±0.58‰ (2 s.d., n=3) and 3.19±0.12‰ (2 s.d., n=4), respectively. This is in agreement with the published data of Tomascak et al. (1999a), Jeffcoate et al. (2004), Magna et al. (2004), Rosner et al. (2007) and others (see GeoREm at www.gorem.mpch-mainz.gwdg.de, Jochum et al., 2005 for an updated list of values). Long term precision of Li isotopic measurements of JB-2 and BHVO-2 reference samples was ~0.3‰ (2 s.d.). Total procedural blank was less than 20 pg Li which and it was negligible for the analyzed samples.

4. Results

The major and trace element compositions of the JRIVG samples are given in Table 1 and the corresponding major element characteristics are shown in Figs. 3 and 4. The rocks have Na₂O and K₂O contents of less than 4.0 and 1.5 wt.%, respectively, with only one olivine basalt...
Unlike the enrichment in Pb and Sr, which is consistent for all JRIVG from the composition of N-MORB and E-MORB (Figs. 5 and 6). While incompatible elements, including light REEs and deviate significantly from the composition of OIB, marked depletion in trace element patterns follow the composition of OIB, marked depletion in incompatible elements, including light REEs and deviate significantly from the composition of N-MORB and E-MORB (Figs. 5 and 6).
ranging from a strong enrichment (altered sample JR16) to a slight depletion in one sample (JR1). The Nb/Yb–Th/Yb compositions plot along the MORB–OIB array of Pearce and Peate (1995) with some, but not all samples overlapping compositional field of alkaline basalts from the Bransfield Strait (Fretzdorff et al., 2004; Fig. 7). The JRIVG suite differs significantly from other (non alkaline) lavas from the Bransfield Strait that have, consistently with their derivation from magmatic arc setting, higher Th and lower Nb contents.

The isotopic composition of Sr, Nd and Pb is given in Table 2 and shown in Fig. 8. The isotopic data in these plots have not been age corrected. However, given the Rb/Sr and Sm/Nd ratios, and the low U contents (mostly less than 1 ppm) in the samples, an age correction up to 6.16 Ma (i.e., the maximum reported age for samples from the area, Kristjánsson et al., 2005) would not change the Sr, Nd and Pb isotopic ratios outside the quoted analytical uncertainties. The Sr and Nd isotopic composition of most of the basalts is uniform and the data plot in a tight
Analytical uncertainties are given as 2 sigma (internal). Lithium isotopic composition is expressed relative to the L-SVEC Li isotopic standard, data in brackets correspond to replicate (including ion exchange separation) measurements of Li isotopic composition.

<table>
<thead>
<tr>
<th>Sample</th>
<th>87Sr/86Sr</th>
<th>±2 sigma</th>
<th>143Nd/144Nd</th>
<th>±2 sigma</th>
<th>εNdCHUR</th>
<th>±2 sigma</th>
<th>206Pb/204Pb</th>
<th>±2 sigma</th>
<th>207Pb/204Pb</th>
<th>±2 sigma</th>
<th>208Pb/204Pb</th>
<th>±2 sigma</th>
<th>δ7Li (‰)</th>
<th>±2 sigma</th>
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<tr>
<td>JR1</td>
<td>0.703387</td>
<td>0.00009</td>
<td>-18.6</td>
<td>0.512884</td>
<td>0.00005</td>
<td>4.8</td>
<td>18.855</td>
<td>0.001</td>
<td>15.601</td>
<td>0.001</td>
<td>38.556</td>
<td>0.003</td>
<td>3.6</td>
<td>0.3</td>
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<td>JR16</td>
<td>0.703948</td>
<td>0.00008</td>
<td>-10.7</td>
<td>0.512818</td>
<td>0.00005</td>
<td>3.5</td>
<td>18.857</td>
<td>0.001</td>
<td>15.619</td>
<td>0.001</td>
<td>38.644</td>
<td>0.002</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>JR52</td>
<td>0.703773</td>
<td>0.00009</td>
<td>-13.7</td>
<td>0.512896</td>
<td>0.00005</td>
<td>5.0</td>
<td>18.841</td>
<td>0.001</td>
<td>15.603</td>
<td>0.001</td>
<td>38.544</td>
<td>0.003</td>
<td>3.3</td>
<td>0.1</td>
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<td>0.703281</td>
<td>0.00008</td>
<td>-20.1</td>
<td>0.512903</td>
<td>0.00005</td>
<td>5.2</td>
<td>18.859</td>
<td>0.001</td>
<td>15.618</td>
<td>0.001</td>
<td>38.617</td>
<td>0.002</td>
<td>1.5</td>
<td>0.2</td>
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<tr>
<td>JR59</td>
<td>0.703216</td>
<td>0.00008</td>
<td>-21.1</td>
<td>0.512891</td>
<td>0.00005</td>
<td>4.9</td>
<td>18.916</td>
<td>0.001</td>
<td>15.608</td>
<td>0.001</td>
<td>38.626</td>
<td>0.003</td>
<td>4.0</td>
<td>0.1</td>
</tr>
<tr>
<td>JR61A</td>
<td>0.703281</td>
<td>0.00008</td>
<td>-20.1</td>
<td>0.512889</td>
<td>0.00004</td>
<td>4.9</td>
<td>18.972</td>
<td>0.001</td>
<td>15.608</td>
<td>0.001</td>
<td>38.658</td>
<td>0.003</td>
<td>3.9</td>
<td>0.1</td>
</tr>
<tr>
<td>JR61B</td>
<td>0.703175</td>
<td>0.00009</td>
<td>-21.6</td>
<td>0.512890</td>
<td>0.00006</td>
<td>4.9</td>
<td>18.953</td>
<td>0.001</td>
<td>15.637</td>
<td>0.001</td>
<td>38.637</td>
<td>0.002</td>
<td>3.4</td>
<td>0.1</td>
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<td>0.703188</td>
<td>0.00009</td>
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<td>0.512888</td>
<td>0.00005</td>
<td>4.9</td>
<td>18.932</td>
<td>0.001</td>
<td>15.614</td>
<td>0.001</td>
<td>38.646</td>
<td>0.003</td>
<td>4.0</td>
<td>0.1</td>
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<td>0.703256</td>
<td>0.00009</td>
<td>-20.5</td>
<td>0.512866</td>
<td>0.00004</td>
<td>4.4</td>
<td>18.974</td>
<td>0.001</td>
<td>15.616</td>
<td>0.001</td>
<td>38.692</td>
<td>0.002</td>
<td>4.0</td>
<td>0.1</td>
</tr>
<tr>
<td>JR71C</td>
<td>0.703211</td>
<td>0.00008</td>
<td>-21.1</td>
<td>0.512903</td>
<td>0.00005</td>
<td>5.2</td>
<td>18.829</td>
<td>0.001</td>
<td>15.111</td>
<td>0.001</td>
<td>38.463</td>
<td>0.002</td>
<td>4.3</td>
<td>0.2</td>
</tr>
<tr>
<td>JR91</td>
<td>0.703222</td>
<td>0.00007</td>
<td>-21.0</td>
<td>0.512905</td>
<td>0.00005</td>
<td>5.2</td>
<td>18.849</td>
<td>0.001</td>
<td>15.599</td>
<td>0.001</td>
<td>38.549</td>
<td>0.002</td>
<td>4.2</td>
<td>0.1</td>
</tr>
<tr>
<td>JR96</td>
<td>0.703256</td>
<td>0.00008</td>
<td>-20.5</td>
<td>0.512895</td>
<td>0.00005</td>
<td>5.0</td>
<td>18.894</td>
<td>0.001</td>
<td>15.602</td>
<td>0.001</td>
<td>38.554</td>
<td>0.003</td>
<td>6.8</td>
<td>0.1</td>
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<td>0.703216</td>
<td>0.00008</td>
<td>-21.1</td>
<td>0.512891</td>
<td>0.00005</td>
<td>5.1</td>
<td>18.745</td>
<td>0.001</td>
<td>15.596</td>
<td>0.001</td>
<td>38.470</td>
<td>0.003</td>
<td>4.9</td>
<td>0.1</td>
</tr>
<tr>
<td>JR105</td>
<td>0.703369</td>
<td>0.00009</td>
<td>-18.9</td>
<td>0.512886</td>
<td>0.00006</td>
<td>4.4</td>
<td>18.775</td>
<td>0.001</td>
<td>15.625</td>
<td>0.001</td>
<td>38.531</td>
<td>0.002</td>
<td>3.6</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Analytical uncertainties are given as 2 sigma (internal). Lithium isotopic composition is expressed relative to the L-SVEC Li isotopic standard, data in brackets correspond to replicate (including ion exchange separation) measurements of Li isotopic composition.

Fig. 7. Nb/Yb versus Th/Yb plot showing the composition of olivine basalts from the northern part of James Ross Island. Also shown is the composition of volcanic rocks from the Bransfield Strait (Keller et al., 2002; Fretzdorff et al., 2004). Compositions of MORB and OIB are from Sun and McDonough (1989), composition of enriched mantle EMII is from Armienti and Gasperini (2007), dashed lines delimit the MORB-OIB array of Pearce and Peate (1995).

Fig. 8. Isotopic composition of (a.) Sr and Nd and (b.) Pb of olivine basalts from the northern part of James Ross Island. Analytical uncertainties are within the size of the plotted symbols. Also shown are fields for lavas from the central and eastern Bransfield Basin, South Shetland Islands, Antarctic Peninsula alkali basalts and MORB. Sources of data are as in Fig. 3 with additional data from Hanan et al. (1986), Hole (1990), Birkenmajer et al. (1991), and Guangfu et al. (1997).

Cluster in Fig. 8 with epsilon Sr and epsilon Nd values ranging from ca. −19 to −21 and +4.4 to +5.2, respectively. Only two samples (altered basalt JR16 and JR52) have somewhat different Sr isotopic composition with epsilon values of −11 and −14, respectively. In the sample JR16 also differs by 1.5 epsilon units from the mean Nd isotopic composition of all other basalts. Except for these two samples, the isotopic composition of Sr and Nd in the JRIVG suite corresponds well to the isotopic composition of alkaline volcanic rocks from the Antarctic Peninsula (Hole et al., 1993) or straddles the boundary between the composition of the Antarctic Peninsula alkaline volcanics, and alkaline volcanic rocks from the eastern part of the Bransfield Strait (Fretzdorff et al., 2004) and those from the South Shetland Islands (Fig. 8a; see Keller et al., 2002 and Fretzdorff et al., 2004 for complete list of references). The Pb isotopic composition is more radiogenic compared to the volcanic rocks from South Shetland Islands and from the Bransfield Strait (Fig. 8b). Similarly, it also corresponds to the composition of alkaline basalts from the Antarctic Peninsula with only two exceptions (samples JR100 and JR105) that have Pb isotopic composition rather similar to the volcanic rocks from the Bransfield Strait. Isotopic composition of Li in the JRIVG samples varies between +3.8‰ and +6.9‰. The Li isotopic data for 12 out of 14 samples fall in a limited range with average δ7Li = +3.9 ± 0.9‰ (2 s.d.) which is indistinguishable from the Li isotopic composition of rocks associated with magmatic arcs (Tomascak et al., 2002; Leeman et al., 2004), mid-ocean ridge settings (Elliott et al., 2006; Tomascak et al., 2008) and terrestrial mantle (Magna et al., 2006b; Jeffcoate et al., 2007).
parameters that are typical of subduction settings (e.g., Ba/Nb, Ba/La and Sr/Y); $\delta^7$Li shows a weak correlation with indices of crustal assimilation and/or crystal fractionation, e.g., LREE/Pb (Fig. 9). This is, however, largely controlled by two samples with extreme $\delta^7$Li.

Collectively, the JRIVG alkaline basaltic lavas are geochemically different from the subduction (arc)-related magmatic rocks from the Bransfield Strait and from the Antarctic Peninsula. The main differences found in the lavas from James Ross Island include higher K/Na ratio, higher content of incompatible elements, lack of a negative Nb anomaly and more radiogenic isotopic composition of Pb (compared to the rocks found in Southern Shetlands and Bransfield Strait).

5. Discussion

5.1. Origin of alkaline magmas in the Antarctic Peninsula subduction system

Products of alkaline magmatism along the Antarctic Peninsula subduction system were found on South Shetland Islands, in Bransfield Strait, on Brabant Island, on James Ross Island and the adjacent archipelago as far to the north-east as Paulet Island, on Seal Nunataks, on Jason Peninsula, and further south in the Palmer Land on Alexander Island, Seaward Mountains, Merrick Mountains and Rydberg Peninsula (Fig. 1; Smellie, 1987; Hole, 1988, 1990; Hole et al., 1991a,b; Smellie, 1999; Fretzdorff et al., 2004). The age of alkaline magmatism varies from recent to ca. 54 Ma on Alexander Island. There, the formation of alkaline magma has been attributed to opening of a slab window beneath the Antarctic Peninsula, upwelling of a non-altered asthenospheric mantle and decompression melting that started in the garnet stability field and led to the formation of alkaline basaltic magma (Hole et al., 1991b, 1995). Variety of alkaline magmas could have formed from two asthenospheric mantle sources: (i) by partial melting of shallow convecting MORB-like asthenosphere beneath the Antarctic Peninsula and (ii) from a deep-seated mantle plume beneath the West Antarctic rift system, which produced basaltic magma as a result of plume rise and decompression melting. This model assumes very little or no contribution from the subducting slab to the mantle-derived magma (Hole and LeMasurier, 1994 and references therein). While this process can explain formation of alkaline magma on Alexander Island, it is unlikely for the origin of other occurrences of alkaline rocks further north where it is not consistent with the available geophysical evidence and where the lava eruptions are significantly younger (see discussion in Fretzdorff et al., 2004). Alternative models were proposed to explain the formation and variability in geochemical composition of alkaline and sub-alkaline magmas associated with the Antarctic Peninsula subduction system.

(i) The alkaline magmatism in the JRIVG originated by low but variable degrees (~3%) of partial melting of garnet-bearing mantle and the composition of the melt was further modified by fractional crystallization of olivine and clinopyroxene. Although there is no clear temporal association of the alkaline magmatism with the within-plate setting (e.g., migration of the plate over a stationary mantle hot-spot), regional extension was a prerequisite for magma ascent to the surface (Smellie, 1987).

(ii) The sub-alkaline magma formation in the Bransfield Strait has been explained by melting of a MORB-like mantle source contaminated by variable amounts (up to 5%) of subduction-related component, either metalliferous sediments (Keller et al., 2002) or LILE-rich fluid with radiogenic Sr, Nd and Pb isotope compositions derived predominantly from subducted sediments (Fretzdorff et al., 2004). Lee et al. (2008) explain the formation of volcanic rocks of the South Shetland Islands by addition of a relatively constant subduction component, either metalliferous sediments (Keller et al., 2002) or radiogenic Sr, Nd and Pb isotope compositions, that is derived from recent to ca. 54 Ma on Alexander Island. There, the formation of alkaline magma has been attributed to opening of a slab window beneath the Antarctic Peninsula, resulting in upwelling and melting of asthenosphere and mixing of the melts with MORB-like crust underneath what has later became the JRIVG (Hole et al., 1995).

5.2. Origin of alkaline rocks from the northern part of James Ross Island

Compared to the geochemical signatures of alkaline rocks discussed in the previous section, a model of magma formation for olivine basalts from the northern part of James Ross Island must also account for elevated contents of incompatible elements, as well as for a significantly more radiogenic isotopic composition of Pb and the observed range of Li isotopic compositions. The level of trace element enrichment is significantly higher compared to that of volcanic rocks
from the Bransfield Strait (Keller et al., 2002; Fretzdorff et al., 2004) and markedly different from the composition of the N-MORB both from MAR and EPR (cf. Klein, 2003). A simple two-component mixing model similar to that used by Keller et al. (2002) has been attempted to explain the composition of the JRIVG samples (Fig. 10). Similar to average Atlantic sediment (87Sr/86Sr=0.7092, Sr=150 ppm, 143Nd/144Nd=0.5132, Nd=0.1 ppm, 206Pb/204Pb=17.60, Pb=0.043 ppm; cf. Keller et al., 2002) and two potential sedimentary contaminants: an average Atlantic sediment with ca. 14-fold Pb content) can explain the composition of the JRIVG lavas (Fig. 10). A similar model based on the composition of depleted mantle-derived magma and average Atlantic sediment (Fig. 10). Contrary to this, Lee et al. (2008) have shown that a great proportion of fluid mobile elements in sub-alkaline lavas from South Sandwich Islands (~200 km NNW) were derived from a subducted altered crust component. Therefore, when combined with our data, progressively decreasing input of fluid phase originated from subducting plate into the melting region provides evidence of drastically reduced role of sedimentary component in generation of back-arc volcanics.

In contrast to the contamination of depleted mantle component by sediments, its mixing with ca. 25–35 wt.% of enriched mantle component, such as is EMII (assuming Pb/Sr/Nd=1/10/2 and 87Sr/86Sr=0.7078, 143Nd/144Nd=0.5126, 206Pb/204Pb=19; Armiinti and Gasperini, 2007; Fig. 10), can explain the composition of the bulk of the JRIVG lavas. The somewhat higher proportion of enriched mantle component required to model the composition of the JRIVG lavas in the Pb–Nd system compared to the Pb–Sr mixing may reflect Sr–Nd elemental decoupling during the melting. Small variations in the isotopic compositions of Sr and Nd might reflect variable proportions of the two main magma sources in the mixture. Interestingly, most of the samples plot within the composition field of alkaline basalts from the Antarctic Peninsula in Fig. 10 (Hole, 1990; Hole et al., 1993; cf. also Keller et al., 2002), i.e., they contain substantially more radiogenic Pb than samples from other back-arc settings, such as the Japan Sea, the Mariana Trough or the Scotia Arc (cf. Fig. 10). Although some of the observed Sr, Nd and Pb isotopic signatures could be explained by contamination of MORB-like magma with a more geochemically evolved material of the Antarctic Peninsula crust, this is not consistent with their trace element signatures, Li isotopic composition and field or geophysical information. There is no direct evidence (e.g., seismic data or occurrence of xenoliths in volcanic rocks) of the crustal rocks from the northern part of the Antarctic Peninsula extending further east beyond the Prince Gustav Channel and forming a basement of the Triassic–Tertiary sediments in the James Ross Basin, although similarities exist between the northern part of Antarctic Peninsula (Graham Land) and southern South America (e.g., Magallanes Basin) where the volcanic and plutonic basement rocks extend east of the cordillera and partly underlie the back-arc basin (see discussion in Hathway, 2000). Alternatively, a magma contamination by the Triassic–Tertiary clastic sedimentary rocks that occur in the James Ross Basin and that were derived from the Antarctic Peninsula (Pirrie, 1994) could have also provided the radiogenic Pb for the mantle-derived parent magma of the JRIVG basalts. Field evidence for variable contamination of basaltic magma by sediments was found on several outcrops during this study. It varies from occurrence of sedimentary xenoliths in the basalts to partial and sometimes almost complete melting of the sedimentary xenoliths and sediments adjacent to magma intrusions. The available data do not allow for a quantitative estimate of the sediment contribution to the magma but our field observations suggest that assimilation of the sediments did not have a profound effect on the composition of the JRIVG lavas.

5.3. Lithium isotopes in JRIVG lavas

Lithium isotopes have been used to unravel processes of seafloor alteration, subduction, dehydration and arc volcanism (Chan et al.,
The isotopic compositions and major and trace element contents in olivine basalts from the back-arc basin exposed in the northern part of James Ross Island are fairly homogeneous, except for only few outliers. They are indicative of ca. 25–35 wt.% contribution of an enriched mantle component to a MORB-like depleted mantle with no significant contribution of sedimentary material from the subducted oceanic lithosphere of the Antarctic plate. Limited number of samples shows variations in contents of trace elements and also Li isotopes, and to a minor extent also Sr and Pb isotopes but these are interpreted as resulting from localized contamination of the magma by Triassic–Tertiary clastic sediments at a late stage of the lava emplacement. Composition of the JRIVG lavas is different from the composition of other volcanic rocks in this region, in particular basaltic rocks that form the South Shetland Islands (e.g., Machado et al., 2005 and references therein) and the ocean floor in the Bransfield Strait (Keller et al., 2002; Fretzdorff et al., 2004) that have lower K2O/Na2O ratios, lower contents of incompatible elements and less radiogenic isotopic composition of Pb. These differences are attributed mainly to the presence of a slab-derived component in the rocks of South Shetland Islands and Bransfield Strait. The K-enrichment in the JRIVG basalts relative to other volcanic rocks in the area (Fig. 4) most likely reflects different magma sources and low-degree partial melting in the enriched mantle component that contributed to the JRIVG lavas. The presence of enriched mantle component in the back-arc lavas from James Ross Island and its lack in the magmatic rocks found west of the Antarctic Peninsula are consistent with the model of regional extension linked to the roll-back of the subducted slab of Antarctic plate (cf. cartoon on Fig. 10, Hole et al., 1995). In this model, the roll-back of the trench resulted in upwelling and melting of the enriched mantle asthenosphere and mixing of the melts with MORB-like crust underneath the JRIVG. Consistently with the available data, the contribution of a slab-derived component in this model should increase towards the trench. The newly obtained geochemical data point to the importance of tectonic control during the formation of alkaline volcanic rocks in the JRIVG in western Antarctica.

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Appendix A. Details of major and trace element analysis

Major element concentrations were determined after combined HF–HNO3 digestion of rock powder by the following techniques:
Table A1
Measured and reference values (GeoReM; Jochum et al., 2005) for standard reference materials analyzed during this study

<table>
<thead>
<tr>
<th>Measured values</th>
<th>GeoReM values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>1 s.d.</td>
</tr>
<tr>
<td>Ni in ZGI-BM</td>
<td>47.99</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.12</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>17.18</td>
</tr>
<tr>
<td>MgO</td>
<td>10.03</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>7.42</td>
</tr>
<tr>
<td>MnO</td>
<td>0.167</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.02</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.196</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.133</td>
</tr>
</tbody>
</table>

ZGI-BM (wt.%), standard deviation calculated from 14 replicate measurements

<table>
<thead>
<tr>
<th>Measured values</th>
<th>GeoReM values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1 s.d.</td>
</tr>
<tr>
<td>CaO</td>
<td>6.54</td>
</tr>
<tr>
<td>MgO</td>
<td>7.36</td>
</tr>
<tr>
<td>CO₂</td>
<td>1.34</td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.68</td>
</tr>
<tr>
<td>H₂O</td>
<td>3.92</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.15</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Mean values of trace element concentrations (in ppm) calculated from two ICP-MS measurements of the BCR-2 basaltic standard reference material and the corresponding GeoReM values are given in Table A1. The relative precision of individual SRM and sample ICP-MS trace element analyses calculated from 3 repeat measurements (each 5 spectrum sweeps) was better than 3% (1 s.d.).
Hole, M.J., Smellie, J.L., Mariner, G.F., 1991a. Geochemistry and tectonic setting of alkalial-

volcanism and sial window formation. Geology 19, 657–660.

Hole, M.J., Smellie, J.L., 1993. Tectonic element and isotope characteristics of small
degree melts of the asthenosphere: evidence from the alkalic basalts of the
Antarctic Peninsula. Chem. Geol. 109, 51–68.

Com�s back-arc alkaline volcanic rocks from West Antarctica. Contrib. Mineral.

alkaline magmatism, lithospheric extension and sial window formation along
continental margins described at plate margins. In: Smellie, J.L. (Ed.), Volcanism Associated


determinations of lithium isotopic compositions of geological reference materials

network for exact measurement of small samples of lithium using multiple-collector ICPMS. Int. J.
Radioanal. 91, 593–659.


Geochemistry of back arc basin volcanism in Bransfield Strait, Antarctica: subducted
contributions and along-axis variations. J. Geophys. Res. 107 (B8), 2171.

measurement of small samples of lithium using multiple-collector ICPMS. Int. J.
Radioanal. 91, 593–659.

arc basin volcanism in Bransfield Strait, Antarctica: subducted contributions and
along-axis variations. J. Geophys. Res. 107 (B8), 2171.

Jeffcoate, A.B., Elliott, T., Fisk, M.R., White, W.M., Birkenmajer, K., 1992. Isotopic and trace element
constraints on mixing and melting models of marginal basin volcanism, Bransfield


constraints on mixing and melting models of marginal basin volcanism, Bransfield


