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The Blackstones Bank igneous complex: geochemistry and crustal context of a submerged Tertiary igneous centre in the Scottish Hebrides

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Abstract – The Blackstones Bank, located about 60 km WSW of the Isle of Mull in Western Scotland, is a submarine plutonic complex in the British Tertiary Igneous Province. Geochemical and isotopic analysis of gabbros, microgabbros and basic dykes shows that the magmas interacted strongly with crustal rocks during their emplacement. The isotopic signature of the contaminated Tertiary intrusions shows no evidence of any interaction with Archaean basement, despite the location of the Blackstones complex to the west of the Great Glen fault. Instead, the Blackstones rocks have crustal signatures resembling the Proterozoic basement and cover rocks of western Islay. It is therefore inferred that Early Proterozoic crust extends to the west of the Great Glen fault at this point on the Scottish continental shelf. In addition, the occurrence of similar isotopic signatures in Tertiary igneous rocks east of the Loch Gruinard fault confirms that Early Proterozoic basement extends under the Grampian block of mainland Scotland. When combined with published evidence from the Rockall bank, the new data constrain the location of an Archaean–Proterozoic crustal suture with a WNW trajectory which cuts across the continental shelf of northwest Britain.

1. Introduction

The Blackstones Bank igneous complex is situated about 60 km WSW from the Ross of Mull in western Scotland (Fig. 1a), where it rises from a relatively flat sea bed 100 m deep to form submarine shoals which come within 20 m of the sea surface (Durant, Kokelaar & Whittington, 1982). The general structure of the igneous centre has been determined by geophysical mapping. A huge Bouguer gravity anomaly (+134 milligals) centred on the Blackstones Bank is evidence for a large dense cylinder of basic/ultrabasic rock, similar to those inferred under several Hebridean Tertiary igneous centres. Seismic reflection and refraction work (McQuillin, Bacon & Binns, 1975) showed that 10 % of the surface area of the complex was exposed as basic igneous rock, while the remainder was covered by a variable thickness of sediment, probably representing the original roof of the complex as well as more recent deposits. Fortunately, much of the outcrop area of the igneous complex was shallower than 50 m water depth, bringing it within the range of examination by SCUBA diving (G. P. Durant, unpub. Ph.D. thesis, Univ. Wales, Aberystwyth, 1977).

Durant, Kokelaar & Whittington (1982) presented a geological map of the Blackstones complex (Fig. 1b) based on examination during numerous dives in 1974, 1975 and 1980. Most of the igneous outcrop was seen to consist of gabbro, along with some small areas of granophyre and numerous NW-trending basaltic dykes. Petrographic examination of the gabbros revealed cumulate textures similar to those seen in other Hebridean layered complexes. Unfortunately it has not been possible to reconstruct a detailed ‘cryptic layering’ magma chamber history for the Blackstones layered gabbros. However, bearing in mind the complexities of the other Hebridean layered complexes such the Cuillin Hills of Skye (Dickin *et al.* 1984) , it should not be surprising that a dozen gabbroic samples from scattered localities in the Blackstones complex have not been sufficient to reconstruct a detailed differentiation model.

Geophysical and geological evidence suggested that the Blackstones complex was probably Tertiary in age, based on its similarity to the other Tertiary Hebridean centres. This has been confirmed by a limited amount of K–Ar age dating. Durant *et al.* (1976) reported an age of about 70 Ma for a basalt from site 74-2, while unpublished K–Ar data for feldspar separates from two granophyre localities (75-17 and 80-4) indicate an age of 58.6 ± 1 Ma (R. Macintyre, pers. comm.). Hence we can now verify that the Blackstones complex is of approximately the same age as the other Hebridean centres.

The present work represents an investigation of the major-element, trace-element and radiogenic isotope systematics of selected 1974, 1975 and 1980 dive samples in order to reconstruct as far as possible the

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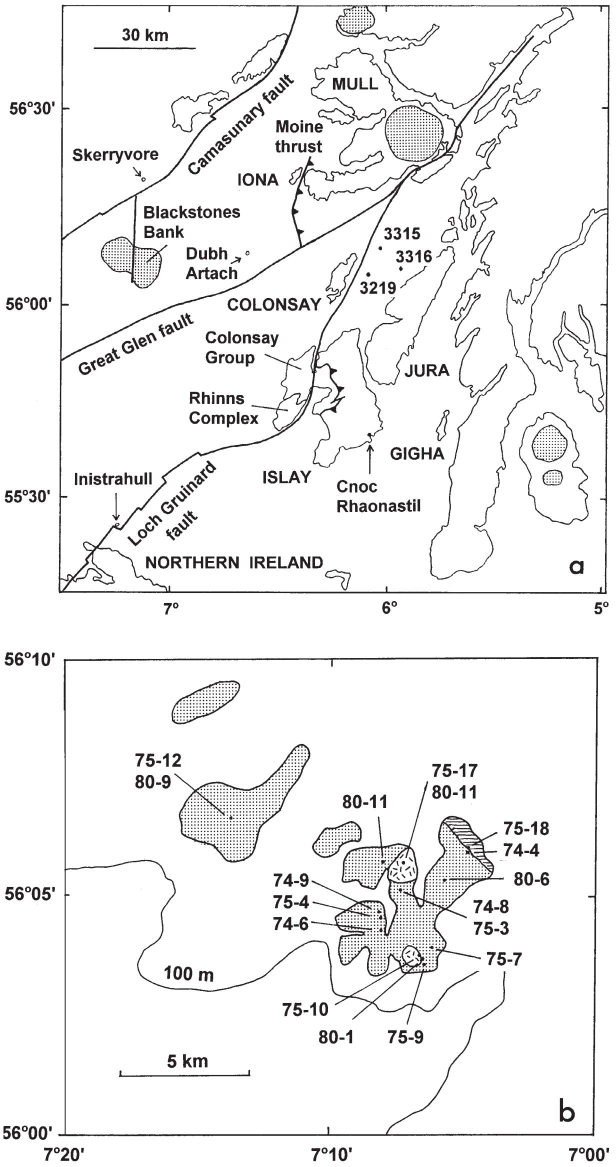

Figure 1. Maps showing (a) the location of the Blackstones Bank plutonic centre and other sampling sites relative the major crustal terranes and other Tertiary igneous centres in western Scotland; (b) geological map of rock outcrop on the Blackstones Bank, along with sampling sites. Finely dotted ornament = gabbroic rock; horizontal rule = metasediments; coarse stipple = granophyres.

differentiation history of the whole complex and the nature and affinity of the crustal section into which it was emplaced.

The geological context of the Blackstones Complex is shown in Figure 1a. The complex lies to the northwest of the Great Glen fault and west of the Moine thrust. Hence, the expected crustal rock types are Archaean gneissic basement and overlying Torridonian supracrustal sediments. However, the complex also lies close to the Early Proterozoic gneiss terrane of Islay (the Rhinns Complex of Muir, Fitches & Maltman, 1994). Hence, all three of these crustal rock types are examined as possible crustal contaminants of the Tertiary magmas. In addition, Tertiary minor intrusions from the Firth of Lorne north of Jura, from Islay and from Gigha (Fig. 1a) were examined for comparative purposes.

2. Experimental techniques

Most submarine samples recovered were quite fresh, but covered in surface encrustations. These were carefully removed using a diamond saw and grinding wheel, after which the rock slabs were cleaned with ultra-pure water in an ultrasonic bath before crushing and powdering.

Major and trace element data (Table 1) were obtained by Activation Laboratories, Ancaster, Ontario, using flux-aided dissolution. Major elements were analysed by ICP-AES, and trace elements by ICP-MS. Rb and Sr concentration data from Table 1 were used to determine $^{87}Rb/^{86}Sr$ ratios, and hence to calculate Sr isotope ratios at 60 Ma. These age corrections are generally quite modest in size and only contribute to significant initial ratio uncertainties in the acid rock types. Furthermore, duplicate Rb/Sr determinations on the three granophyres by isotope dilution yielded excellent reproducibility, to within 3% of the ICP data. Some samples were also analysed by XRF at Glasgow, yielding an average reproducibility of 7% relative to ICP data for Rb/Sr ratios. For samples which were too small for complete geochemical characterization, Rb/Sr ratios in Table 2 are based on XRF data alone.

Isotopic analysis (Table 2) was performed at McMaster University using routine techniques for chemical separation and mass spectrometry. Powdered samples for Pb isotope analysis were leached in warm dilute HCl before acid digestion. Pb isotope ratios are quoted after a fractionation correction of 0.1% per a.m.u., based on analysis of the NBS 981 standard (average measured 207/204 value = 15.44). Reproducibility of fractionation-corrected Pb isotope data is estimated to be 0.1% (2 sigma), based on sample repeats and standard reproducibility. Sr isotope analyses were normalized to 86/88 = 0.1194 and are quoted relative to a value of 0.71024 for the NBS 987 standard. Nd isotope analyses were normalized to 146/144 = 0.7219 and are quoted relative to a value of 0.51185 for the La Jolla standard. Within-run precision averaged 0.00002 for Sr and 0.000014 for Nd (2 sigma).

No age corrections were made for Pb and Nd isotope ratios. These corrections would be very small relative to the range of isotope compositions in the data, and would be more or less the same for the Tertiary igneous rocks and possible sources. In addition, the quality of Pb concentration data (not presented) was poor. Hence, age corrections for Pb and Nd would not significantly enhance the evaluation of the isotopic data.

Table 1. Major and trace element chemistry

	Uncontaminated basic			Contaminated basic											Hornfels		Granophyre
	75-9b	75-18	80-4c	74-4	75-4a	75-4b	75-7	75-9a	75-10	75-12a	75-12c	80-1c	80-1m	80-9c	75-3	80-11	75-17
SiO_2	46.60	47.10	47.44	44.66	46.61	45.57	47.99	44.66	48.11	47.03	46.24	45.11	46.65	47.20	51.95	49.26	67.75
TiO_2	2.05	1.54	1.21	0.71	0.32	0.89	1.08	0.71	1.41	0.24	2.02	2.78	0.95	1.87	1.69	0.73	0.73
Al_2O_3	13.58	15.55	15.79	14.11	21.61	13.67	16.65	14.11	15.29	20.69	13.44	12.99	16.82	14.29	15.92	11.49	14.38
Fe_2O_3	14.15	12.38	11.32	11.38	6.56	11.00	10.49	11.38	11.93	5.43	12.40	16.16	10.44	13.66	11.58	9.76	4.39
MnO	0.21	0.19	0.17	0.16	0.09	0.19	0.15	0.16	0.18	0.07	0.20	0.24	0.14	0.22	0.17	0.17	0.06
MgO	6.46	8.23	10.33	16.03	7.09	14.70	6.85	16.03	6.77	7.48	6.54	5.53	8.41	6.93	4.56	11.24	0.83
CaO	11.33	12.76	12.08	11.05	14.28	9.96	13.42	11.05	11.86	16.57	11.50	9.54	12.21	11.79	10.00	13.80	2.10
Na_2O	3.13	1.99	1.87	1.26	1.60	1.84	2.21	1.26	2.71	1.31	3.15	2.95	1.89	2.68	3.06	1.35	3.93
K_2O	0.48	0.64	0.27	0.10	0.12	0.41	0.31	0.10	0.48	0.09	0.14	0.83	0.17	0.22	1.07	0.55	4.88
P_2O_5	0.19	0.10	0.17	0.03	0.03	0.07	0.10	0.03	0.14	0.01	0.17	0.27	0.07	0.15	0.20	0.06	0.18
H_2O	1.94	0.08	0.00	0.00	1.15	2.59	0.26	0.00	1.84	1.03	2.80	2.20	2.84	1.63	0.35	0.69	0.51
Total	100.12	100.56	100.65	99.49	99.46	100.89	99.51	99.49	100.72	99.95	98.60	98.60	100.59	100.64	100.55	99.10	99.74
Mg no.	56	65	72	74	75	79	64	80	61	79	59	49	69	58	52	76	34
Cr	90	252	411	90	243	1050	245	723	158	549	130	22	237	192	11	162	0
Ni	100	111	174	99	129	264	21	274	85	84	87	97	108	100	71	99	33
Ba	114	92	36	59	36	96	73	18	109	10	58	159	28	51	319	127	839
Rb	11	39	18	8	5	13	6	4	13	2	2	29	4	6	32	22	145
Sr	171	194	159	157	196	129	180	109	171	279	226	138	114	186	224	125	138
Y	36	25	23	13	7	19	22	12	34	5	31	50	21	34	36	22	36
Zr	108	88	63	43	21	46	62	28	74	13	131	175	38	94	91	62	287
Hf	3.6	2.7	2.3	1.4	0.6	1.7	2.0	0.9	2.9	0.4	3.9	5.0	1.7	3.2	2.8	1.9	7.9
Nb	7.2	1.5	1.8	1.7	0	2.7	0.8	0.7	4.6	0	8.6	14.0	3.0	3.3	6.7	0.8	13.0
La	5.3	2.8	3.0	3.6	1.4	3.6	5.1	1.3	5.4	1.1	8.5	8.9	1.9	5.2	16.3	7.5	41.1
Ce	12.3	9.2	8.1	7.5	3.2	7.6	12.3	3.4	11.9	2.7	19.9	21.3	4.7	13.5	33.0	18.7	77.4
Nd	13.9	9.8	8.7	5.8	2.6	7.3	8.9	3.3	11.4	2.2	17.1	21.1	5.9	13.1	21.7	11.4	35.3
Sm	5.0	3.5	3.1	1.7	0.9	2.4	2.9	1.4	4.2	0.8	4.8	7.0	2.5	4.3	5.8	3.4	7.5
Eu	1.67	1.30	1.04	0.65	0.50	0.84	1.10	0.60	1.34	0.50	1.65	2.29	0.90	1.50	1.58	0.85	1.39
Gd	5.8	4.2	3.7	2.2	1.1	3.0	3.6	1.8	4.9	0.9	6.0	8.5	3.2	5.4	5.9	3.8	6.9
Tb	1.21	0.78	0.70	0.39	0.20	0.63	0.67	0.34	1.03	0.17	1.00	1.62	0.67	1.01	1.09	0.66	1.00
Dy	6.7	4.3	4.0	2.3	1.3	3.5	4.3	2.3	6.0	1.1	5.3	8.7	3.8	5.5	6.2	4.4	5.9
Er	4.1	2.8	2.6	1.4	0.8	2.2	2.6	1.3	3.6	0.6	3.5	5.6	2.4	3.7	3.4	2.3	3.5
Yb	4.0	2.3	2.2	1.4	0.7	2.1	2.2	1.2	3.5	0.5	2.6	4.7	2.2	3.0	3.4	2.2	3.6
Lu	0.59	0.38	0.33	0.21	0.11	0.31	0.34	0.19	0.53	0.08	0.42	0.69	0.32	0.49	0.50	0.34	0.56
Ta	0.53	0.07	0.10	0.12	nd	0.20	nd	nd	0.31	nd	0.46	0.83	0.17	0.18	0.44	nd	0.98
Th	0.62	0.30	0.36	1.02	0.22	0.87	0.50	0.26	0.86	0.17	0.89	0.99	0.27	0.52	3.33	1.39	15.3
U	0.22	0.16	0.21	0.26	0.07	0.45	0.16	0.07	0.32	0.06	0.27	0.29	0.16	0.25	1.24	0.52	3.9

Major element oxides are quoted in weight % and trace elements in ppm (microgram/gram).

3. Elemental geochemistry

Elemental analyses of Blackstones Tertiary igneous rocks (Table 1) are divided into four categories, based on a combination of elemental and isotopic data. The largest group is of fresh basic rocks, sub-divided into contaminated and uncontaminated groups based on isotopic data to be discussed in Section 4. Another group comprises three ‘basic hornfels’, fine-grained altered basic rocks with a distinct isotopic signature, of which representative analyses are presented in Table 1. The last group is comprised of three samples of granophyre with similar elemental compositions, of which one is also included in Table 1.

Several of the basic rocks are cumulate gabbros, and therefore do not truly represent liquid compositions. Hence, their major element geochemistry can only be used to make tentative comments about the relationships between them. This is indicated on plots of MgO, CaO and total Fe (as Fe_2O_3) against differentiation index (Mg no.), on which the data display considerable scatter (not shown). It is also notable that silica contents in all the basic rocks are essentially constant. In contrast, incompatible trace elements such as Nd (Fig. 2) are quite strongly anti-correlated with Mg no. in all of the fresh basic rocks except 80-6e. The latter sample is abnormal for several elements, and was evidently the most strongly affected by cumulate processes. Hence, its elemental chemistry will not be considered further. However, in the remaining samples, modal mineral variations caused by cumulus processes apparently did not prevent these rocks from preserving the incompatible element signatures of the liquids.

On a chondrite-normalized incompatible element diagram, the two lowermost profiles in Figure 3a (solid diamonds) represent basic rocks which show insignificant amounts of crustal contamination, based on isotopic compositions in Table 2. These samples define hump-backed REE profiles that are typical of primitive Tertiary Hebridean basalts, attributed to depletion of the mantle source by a previous melting event (Morrison *et al.* 1980). These two samples have anomalously

Table 2. Isotopic data for the Blackstones Complex

Sample number	Unit	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_i$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Blackstones Complex, uncontaminated basic rocks								
75-9b (3326b)	Basalt-dyke?	0.19	0.70341	0.70325	0.513114	18.39	15.49	38.30
75-18 (3336e)	Micro-gabbro	0.58	0.70352	0.70303	0.513129	18.59	15.55	38.64
80-4c	Gabbro?	0.33	0.70338	0.70310	0.513100	ND	ND	ND
80-6e	Gabbro cumulate	0.00	0.70289	0.70289	0.513076	18.78	15.56	38.63
Blackstones Complex, contaminated basic rocks								
74-4 (3250a)	Gabbro	0.15	0.70551	0.70538	0.512515	18.56	15.53	38.65
74-6 (3276a)	Gabbro	0.06*	0.70488	0.70483	0.512645	ND	ND	ND
74-9 (3278a)	Gabbro	0.32*	0.70669	0.70642	0.512613	ND	ND	ND
75-4a (3321a)	Gabbro cumulate	0.07	0.70472	0.70466	0.512771	18.42	15.50	38.53
75-4b (3322b)	Micro-gabbro porphyry	0.29	0.70550	0.70525	0.512810	18.81	15.53	38.73
75-7 (3325a)	Basic dyke	0.10	0.70671	0.70663	0.512666	ND	ND	ND
75-9a (3326a)	Gabbro	0.11	0.70374	0.70365	0.512889	18.62	15.51	38.53
75-10 (3327c)	Micro-gabbro	0.22	0.70442	0.70423	0.512784	19.10	15.57	38.67
75-12a (3329a)	Gabbro	0.02	0.70658	0.70656	0.512698	18.63	15.54	38.59
75-12c (3330c)	Dyke contact	0.03	0.70399	0.70396	0.513014	ND	ND	ND
80-1c	Gabbro cumulate	0.61	0.70426	0.70374	0.513063	18.51	15.50	38.33
80-1m	Gabbro cumulate	0.11	0.70380	0.70371	0.513021	ND	ND	ND
80-9c	Gabbro	0.09	0.70410	0.70402	0.513001	18.51	15.52	38.38
Blackstones Complex, basic hornfels								
74-8 (3277a)	Basic hornfels	0.80*	0.71280	0.7121	0.512146	20.43	15.78	39.24
75-3 (3320b)	Basic hornfels	0.41	0.71253	0.7122	0.512143	20.47	15.73	39.15
80-11	Basic hornfels	0.51	0.71019	0.7098	0.512099	20.76	15.81	39.50
Blackstones Complex, granophyres								
75-17 (3334)*	Granophyre	3.05	0.71529	0.7127	0.511678	19.30	15.56	39.43
80-4a	Granophyre	3.28	0.71403	0.7112	0.511625	19.17	15.54	39.41
80-4b	Granophyre	3.26	0.71335	0.7106	0.511680	19.09	15.53	39.38
Firth of Lorne-Islay-Gigha								
3200	Dubh Artach, sill	0.14*	0.70499	0.70487	0.512295	16.42	15.19	36.55
3219	Scalasaig, plug	0.33*	0.70959	0.70931	0.512227	18.40	15.52	38.19
3315	Colonsay-Jura, dyke	0.29*	0.70842	0.70817	0.512284	18.39	15.53	38.14
3316	Colonsay-Jura, dyke	0.25*	0.70933	0.70912	0.512085	18.01	15.49	37.79
3213-1	Cnoc Rhaonastil, Islay	0.09	0.70482	0.70474	0.512746	18.15	15.54	37.91
3213-5	Cnoc Rhaonastil, Islay	0.06	0.70484	0.70479	0.512695	18.12	15.54	37.89
3205-1	Cairnvickie, Gigha	0.10	0.70371	0.70363	0.512984	18.36	15.44	38.11
Islay basement								
PH1	Granitoid orthogneiss	0.28	0.70960	0.7094	0.51171	16.48	15.29	35.59
PH2	Granitoid orthogneiss	0.25	0.70812	0.7079	0.51150	17.97	15.49	36.56
PW1	Granitoid orthogneiss	0.36	0.71310	0.7128	0.51161	18.77	15.53	36.52
PW2	Mafic orthogneiss	0.01	0.70308	0.7030	0.51179	17.44	15.41	36.57
PW3	Granitoid orthogneiss	0.57	0.71683	0.7163	0.51164	16.82	15.36	35.46
Islay Torridonian								
T5	Metagreywacke	1.01	0.72403	0.7232	0.511891	21.13	15.72	38.46
T6	Metagreywacke	0.58	0.73398	0.7335	0.511767	20.01	15.73	38.45
T7	Metagreywacke	1.42	0.74233	0.7411	0.511725	19.87	15.71	37.89
T8	Metagreywacke	2.04	0.72553	0.7238	0.511776	19.85	15.71	38.51

* = Rb/Sr data from Durant (G. P. Durant, unpub. Ph.D. thesis, Univ. Wales, Aberystwyth, 1977); ND = not determined; 0 = below detection limit.

large rubidium and potassium contents, but this may reflect sub-solidus mobility of these elements.

Four profiles shown in Figure 3b represent basic rocks whose isotopic signatures are suggestive of strong crustal contamination. The spidergrams are relatively flat, with significant enrichments in Th, Nb, Ta and light REE relative to the isotopically uncontaminated rocks in Figure 3a. It is notable that these profiles are very different from the Skye Main Lava Series or the Mull Plateau Basalts (Thompson *et al.* 1982, 1986). This could reflect the involvement of different crustal contaminants in the Blackstones centre, relative to Skye and Mull, a suggestion that will be examined further using isotopic evidence.

Going back to Figure 3a, the third profile (solid circles) is a basic hornfels whose chemistry is typical of

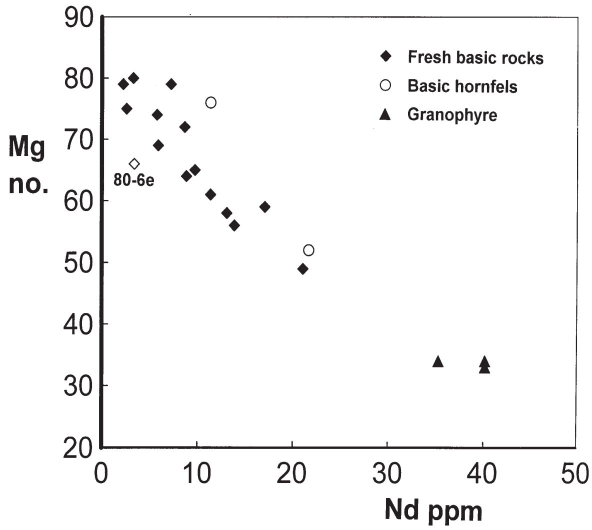

Figure 2. Plot of Nd concentration against Mg number for Blackstones samples showing a strong correlation for the main suite of mafic rocks. Two basic hornfels samples lie off the main trend, while sample 80-6e shows anomalous behaviour.

that group. The enriched incompatible element signature and the distinct isotopic signature of this rock are suggestive of a combination of crystal fractionation and crustal contamination, of which the details will be discussed in Section 4. Finally, the top profile in Figure 3a (solid triangles) is a granophyre. Elemental evidence cannot clearly distinguish between a origin by crustal anatexis or by crustal assimilation during fractional crystallization (AFC: DePaolo, 1981). However, a notable feature of this profile is the strong depletion in Sr and Ti (and also Eu), which suggests that the parent magma of this rock underwent strong plagioclase and magnetite fractionation. This would be consistent with an origin from a differentiated basic magma.

4. Isotope geochemistry

Isotope data are presented in Table 2 and in several isotope–isotope plots. However, we will first examine the relationship between Nd isotope composition and elemental concentration on a plot of $^{143}Nd/^{144}Nd$ against 1/Nd ppm (Fig. 4). Most of the basic samples on this diagram fall on two arrays with negative slope. These relatively strong anti-correlations between Nd isotope ratio and concentration provide strong evidence that the isotopic variations in the Blackstones rocks are due to crustal contamination rather than inherited mantle heterogeneity. In addition, correlations on the isotope–isotope plots are also totally consistent with contamination processes.

The negative arrays in Figure 4 resemble the data of Thirlwall & Jones (1983) from the Skye Main Lava Series. Each array corresponds to a constant amount of crustal contamination, acting on a suite of magmas with variable Nd contents. A possible mechanism for this kind of contamination was proposed by Huppert & Sparks (1985), who suggested that the turbulent flow of hot mafic magmas could erode and incorporate wall rocks in a process termed ‘contamination

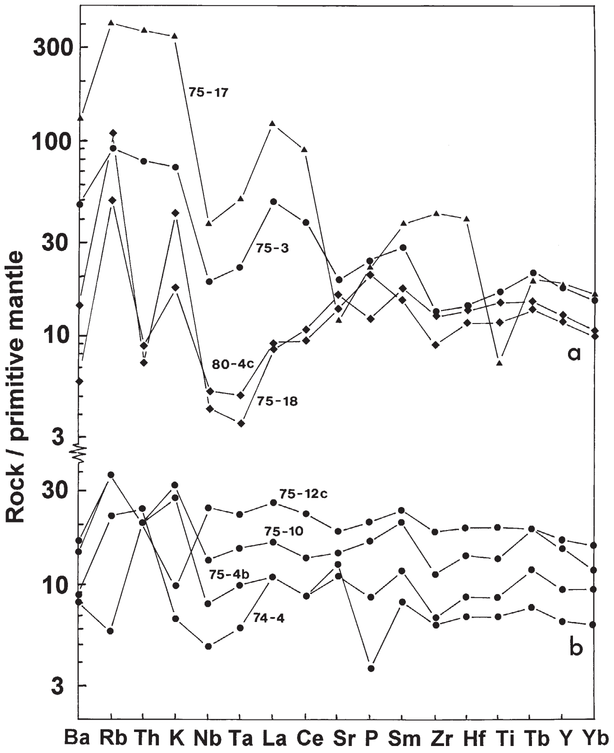

Figure 3. Chondrite-normalized incompatible element profiles for Blackstones samples: (a) two uncontaminated basic rocks, plus a basic hornfels and granophyre; (b) basic samples showing isotopic evidence of strong crustal contamination.

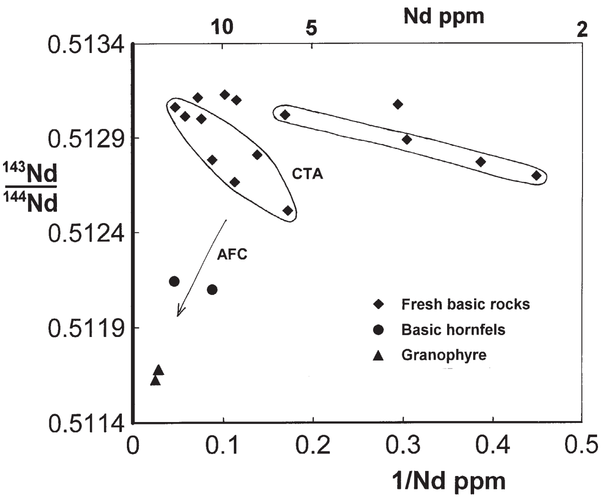

Figure 4. Plot of Nd isotope ratio against 1/Nd concentration showing alternative contamination mechanisms of Assimilation Fractional Crystallization (AFC) and Contamination during Turbulent Ascent (CTA). The two arrays attributed to a CTA process can be explained by *c.* 5% and 1% contamination respectively by typical Palaeoproterozoic basement gneiss.

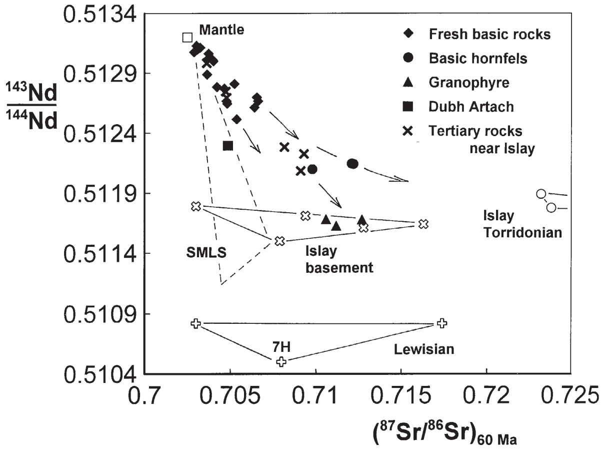

Figure 5. Sr–Nd isotope plot showing Blackstones igneous rocks relative to possible crustal contaminants.

during turbulent ascent' (hence the acronym 'CTA' in Fig. 4). However, contamination of magmas during their residence in sill complexes is also possible (Thompson *et al.* 1982).

In this contamination scenario there will always be some magmas which had less opportunity for crustal interaction because of their more rapid ascent through the crust. These magmas comprise an uncontaminated suite across the top of Figure 4. In contrast, the basic hornfels and granophyre samples show the opposite behaviour, with strong displacement to the lower left of the diagram, probably due to Assimilation Fractional Crystallization (labelled 'AFC' in Fig. 4).

Unlike Nd, Sr isotope ratios do not display any correlation with Sr concentration. This is probably due to the extra complexity of this system resulting from the change in Sr bulk distribution coefficient as plagioclase fractionation begins part way through igneous differentiation.

On the Sr–Nd isotope diagram (Fig. 5) the Blackstones data form a distribution which fans out from a presumed mantle source composition at the top left towards compositions typical of ancient crustal rocks. Three crustal suites shown for reference are Archaean gneisses from the Lewisian terrane of northwest Scotland (e.g. Dickin *et al.* 1984, 1987), Proterozoic basement gneisses from Islay (Marcantonio *et al.* 1988), and Torridonian metasedimentary rocks from the Colonsay Group of western Islay (new data in Table 2). Depleted mantle model ages of 1.75–1.89 Ga in the latter suite suggest that they were derived by erosion from Early Proterozoic rocks similar to those of the Rhinns Complex upon which they presently lie.

The array of gabbro, micro-gabbro and basaltic dyke compositions (shown by diamonds) is extended to the southeast quadrant of the diagram by samples of basaltic hornfels (circles) and granophyre (triangles). Tertiary minor intrusions from the Colonsay–Islay–Gigha region (crosses) also lie within the same data array in Figure 5. The Blackstones array as a whole is shallower than the Skye Main Lava Series array (SMLS: Thirlwall & Jones, 1983), which was attributed to contamination by granulite-facies Lewisian gneisses. Sr–Nd data alone do not allow a choice between contamination models involving amphibolite-facies Lewisian gneiss or involving the Islay gneiss complex. However, this ambiguity can be resolved using Pb isotope data (Fig. 6).

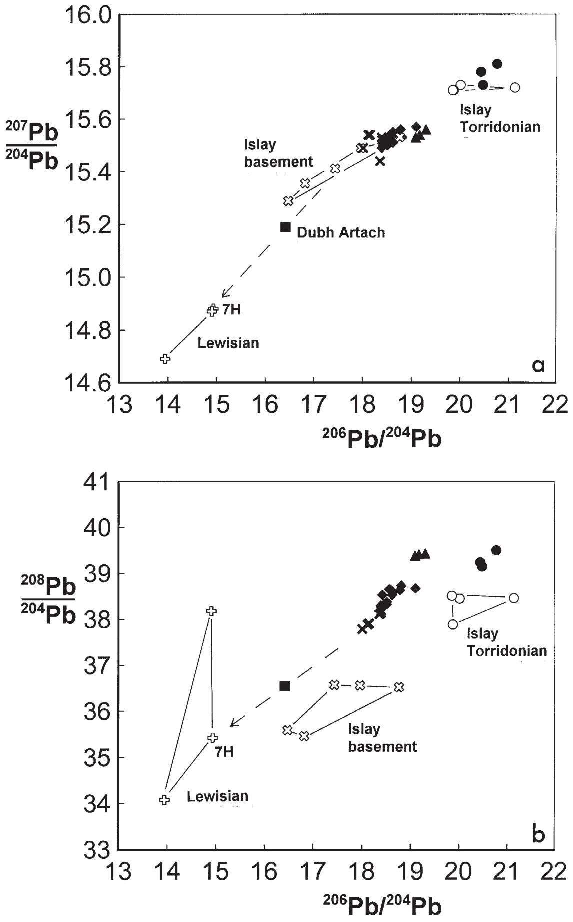

Figure 6. Pb isotope plots for samples shown in Figure 5.

On Pb isotope plots (Fig. 6a,b) the Blackstones data fall into two groups. Most of the mafic rocks, along with the granophyres, define a short array close to the typical modern mantle field, while the basaltic hornfels samples are displaced to more radiogenic compositions. All of these signatures are very different from the Skye and Mull lava series, which trend towards the composition of Lewisian gneisses (Dickin, 1981). This type of signature is displayed by the Dubh Artach sill from the Firth of Lorne (Fig. 1a), which trends towards the Lewisian acid gneiss 7H on both this diagram and Figure 5.

On the plot of uranogenic Pb (Fig. 6a), the main Blackstones array plots at the upper end of the Islay basement gneiss array, while the basaltic hornfels samples plot close to Islay Torridonian rocks. This distribution suggests that, despite a location north of the Great Glen fault, magmas of the Blackstones complex

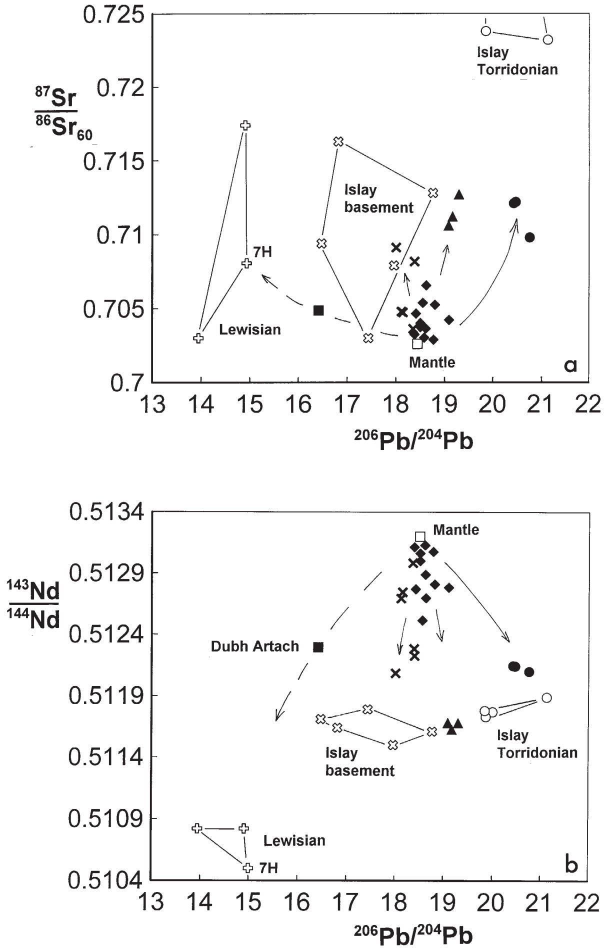

Figure 7. Plots of Sr and Nd against Pb isotope ratio for samples shown in Figure 5. Possible mixing lines are shown for crustal contamination processes.

interacted only with Early Proterozoic crust. Given the wide range of rock types analysed from the Blackstones complex (cumulate gabbros, massive gabbros, microgabbros, basalts and granophyres), and the wide range of isotope ratios displayed in the complex, it would be expected that if Archaean rocks were present in the Blackstones crust then at least one of these sample types would have picked up this very distinctive signature. Hence, it is concluded that at this locality the basement is of Early Proterozoic rather than Archaean age.

On a plot of thorogenic Pb (Fig. 6b) the Islay basement and supracrustal rocks are not a perfect fit to the Blackstones igneous rocks, since the latter have quite thorogenic Pb. However, uranogenic and thorogenic Pb are often very poorly correlated in old crustal rocks, even in a closely related suite. This is seen in Figure 6b for the Lewisian gneisses, and was seen in Archaean tonalitic gneisses of the Grenville Province by Dickin (1998). Hence, it is suggested that if magma–crust interaction in the Blackstones complex occurred at a different crustal level to that sampled in western Islay, this could easily explain the offset of Pb isotope signatures for contaminated magmas, relative to the sampled country rocks. This interpretation is supported by the observation that Tertiary minor intrusions from the Colonsay–Islay–Gigha area are completely colinear with the Blackstones data, but offset relative to the Islay crustal fields in Figure 6b.

By examining plots of Sr and Nd against Pb isotope composition (Fig. 7), more subtle distinctions can be made between the roles of Proterozoic basement and supracrustal rocks as crustal contaminants of the Blackstones and the Colonsay–Islay–Gigha Tertiary igneous rocks. The basaltic hornfels samples have a signature indicating strong contamination by Torridonian crust. A curved mixing line is shown, which is consistent with the much lower Pb concentration in primary basic magmas (*c.* 1 ppm) compared with partial melts of typical crustal rocks (> 10 ppm). However, the exact trajectory of the mixing line is strongly dependent on the assumed compositions of the primary basic magma and the crustal melt, both of which are unknown.

Colonsay–Islay–Gigha rocks show variable to strong contamination by the Islay basement. This confirms the presence of Early Proterozoic basement under the Grampian block east of the Loch Gruinard fault (Fig. 1a), as proposed by Dickin & Bowes (1991). Gabbroic samples from the Blackstones show slightly lesser degrees of contamination, apparently by a mixture of Proterozoic basement and supracrustal rock types. However, the crustal end-member may in fact be intermediate between the two crustal fields, reflecting basement rocks which are at a shallower crustal level than those sampled from Islay, and hence having more radiogenic Pb isotope signatures. Finally, the Blackstones granophyres appear to be either intensively contaminated by similar Proterozoic crustal rocks, or possibly formed by crustal melting of this material.

5. Implications for the Archaean–Proterozoic boundary in Scotland

Because of the susceptibility of flood basalt magmas to crustal contamination, Tertiary igneous rocks from western Scotland have often been used as probes for the nature of the crust at depth. Based on the relatively wide variety of rock types analysed from the Blackstones Bank, and the fact that it is an igneous centre, it provides a very reliable picture of the nature of the local crust. This is in contrast (for example) to samples from dyke swarms, which may have been injected laterally for large distances through the crust. Hence, the Blackstones samples provide strong evidence that the local crust is Early Proterozoic, despite their location northwest of the Great Glen fault. On the other hand, the sample from Dubh Artach, believed to be a sill, provides somewhat weaker evidence for the southwesterly extent of Archaean basement 30 km east of the Blackstones Bank. However,

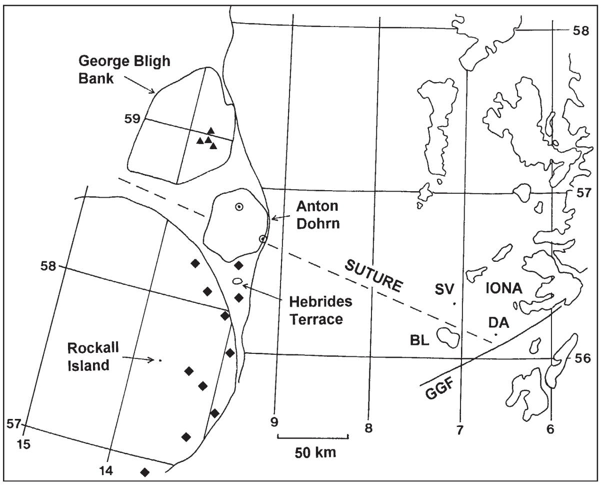

Figure 8. Reconstruction of the Scottish continental shelf before the opening of the North Atlantic, showing evidence from Tertiary igneous rocks for the location of the Archaean–Proterozoic suture northwest of the Great Glen Fault (GGF). 1000 m bathymetric contours are shown for each micro-continental fragment. Triangles = sites sampled by Hitchin *et al.* (1997) from areas of Archaean basement; diamonds = sites sampled by Hitchin *et al.* from areas of Early Proterozoic basement; open circles = sites from the Anton Dohrn bank, of unclear crustal affinity; BL = Blackstones bank; DA = Dubh Artach; SV = Skerryvore.

this is backed up by Nd isotope analysis of basement gneisses from Iona, located only 30 km northeast of Dubh Artach (Dickin & Bowes, unpub. data).

Dickin (1992) proposed that the suture boundary between Archaean and Proterozoic crustal basement in Scotland would define a line which is oblique to the trace of the Great Glen fault, and offset by this fault. This boundary can now be defined with greater accuracy on the western Scottish shelf, based on the new evidence from the Blackstones Bank and on recently published data from other Tertiary centres off western Scotland (Hitchin *et al.* 1997). A revised trajectory for the suture is shown in Figure 8 on a reconstruction of the continental shelf of western Britain before the opening of the North Atlantic. This is based on fitting 1000 m bathymetric contours from Hitchin *et al.* (1997) (Fig. 1) according to the geometry used by Dickin (1992).

On this reconstruction, the relative positions of the Rockall and George Bligh banks are presumed to be the same as the present day, since the axis of spreading between Rockall and Scotland is orthogonal to the Rockall–George Bligh boundary. The location of the Hebrides Terrace, which barely rises above 1000 m depth, is kept at its present latitude relative to the Scottish Shelf. Finally, the Anton Dohrn bank is placed in the middle of the remaining gap between the three larger fragments.

The trajectory of the Archaean and Proterozoic suture in Figure 8 is constrained between the Rockall and George Bligh banks by the data of Hitchin *et al.* (1997) and between the Blackstone Bank and Dubh Artach based on the data from the present study. The boundary is shown straddling the Anton Dohrn bank because the crustal affinity of this block is unclear. East of the Blackstones centre, the suture line must be truncated by the Great Glen fault, since isotopic evidence indicates that the whole Grampian block is underlain by Early Proterozoic crust (Dickin & Bowes, 1991). However, the suture line probably re-emerges in the continental shelf north of Aberdeenshire, after an offset of approximately 200 km along the Great Glen fault (Dickin, 1992). From here it trends across the North Sea to link up with the Archaean–Proterozoic suture line across the Baltic Shield (Mellqvist *et al.* 1999). Doubtless, the linear boundary shown in Figure 8 is an oversimplification of the real trajectory of the suture, but this is the best position that can be determined at the present time, and can be a starting position for further work.

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