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Strontium isotope variations in Lower Tertiary-Quaternary volcanic rocks from the Kurile island arc

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Abstract. Average $^{87}Sr/^{86}Sr$ ratios for lavas from Quaternary and Pleistocene volcanoes of the Kurile island arc, NW Pacific, decrease from 0.7035 in the south to 0.7032 in the north. The northern Kuriles are characterised by K_2O-richer volcanics and by an older crust. Varying ratios show no simple relation to crustal thickness or geochemical indicators of crustal contamination. This is thought to reflect the immature character of the crust – its simatic composition, low Rb/Sr ratios and youthfulness. Older lavas from the Kuriles (Lower Tertiary, Miocene) have similar or slightly higher $^{87}Sr/^{86}Sr$ ratios; some have suffered slight alteration and possibly crustal contamination. Quaternary volcanics from the Kurile and Aleutian arcs have the lowest $^{87}Sr/^{86}Sr$ ratios of all circum-Pacific arcs and this may be ascribed to (a) the isotopic individuality of the landward North American plate and/or (b) the high degree of mechanical coupling between the Pacific and North American plates reducing the amount of subducted ^{87}Sr-rich sediments and seawater. An isotopic boundary between island arcs is located in central Hokkaido. The primary basaltic magmas of the Kuriles were derived from mantle recently contaminated by radiogenic Sr. Subsequent fractionation to andesites and dacites occurred by closed-system fractional crystallization.

Introduction

The Kurile Islands form part of a volcanically active arc-trench system extending from central Hokkaido to Kamchatka in the NW Pacific. An older inactive arc (Lesser Kurile Ridge) is located between the Kurile trench and the presently active arc (Fig. 1).

A great volume of geological and geophysical data has been assembled for the Kurile arc but there is no consensus on the deep-seated forces responsible for its formation. Adherents of plate tectonics relate formation of the trench – arc – back-arc basin system to a subduction model whereby cold oceanic crust migrates down a Benioff zone dipping beneath the margin of the Asian continent and the underlying mantle wedge. In contrast, Beloussov (1984) and a number of Soviet geoscientists emphasise the role of vertical movements along deep faults and explain the inclination of Benioff zones by the flow of denser, colder sub-oceanic mantle beneath the lighter, hotter mantle which lies below the island arcs.

The nature of the underlying crust for the Kuriles is not fully established. Early studies (summarised in Gorshkov 1970; Sergeev 1976) suggested that essentially oceanic crust (5–10 km thick) was present in the central Kuriles with a gradual thickening and appearance of "intermediate-granitic" materials (up to >30 km thick) to the north and south (Fig. 1). The so-called "granitic" layer has velocities of 5.0–5.5 km/s and has been considered as consolidated volcanics or geosynclinal materials (various metamorphic rocks and granites) (Zlobin et al. 1982). Dredging by Vasiliev et al. (1979) and Gnibidenko et al. (1983) showed that the basement outcrops of the active and inactive arcs are composed of pre-late Cretaceous metasediments and granitoids. There are also numerous pebbles of granitoids, gneisses and granulites in Miocene sediments on the islands. Based on these and other regional studies, Gnibidenko and Khvedchuk (1984) suggested that an older crust is present beneath the northern Kuriles: geosynclinal sedimentation began in late Palaeozoic and the crust was deformed in late Cretaceous – early Palaeogene. Beneath the rest of the Kuriles, geosynclinal sedimentation began in late Palaeozoic-early Mesozoic and deformation took place in the late Neogene.

However, schists and gneisses only constitute about 15% of the inclusions found in lavas of the Kuriles; the bulk chemistry of 225 inclusions from many lavas is close to 51% SiO_2 and 0.6% K_2O (Rodionova and Fedorchenko 1971). This suggests that a primitive, largely but not wholly, simatic crust forms the foundation to the Kurile arcs.

Volcanism on the Lesser Kurile Ridge can be assigned to a late Cretaceous – early Tertiary arc-trench system. The earliest volcanics on the island Shikotan are tholeiitic pillow basalts and these are overlain by calcalkaline, submarine volcanic conglomerates. The succeeding shoshonites occur as sills and dykes in the flysch of the Malokuril'sk suite (Frolova et al. 1977, 1978); samples from Tanfil'eva have been analysed in the present study. A major unconformity on the Lesser Kurile Ridge can be dated to the Lower Tertiary when most of the region underwent uplift and volcanism was virtually absent.

In earliest Miocene or late Oligocene, a new arc-trench system appeared along the present-day Kurile arc. The initial volcanism took place simultaneously on the Lesser and Greater Kurile Ridges but subsequent volcanism only occurred on the Greater Kurile Ridge where it has continued to the present day. On Kunashir, in the southern Kuriles, the oldest rocks (Kunashir suite) are composed of effusive and tuffogenic rocks of basic to acidic composition which

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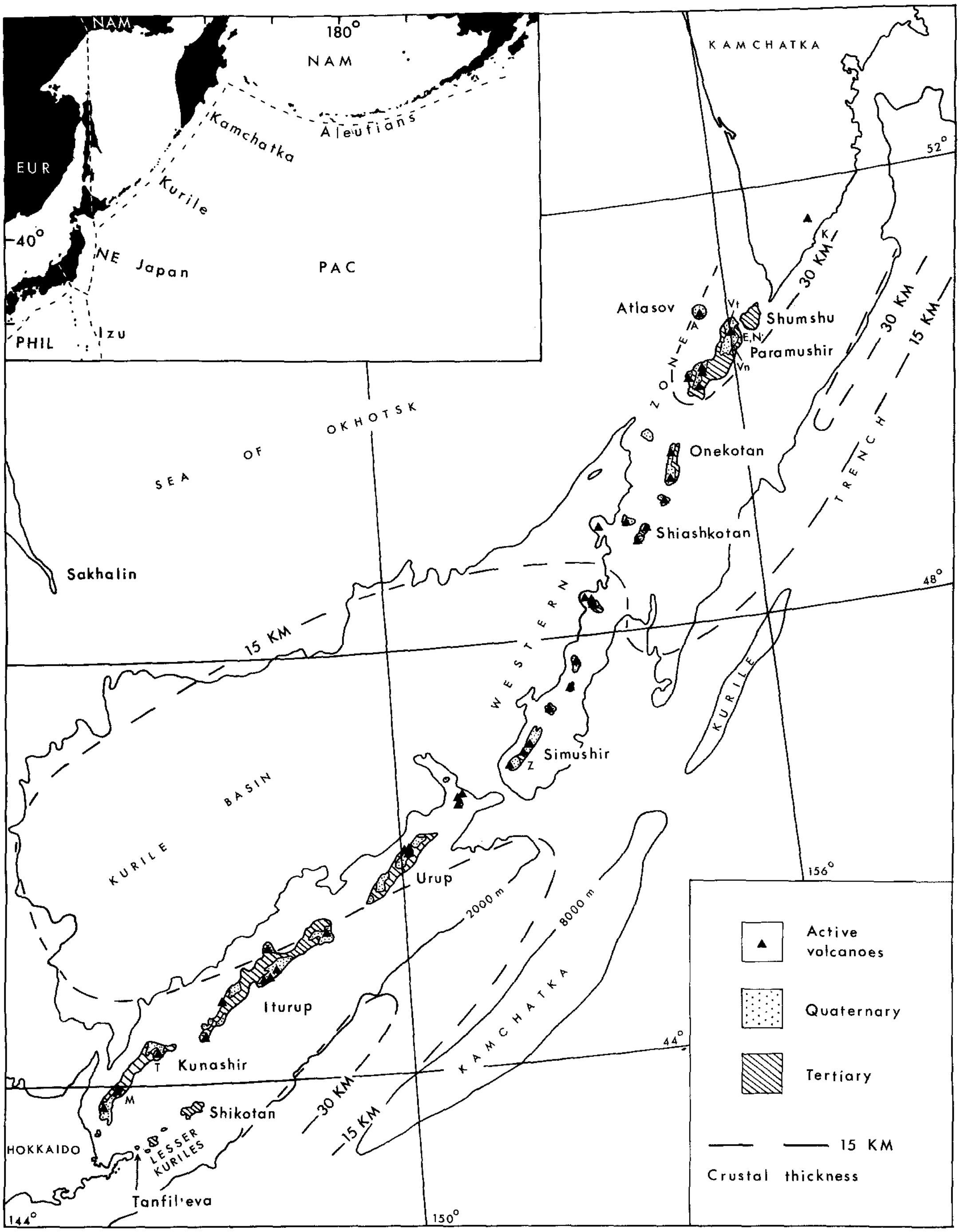

Fig. 1. Geology map for Kurile Islands, NW Pacific, showing crustal thickness (Sergeev 1976) and sampled volcanoes: *M* Mendeleev, *T* Tyatya, *Z* Zavaritskii, *Vn* Vernadskii, *E* Ebeko, *N* Neozhidannyi, *Vt* Vetrovoi, *A* Alaid, *K* Ksudach. *Inset* shows island arcs and plates of NW Pacific (Chapman and Solomon 1976). Plates: *PAC* Pacific, *NAM* North America, *EUR* Eurasia, *PHIL* Philippine

are deformed and propylitised. This suite is analogous to the "Green Tuff" formation of Japan. The overlying, unconformable middle-upper Miocene rocks are characteristically marine tuffs of acidic composition; they include the Alekhin suite analysed here. In the lower and upper Pleistocene, plateau lavas of basaltic and andesitic composition covered the older rocks of the island like a blanket. Lying on this basement are four Quaternary volcanoes: Rurui and Tyatya in the north, and Golovnin and Mendeleev in the south.

On the island Paramushir, in the northern Kuriles, a similar sequence of Neogene-Quaternary events took place. Isotopic results are presented for Upper Pliocene-Pleistocene plateau lavas ranging from basalt to andesite in composition and for Quaternary volcanoes: Vernadskii, Ebeko, Neozhidannyi and Vetrovoi.

On the central Kuriles island of Simushir, the active Zavaritskii volcano is dominantly composed of basaltic andesites and andesites; two anorthite-bearing inclusions were also analysed.

Earlier petrologic work suggested that an independent western zone of volcanic islands, with alkalic affinities, extends along the rear side of the main Kurile islands. However, recent work has emphasised a steady transition in major element chemistry across the whole arc (Piskunov 1975). Samples of this volcanism behind the volcanic front were studied from Alaid volcano on the island Atlasov. They range from widespread low-Mg basalts and basaltic slag to high-Mg basalts with a restricted occurrence.

From the Kamchatka peninsula, we have only analysed lavas and inclusions from Ksudach volcano, located on the volcanic front. Most of the volcanic products are andesites and many are rich in anorthite-olivine-bearing inclusions and derivative crystals.

The present Rb–Sr study was undertaken to see (a) if a continental crustal signature was present in the Kurile volcanic rocks or their inclusions and (b) whether magmas of different ages and settings within the arc and belonging to different magma types (summarised in Table 1) also possessed varying isotopic characteristics. Isotopic values for the Kuriles have also been compared with published values from the adjacent sections of this arc in NE Hokkaido and Kamchatka, and with other arcs of the NW Pacific.

Techniques

Sr-isotopic ratios were measured on a Varian MAT TH5 solid source mass spectrometer with digital data reduction. The measured ratios were linearly corrected for fractionation using an $^{88}Sr/^{86}Sr$ ratio adjusted to yield 0.70800 for the Eimer and Amend carbonate standard.

The internal precision based on single-run statistics ranged from 0.00004 to 0.00014 (2σ). The isotopic measurements were made over a period of two years. During this time the overall external precision, which besides recording the level of reproducibility also includes errors of normalization, varied considerably. We estimate that samples from the Mendeleev, Zavaritskii, Alaid and Ksudach volcanoes were measured with a 2σ precision of 0.00010, whereas the remaining samples can only claim a precision of 0.00018 (2σ).

Reported ratios were corrected for age variations on the basis of published fossil evidence and K–Ar dating (Table 1) using the decay constant for ^{87}Rb of 1.42×10^{-11}/y and measured Rb/Sr ratios.

Rb and Sr values were measured on a Philips PW1400 X-ray spectrometer with corrections for background and matrix variation, and with standardization against USGS reference materials. Rb/Sr ratios were reproducible inside $\pm 1\%$ down to ratios of 0.01 and $\pm 10\%$ down to 0.001. Uncertainties for Rb and Sr concentrations are roughly ± 0.5 ppm over the range 0.5–50 ppm, and 1–2 ppm at >50 ppm. Major element analyses were obtained by conventional XRF analysis of glass discs.

Results and discussion

Measured and corrected $^{87}Sr/^{86}Sr$ ratios together with $^{87}Rb/^{86}Sr$, Rb, Sr, SiO_2 and K_2O values are given in Table 1. Although the full range of initial $^{87}Sr/^{86}Sr$ ratios is relatively narrow (0.7030–0.7039_5), systematic differences appear to be present.

Kuriles crust

An along-arc decrease in the $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanics from the Kuriles is observed on passing from south to north (Fig. 2). Thus lavas from Mendeleev volcano in the south (0.7035) have a higher average ratio than lavas from Zavaritskii volcano in the central Kuriles (0.7033) and lavas from the northern, Paramushir volcanoes (0.7031–0.7032). The decrease is small and lies exactly at the limit of our 2σ uncertainty; however, plotted against distance along arc we obtain a high correlation coefficient (-0.88, or -0.90 when 5 decimal places are considered) and thus consider the decrease to be genuine. The same trend and absolute levels are observed when Pleistocene plateau lavas from Kunashir in the south (0.7035) are compared with contemporaneous lavas from Paramushir in the north (0.7032).

Along-arc variations in Kurile volcanism were noted by Frolova et al. (1985). The northern Kuriles are characterised by volcanics with higher K_2O contents and by a greater proportion of calcalkaline and alkalic as opposed to tholeiitic magma series. The same area is marked by the presence of an older underlying crust and according to the older seismic studies by the thickest crust in the Kuriles (see Introduction). An along-arc relationship between magma chemistry and crustal type and/or thickness has been noted in some other island arcs (Gill 1981) but, unlike the Kuriles, an increase in $^{87}Sr/^{86}Sr$ ratios is found in volcanics lying over the thickest crustal sections. Since the Sr isotopic compositions of the varying crustal materials along the Kuriles are unknown, we are unable to predict their influence on magma chemistry.

Quaternary volcanics from Ksudach volcano in south Kamchatka probably do not lie on the same along-arc trend; the average $^{87}Sr/^{86}Sr$ ratio (0.7034) is higher than ratios in the adjacent Kurile islands, though the difference lies at our 2σ limit of uncertainty. Ksudach is located along the front-arc side of the South Kamchatka volcanic zone (Popolitov and Volynets 1981) and lies closer to the ocean than the extension of the Kuriles volcanic front.

Examination of Fig. 3 indicates that the relatively low and monotonous $^{87}Sr/^{86}Sr$ values of Kuriles volcanics can be more closely matched with volcanics from arcs assigned to an oceanic crustal setting (western Aleutians, Izu) than to volcanics from arcs with a mature continental crust (NE Honshu, Kamchatka).

Pre-Quaternary samples from Kunashir and Tanfil'eva show higher $^{87}Sr/^{86}Sr$ ratios and higher variability than the Quaternary volcanics. Only values ≥ 0.7039 are statistically distinct from the Quaternary values. Some of the variation and higher ratios may arise from seawater contamination during eruption or low-grade metamorphism. Jahn et al. (1980) demonstrated that the $^{87}Sr/^{86}Sr$ ratios of altered ocean-floor basalts were significantly reduced by leaching with 5N HCl and Gill and Compston (1973) found the same result for greenschist volcanics from Fiji. The Kunashir suite was erupted largely under submarine conditions and has also suffered greenschist facies metamorphism. Rb and Sr contents in this suite do not correlate with SiO_2 or other fractionation indices and have almost certainly been disturbed. The five samples of this suite were leached for 24 h with 5N HCl and the washed and dried residues were re-analysed. Table 2 shows that 4 out of 5 samples decreased in $^{87}Sr/^{86}Sr$ following leaching. The variability of ratios was also reduced and the average after leaching is comparable with the Quaternary volcanics of Kunashir. However, there is no correlation between the intensity of greenschist alteration (judged petrographically or by chemical parameters such as Fe_2O_3/FeO, H_2O and K_2O) and the measured $^{87}Sr/^{86}Sr$ ratios before or after leaching. We conclude that the range and average of ratios

Table 1. Sr isotopic and elemental values for Lower Tertiary-Quaternary igneous materials from the Kurile island arc

Sample	Rock type	SiO_2 (%)	K_2O (%)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ Measured	$^{87}Sr/^{86}Sr$ Age corrected
Tanfil'eva. Malokuril'sk suite, 61 m.y.[1], shoshonitic[b]								
B103 a	basaltic andesite	53.3	4.51	73.9	400	0.535	0.7040_4	0.7035_8
B103 d	basaltic andesite	53.1	4.66	73.0	344	0.615	0.7040_7	0.7035_4
B104 v	basalt	50.0	3.53	62.7	547	0.332	0.7040_3	0.7037_4
B109	basalt	50.0	2.41	45.2	579	0.226	0.7040_1	0.7038_1
							Average:	$0.7036_7 \pm 0.00013$[7]
Kunashir. Kunashir suite, 20 m.y.[2], low-K tholeiitic								
B519	andesite	61.5	0.15	1.6	172	0.027	0.7039_0	0.7038_9
B520	basalt	51.2	0.41	2.6	129	0.059	0.7039_7	0.7039_5
B521a	rhyolite	72.1	0.26	1.7	157	0.031	0.7038_6	0.7038_5
B527	basalt	45.5	0.58	8.7	303	0.083	0.7034_6	0.7034_4
B530	basalt	45.3	0.60	19.1	210	0.264	0.7037_7	0.7037_0
							Average:	$0.7037_7 \pm 0.00020$
Kunashir. Alekhin suite, 11 m.y.[2], low-K calcalkaline								
B301	dacite	68.5	0.79	12.8	198	0.187	0.7034_6	0.7034_3
B301 g	dacite	69.1	1.19	12.4	174	0.207	0.7035_2	0.7034_9
B7/8	dacite	68.8	1.09	13.5	155	0.252	0.7038_4	0.7038_0
B7/9	dacite	68.3	0.99	13.3	173	0.223	0.7038_5	0.7038_2
B8	dacite	62.5	1.07	14.1	181	0.226	0.7037_4	0.7037_0
							Average:	$0.7036_5 \pm 0.00018$
Kunashir. Plateau lavas, 2 m.y.[3], low-K calcalkaline								
G78/1	basaltic andesite	54.2	0.40	6.2	242	0.074	0.7034_1	
C220/1	basaltic andesite	54.9	0.23	2.2	209	0.031	0.7035_3	
C221	basaltic andesite	53.2	0.18	1.3	228	0.017	0.7035_2	
C222	basalt	50.2	0.11	0.5	205	0.007	0.7034_7	
						Average:	$0.7034_8 \pm 0.00005$	
Kunashir. Mendeleev volcano, <0.01 m.y.[4,5], low-K tholeiitic								
G94/1	basaltic andesite	57.4	0.45	7.5	219	0.099	0.7034_7	
G94/4	andesite	58.5	0.47	7.1	219	0.094	0.7035_0	
G81/1	andesite	57.9	0.44	6.1	214	0.081	0.7034_8	
G76/2	basaltic andesite	55.6	0.41	6.3	265	0.069	0.7034_3	
G76/1	dacite	67.8	0.84	15.2	224	0.197	0.7034_2	
G77/1	andesite	57.1	0.45	6.9	228	0.088	0.7034_5	
G94/5	inclusion	43.9	0.07	0.5	248	0.006	0.7035_4	
G94/8	inclusion	43.6	0.05	0.5	298	0.005	0.7035_1	
G94/9	inclusion	44.4	0.02	0.4	222	0.005	0.7034_3	
G94/10	inclusion	44.7	0.05	0.9	290	0.009	0.7034_1	
						Average:	$0.7034_6 \pm 0.00003$	
Kunashir. Tyatya volcano, <0.01 m.y.[4,5], medium-K tholeiitic								
B515	basaltic andesite	53.0	0.68	9.7	348	0.081	0.7034_3	
B516	basaltic andesite	53.9	0.76	13.9	347	0.116	0.7032_7	
B517	basalt	51.8	0.73	15.0	349	0.125	0.7032_6	
						Average:	$0.7033_2 \pm 0.00009$	
Simushir. Zavaritskii volcano, <0.01 m.y.[4,5], low-K tholeiitic								
C314/1	basaltic andesite	55.8	0.44	5.4	279	0.056	0.7032_7	
C314/3	basaltic andesite	54.9	0.41	5.4	286	0.055	0.7033_2	
C314/5	basaltic andesite	54.9	0.41	4.6	276	0.049	0.7033_3	
C314/9	andesite	57.5	0.50	5.4	255	0.062	0.7033_6	
C314/10	andesite	57.4	0.55	7.4	259	0.083	0.7033_9	
C314/13	andesite	57.3	0.49	6.2	264	0.068	0.7032_7	
C314/14	andesite	57.5	0.58	6.2	255	0.071	0.7032_3	
C314/15	basaltic andesite	55.6	0.47	5.6	262	0.062	0.7032_6	
C314/16	basaltic andesite	55.4	0.46	5.7	260	0.064	0.7033_4	
C314/19	andesite	57.4	0.54	6.8	259	0.076	0.7033_4	
C314/20	basaltic andesite	53.6	0.36	4.6	254	0.053	0.7032_2	
C310/1	basaltic andesite	54.9	0.40	5.3	270	0.057	0.7031_2	
C310/2	basaltic andesite	54.9	0.43	5.7	270	0.061	0.7032_2	

Table 1 (continued)

Sample	Rock type	SiO_2 (%)	K_2O (%)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ Measured	$^{87}Sr/^{86}Sr$ Age corrected
C310/3	basaltic andesite	54.9	0.40	5.4	267	0.059	0.7033_6	
C307/5	basaltic andesite	56.3	0.48	6.3	255	0.072	0.7032_8	
C307/7	andesite	59.5	0.66	8.2	231	0.103	0.7032_8	
C311/3	andesite	57.5	0.49	8.5	238	0.103	0.7033_3	
C312	andesite	61.6	0.64	5.4	251	0.062	0.7032_2	
C321	dacite	63.9	0.64	8.6	248	0.103	0.7031_0	
C308/1	dacite	64.1	0.66	8.2	229	0.104	0.7033_5	
C320/1	inclusion	44.4	0.04	0.9	253	0.010	0.7033_0	
C320/2g	inclusion	44.0	0.01	0.6	191	0.009	0.7033_3	
						Average:	$0.7032_8 \pm 0.00008$	
Paramushir. Plateau lavas, 2 m.y.[3], high-K calcalkaline								
G112/1	andesite	60.9	2.43	56.3	358	0.456	0.7033_3	0.7033_2
G118/1	andesite	57.5	2.02	46.0	418	0.319	0.7031_9	0.7031_8
G123/1	andesite	58.4	2.08	47.0	374	0.364	0.7032_3	0.7032_2
G124/1	andesite	57.4	1.90	38.3	355	0.313	0.7032_5	0.7032_4
G125/1	basaltic andesite	53.6	1.58	31.7	420	0.219	0.7031_3	0.7031_2
							Average:	$0.7032_2 \pm 0.00007$
Paramushir. Vernadskii volcano, <0.01 m.y.[4], medium-K calcalkaline								
G134/1	andesite	60.7	1.86	41.5	384	0.313	0.7030_8	
G134/2	andesite	61.1	1.97	45.9	384	0.346	0.7032_1	
G134/4	basaltic andesite	56.7	1.64	37.7	400	0.273	0.7032_5	
G134/7	basaltic andesite	54.2	1.40	32.2	362	0.258	0.7032_7	
						Average:	$0.7032_0 \pm 0.00009$	
Paramushir. Ebeko volcano, <0.01 m.y.[4, 5], high-K tholeiitic								
G111	andesite	57.9	2.17	44.3	478	0.269	0.7033_3	
G114/1	basaltic andesite	54.3	1.67	37.2	496	0.217	0.7031_1	
G113/1	basaltic andesite	56.0	1.87	43.8	466	0.272	0.7031_3	
G117/1	andesite	58.3	2.21	53.5	441	0.351	0.7031_4	
						Average:	$0.7031_8 \pm 0.00010$	
Paramushir. Neozhidannyi volcano, <0.01 m.y.[4], high-K calcalkaline								
B416/1	andesite	62.3	2.64	69.5	330	0.610	0.7030_9	
B412/1	andesite	58.0	1.83	41.6	370	0.326	0.7032_3	
B411/1	andesite	57.1	2.04	48.6	430	0.327	0.7032_8	
B410/1	andesite	58.5	2.10	49.5	453	0.317	0.7032_5	
B408/1	andesite	58.4	2.14	49.6	437	0.329	0.7033_1	
						Average:	$0.7032_3 \pm 0.00008$	
Paramushir. Vetrovoi volcano, <0.01 m.y.[4], high-K tholeiitic								
G121/1	basalt	45.2	0.61	8.1	571	0.041	0.7029_6	
G122/1	basalt	46.5	0.93	11.5	765	0.044	0.7030_4	
G135	basalt	48.5	0.87	9.1	527	0.050	0.7031_8	
B428	andesite	58.2	2.46	50.5	372	0.393	0.7033_5	
B429/1	andesite	58.0	2.77	65.6	357	0.532	0.7033_5	
B510/v	basalt	45.8	0.80	7.1	539	0.038	0.7032_1	
B510/d	basalt	45.1	0.59	9.6	669	0.042	0.7029_4	
						Average:	$0.7031_5 \pm 0.00017$	
Atlasov. Alaid volcano, <0.01 m.y.[4, 5], high-K tholeiitic (alkali basaltic)								
C15/4	basalt	49.2	2.09	35.6	680	0.194	0.7031_4	
C16	basalt	49.3	1.44	30.7	611	0.145	0.7030_2	
C17	basalt	52.6	2.02	51.6	830	0.180	0.7031_2	
C18a	basalt	50.2	1.95	39.0	573	0.197	0.7029_9	
C22	basalt	49.2	1.86	41.4	635	0.189	0.7030_6	
C27b	basalt	48.8	1.90	44.1	607	0.211	0.7031_7	
C23	basalt	46.7	1.23	22.4	469	0.138	0.7031_0	
C24a	basalt	46.6	1.32	24.3	502	0.140	0.7030_8	
B536	basalt	50.4	1.78	37.8	671	0.163	0.7031_5	
B537	basalt	50.7	2.00	41.4	663	0.181	0.7030_6	
						Average:	$0.7030_9 \pm 0.00006$	

Table 1 (continued)

Sample	Rock type	SiO_2 (%)	K_2O (%)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ Measured	$^{87}Sr/^{86}Sr$ Age corrected
Kamchatka. Ksudach volcano, <0.01 m.y.[4,5], low-K tholeiitic								
Ka17/7	andesite	57.5	0.66	9.6	328	0.085	0.7034_2	
Ka25a/7	dacite	67.2	1.20	17.2	282	0.177	0.7033_7	
Ka1/7	basaltic andesite	56.8	0.64	7.2	303	0.069	0.7034_7	
Ka38a/7	basalt	49.4	0.22	2.6	355	0.021	0.7034_0	
Ka39/7	basalt	48.2	0.19	1.1	308	0.010	0.7034_4	
Ka110/7	andesite	58.7	0.77	11.3	318	0.103	0.7034_5	
Ka113/7	andesite	58.8	0.91	11.1	313	0.103	0.7034_7	
Ka3/7	inclusion	45.4	0.01	<0.5	279	<0.005	0.7034_2	
Ka77/7	inclusion	44.3	0.03	0.6	387	0.005	0.7034_1	
Ka139/7	inclusion	45.1	0.01	<0.5	206	<0.007	0.7033_4	
							Average: $0.7034_3 \pm 0.00004$	

1 K/Ar dating (Tsvetkov 1982); *2* Fossil evidence; *3* post-Tertiary, pre-glacial; *4* post-glacial, <10,000 years; *5* active since 1700 A.D.; *6* Nomenclature of Gill (1981); *7* 1 standard deviation for the population

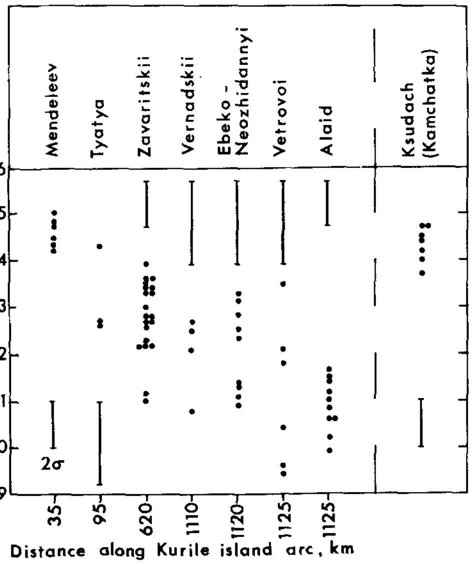

Fig. 2. Northward decrease of $^{87}Sr/^{86}Sr$ ratios in Quaternary volcanics of the Kurile island arc

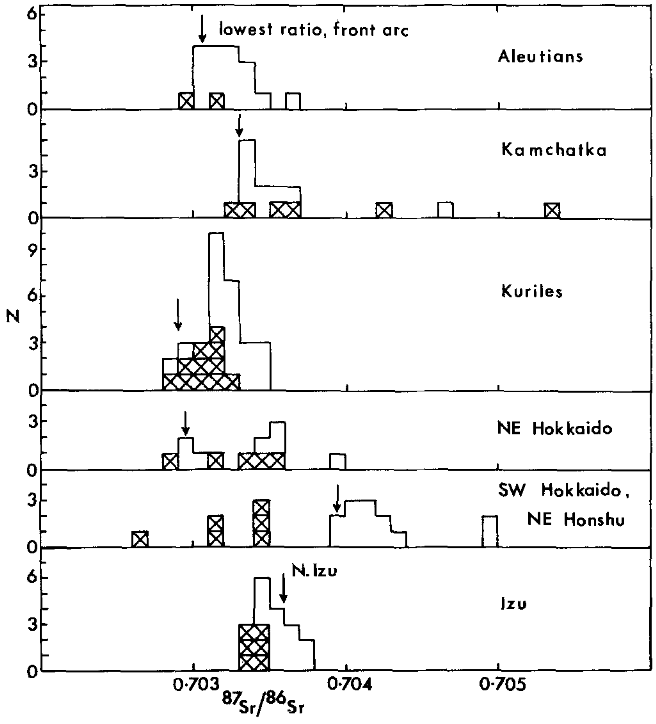

Fig. 3. Initial $^{87}Sr/^{86}Sr$ ratios for Quaternary volcanics from NW Pacific arcs. Each square represents average value for an individual volcano, on or near (*open square*) or behind (*crossed square*) the volcanic front. Sources of data: Aleutians (Kay et al. 1978; Perfit et al. 1980; McCulloch and Perfit 1981; Morris and Hart 1983; White and Patchett 1984; Myers et al. 1985; Drach et al. 1986); Kamchatka (Hedge and Gorshkov 1977; Pampura et al. 1980; Popolitov and Volynets 1981; Drach et al. 1986; this paper); Kuriles (Zhuravlev et al. 1985; this paper); NE Hokkaido (Katsui et al. 1978); SW Hokkaido and NE Honshu (Katsui et al. 1978; Zashu et al. 1980; Nohda and Wasserburg 1981; Notsu 1983); Izu (Notsu et al. 1983)

for the Kunashir suite have both been increased above the original magmatic ratios.

Increasing $^{87}Sr/^{86}Sr$ ratios and greater isotopic variability with increasing age have also been discerned in a number of arc localities from the NW Pacific (Table 3). In Japan, initial $^{87}Sr/^{86}Sr$ values increase from Quaternary to Neogene times both in the Honshu arc of NE Honshu/SW Hokkaido and in the Kurile arc of NE Hokkaido. The higher ratios were attributed by Shibata and Ishihara (1979) to the interaction of mantle-derived magmas with crustal material. A similar conclusion was reached for basalts of different ages from the central Oregon Cascades (McBirney and White 1982). However, to the best of our knowledge temporal trends have not been discerned among intra-oceanic island-arc volcanics where the possibility of contamination by sialic crust is excluded.

Further work is required to assess the relative importance of alteration by metamorphic fluids and contamination by crustal rocks among the pre-Quaternary volcanic suites. For the Quaternary lavas, however, comparison with values on Japanese and Kamchatka volcanics suggests that the Kuriles are underlain by a crust which is thinner and/or less radiogenic and/or only locally sialic. This agrees with our unpublished trace element evidence such as low

Table 2. Results of leaching experiments on Lower Miocene greenschist-facies lavas of Kunashir suite, Kunashir

Sample	Rock type	Initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$	
		untreated	after leaching with 5N HCl
B519	meta-andesite	0.7039	0.7034
B520	meta-basalt	0.7039_5	0.7034
B521a	meta-rhyolite	0.7038_5	0.7037
B527	meta-basalt	0.7034	0.7034
B530	meta-basalt	0.7037	0.7035
	average	0.7038	0.7035

$^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ values were age corrected assuming an age of 20 m.y. for the Kunashir suite

Th,U,Rb,La and La/Yb values in volcanics which suggest that the Kuriles should be grouped with those island arcs developed wholly or partly on oceanic crust (Bailey 1981).

A contradiction is thus apparent between the thick, largely simatic but partly sialic continental crust suggested by the geological/geophysical evidence (see Introduction) and the isotopic and trace element evidence given here. The same contradiction occurs in the Aleutian island arc where there is no change in Sr, Nd or Pb isotopes, or in trace element contents, all with an intra-oceanic character, on passing eastwards along the arc from slightly thickened sub-oceanic crust (ca. 25 km) to a largely continental crust (ca. 35 km) on the Alaska Peninsula (Kay et al. 1978; Marsh 1982; Drach et al. 1986). This contradiction could be explained in several ways. Firstly, there is no immediate reason why mantle-derived magmas should be contaminated every time they pass through the continental crust. Some magmas may be shielded from country rocks by channels whose walls were formed by earlier magmatic activity. However, it is difficult to understand why this should occur throughout the Kurile and Aleutian islands but not in the Japanese and Kamchatka arcs. Secondly, the possibility should be considered that even the thicker sections of the Kurile and Aleutian island arcs were built up largely from older geosynclinal volcanics and immature sediments derived therefrom. An outstanding geochemical feature of the voluminous calcalkaline and tholeiitic magmas of both arcs is their low Rb/Sr ratios (Table 1). Using a typical $^{87}\mathrm{Rb}/^{86}\mathrm{Sr}$ ratio of 0.1, volcano-sedimentary crustal materials with an average $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio of 0.7032 would radiogenically increase their ratio to 0.7033 only after 72 m.y. (since Upper Cretaceous) and 0.7034 only after 144 m.y. (since Upper Jurassic).

Inclusions

Isotopic studies on inclusions from Kuriles lavas were undertaken to see if they carried any information on the nature of the Kuriles crust. It has been found, however, that the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios for these low-silica anorthite-bearing inclusions from the three volcanoes studies (Mendeleev, Zavaritskii, Ksudach) are indistinguishable from the values in the host lavas of these volcanoes (see Table 1). The inclusions are thus thought to be cognate in character and this agrees with petrologic data which suggest they are cognate cumulates. These inclusions cannot be used to constrain the nature of the Kuriles crust.

Comparison with other island arcs

Table 4 and Fig. 3 summarise the main Sr-isotopic and geophysical parameters for NW Pacific arcs. An across-arc decrease, from front to rear, in the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios of Quaternary volcanics, expressed as $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ per 100 km, has been well documented in the NE Honshu (0.0006 to 0.0017) and Izu arcs (0.0008) (Notsu 1983; Notsu et al. 1983). A similar gradient is apparent for SW Hokkaido (0.0008) but the variation in NE Hokkaido is roughly an order of magnitude less (0.00006) and not well established (Katsui et al. 1978). An intermediate gradient (about 0.00035) is suggested by several studies on the Aleutian island arc (Kay et al. 1978; McCulloch and Perfit 1981; Morris and Hart 1983; Drach et al. 1986). In the northern Kuriles, the small difference between ratios near the front on Paramushir (0.70319) and

Table 3. Time-space variations for initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios in igneous rocks from NW Pacific arcs

Arc	Cretaceous-Palaeogene				Neogene				Quaternary			
	Average	Range	No.	Ref	Average	Range	No.	Ref	Average	Range	No.	Ref
NE Honshu/ SW Hokkaido	0.7049[a]	0.7042–0.7058	15	1	0.7052[a]	0.7048–0.7055	5	1	0.7038[a]	0.7031–0.7044	16	2
NE Hokkaido					0.7044	0.7033–0.7053	5	1	0.7033	0.7028–0.7039	24	3
S Kuriles	0.7037	0.7035–0.7038	4	4	0.7036	0.7034–0.7039	14	4	0.7033	0.7029–0.7035	15	4, 5
Kamchatka									0.7034	0.7031–0.7054	20	6
Aleutians	0.7044	0.7036–0.7055	9	7, 8	0.7034	0.7030–0.7037	6	7, 8, 9	0.7031	0.7028–0.7037	85	9, 10, 11 12, 13

[a] NE of Tanakura tectonic line

References: *1* Shibata and Ishihara (1979); *2* Notsu (1983) and references therein; *3* Katsui et al. (1978); *4* this paper; *5* Zhuravlev et al. (1985); *6* Popolitov and Volynets (1981); *7* Zhuravlev et al. (1983); *8* Borsuk et al. (1983); *9* Perfit et al. (1980); *10* Kay et al. (1978); *11* Morris and Hart (1983); *12* White and Patchett (1984); *13* Myers et al. (1985)

Table 4. Sr-isotopic and geophysical parameters for NW Pacific arcs

Arc	Front-arc ^{87}Sr/^{86}Sr	Isotopic gradient ^{87}Sr/^{86}Sr/100 km	Landward plate	Arc crust, thickness (km)	Benioff zone, dip	Degree of coupling[a]
Aleutians	0.7031	0.00035	N America	simatic, 18–25	55°	high
Kamchatka	0.7033	–	N America	sialic, 25–45	50°	high
Kuriles	0.7029	0.00038	N America	simatic, 5–30	38–50°	high
NE Japan	0.7040	0.0011	Eurasia	sialic, 27–36	30°	medium
N Izu	0.7036	0.0008	Phillipine	simatic, 15–18	45–90°	low

[a] High (medium or low) coupling of converging plates is defined by seismic slip rates for earthquakes taking up a high (medium or low) proportion of the total convergeance rate (Seno and Eguchi 1983).

Sources of data: isotopic parameters – same as Fig. 2; geophysical parameters – Gill (1981); Seno and Eguchi (1983); Tarakanov and Kim (1983)

towards the rear on Atlasov (0.70309) could be explained by analytical imprecision. Nevertheless, a gradient ≤ 0.00048 can be safely inferred and agrees with a more precise value (0.00038) from Zhuravlev et al. (1985), i.e. a gradient similar to that across the Aleutians.

Because of these varying isotopic gradients, the ^{87}Sr/^{86}Sr ratio of uncontaminated Quaternary volcanics lying on or close to the volcanic front is considered the most characteristic ^{87}Sr/^{86}Sr ratio for an individual arc. When these ratios are assembled for NW Pacific arcs (arrows in Fig. 3), it is seen that the Kurile islands possess virtually the same ratio as other sections of the Kurile arc (NE Hokkaido, Kamchatka) and as the Aleutian arc.

To the south, the NE Honshu arc including its section in SW Hokkaido is characterised by significantly higher, front-arc ^{87}Sr/^{86}Sr ratios. We thus infer an isotopic boundary in central Hokkaido located at the junction of two arcs. Central Hokkaido, in fact, has been interpreted as a triple junction with a plate boundary extending NNW from Hokkaido through Sakhalin and NE Asia (Yakutia belt) and separating the North American plate from the Eurasian plate (Chapman and Solomon 1976) (Fig. 1, inset). The Yakutian belt lies within the Cherskiy-Verkhoyansk fold belts which Churkin (1972) interpreted as an early Cretaceous suture marking the collision of two continental blocks. In other words, the present-day plate boundary divides blocks which may well have been considerably separated at one time and may have undergone different subcrustal isotopic histories.

Further south, in the Izu arc, the Pacific plate is in contact with the Philippine plate whose upper lithosphere is composed of oceanic crust. Volcanics from the front of the arc have ^{87}Sr/^{86}Sr ratios lower than in NE Honshu but higher than in the Kurile-Aleutian arcs (Fig. 3). This suggests that the isotopic differences between these arcs may be determined by the isotopic individuality of the landward plates or blocks. This suggestion can be tested by analysing mantle nodules and mantle-derived basalts from the different plates at different times in their history.

An alternative viewpoint has been proposed by Notsu (1983) and Notsu et al. (1983) who related the Sr-isotopic differences between the Izu and NE Honshu arcs to differences in subduction mechanics. Table 4 extends their analysis to all arcs of the NW Pacific. It seems fairly clear that the isotopic unity of the Kurile and Aleutian arcs is parallelled by their geological/geophysical similarity. The great strength of mechanical coupling which both these arcs show between the underthrusting Pacific plate and the landward North American plate is expected to reduce the amount of trench sediments carried down during subduction (Uyeda 1982), i.e. they will be largely scraped off the descending plate, and will accordingly reduce the amounts of high-^{87}Sr/^{86}Sr fluids released to the overlying mantle wedge and its derivative island-arc magmas (see Petrogenesis below). In addition, the essentially simatic crust beneath the Aleutians and the Kuriles would contribute only small amounts of radiogenic Sr to the trench sediments.

The NE Honshu arc shows a weaker degree of coupling so that its trench sediments, which may include a radiogenic addition from the sialic crust of Japan, will be subducted in considerable abundance and large proportions of ^{87}Sr/^{86}Sr-rich fluids will be available for release into the sub-arc mantle. The Izu arc is expected to lack any sialic component in its subducted sediments but the negligible coupling should allow large amounts of Pacific floor sediments to pass down into the Benioff zone. The high isotopic gradients across the NE Honshu and Izu arcs probably reflect the high proportion of easily released ^{87}Sr/^{86}Sr-rich fluids from their sediment-enriched Benioff zones. We expect deeper, higher P–T reactions to release smaller amounts of these fluids into the rear-arc regions; the ^{87}Sr/^{86}Sr ratios of these higher P–T fluids are also likely to be more completely equilibrated with the ^{87}Sr/^{86}Sr-poor oceanic lithosphere. This explains the marked decrease in ^{87}Sr/^{86}Sr ratios across these two arcs.

In contradiction to this subduction model, some of the highest values for ^{10}Be in island-arc volcanics come from the Aleutian and Kurile arcs and are thought to indicate a greater subduction of ^{10}Be-rich sediments beneath these arcs (Tera et al. 1986a, b). However, the northward decrease in ^{10}Be values reported for the Kurile arc is matched by the northward decrease in ^{87}Sr/^{86}Sr ratios found here. It should be noted that the suggested linkage between arc-isotope variability and differing subduction mechanics is only supported by two of the authors (J.C.B., O.L.).

Petrogenesis

The initial ^{87}Sr/^{86}Sr values of the studied volcanics appear to be independent of the varying Kurile magma types (see summary in Table 1). Thus tholeiitic magmas (0.7031–0.7038) cover virtually the same range as calcalkaline magmas (0.7032–0.7036_5) of the Kuriles, and this similarity is also valid when only the lavas of a single island are considered. The shoshonitic suite on Tanfil'eva is isotopically indistinguishable from other magma types in the basement of nearby Kunashir. Similarly, there is no correlation between initial $^{87}Sr/^{86}Sr$ ratios and the widely varying K_2O contents of the different series.

Continuous gradations in contents of LIL elements between the various magma types is characteristic for the Kurile volcanics from Lower Tertiary to Quaternary times (Bailey et al., in prep.). The overall chemical coherence of Kurile volcanics receives strong support from the $^{87}Sr/^{86}Sr$ ratios, since the latter also fail to split any individual magma type away from the others. The isotopic data clearly suggest that all magma types are derived from the same isotopic reservoir, presumably the upper mantle, and that only minor, secondary effects arising from isotopic contamination interfere with this conclusion.

The isotopic data also give clues to the nature of fractional crystallization within the individual magma series. When $^{87}Sr/^{86}Sr$ ratios are plotted against SiO_2 (not shown), there is little evidence that fractionation proceeded with any change in $^{87}Sr/^{86}Sr$. Derivation of dacitic and andesitic liquids from basaltic liquids proceeded in a closed system as far as Sr-isotopes are concerned, though greater sample coverage and more precise isotopic analyses are required to confirm this.

The source rocks for the primary, basaltic Kurile magmas are now considered in more detail. The most widely considered geneses for island-arc basalts are (a) melting of subducted ocean-ridge basalts (MORB), (b) melting of upper mantle with a MORB isotopic signature followed by contamination or mixing with continental crust, (c) melting of mantle richer in radiogenic Sr, similar to that tapped by ocean island basalts and (d) melting of mantle contaminated by ^{87}Sr-rich fluids derived from ocean floor sediments and/or seawater and/or altered MORB.

Hypothesis (a) is readily eliminated by Sr-isotopic data since the average $^{87}Sr/^{86}Sr$ ratio for fresh MORB (0.7026 ± 4) is distinctly lower than for island-arc basalts.

Hypothesis (b) is not supported by data from the Quaternary volcanics of the Kuriles since these show a narrow range of $^{87}Sr/^{86}Sr$ ratios quite unlike those found in NE Japan and Kamchatka where sialic contamination has locally taken place (Fig. 3). Contamination or mixing with continental crust is expected to yield igneous materials with positive correlations between $^{87}Sr/^{86}Sr$ ratios, $^{87}Rb/^{86}Sr$ ratios and SiO_2. These are not found among the Quaternary lavas though slight contamination may occur among some of the older Kurile lavas.

Hypothesis (c) was proposed by Morris and Hart (1983) who suggested that island-arc basalts tap the same $^{87}Sr/^{86}Sr$-rich mantle as ocean island basalts, and that this type of mantle has carried this isotopic signature for long periods of time. This does not fit an important feature of the Rb–Sr systematics from the Kuriles and other island-arc regions. The Rb/Sr ratios of the Kurile basalts vary by an order of magnitude (Fig. 4). This variation cannot be explained by low P–T fractionation or by mantle melting processes and must reflect a wide range in Rb/Sr ratios within the mantle source also. Such mantle heterogeneity must have been recently imposed otherwise a radiogenic build-up of ^{87}Sr would be discerned in the high-Rb/Sr volcanics derived from this mantle (see 65 m.y. and 20 m.y. isochrons in Fig. 4). Thus the $^{87}Sr/^{86}Sr$ signature of the Kurile mantle source has appeared since the onset of island-arc volcanism in the Kuriles (at least 80 m.y.). This leads us to infer that it was imposed during and by the processes connected with island-arc volcanism. The similarity of $^{87}Sr/^{86}Sr$ ratios in island-arc and ocean island basalts (Morris and Hart 1983) is thus regarded as coincidental. A number of other geochemical parameters (Cs/La, K/La, Ba/La, Zr/La, Nb/La, U/La, Morris and Hart 1983; White and Patchett 1984; Bailey et al. in prep.) also testify to their unrelatedness.

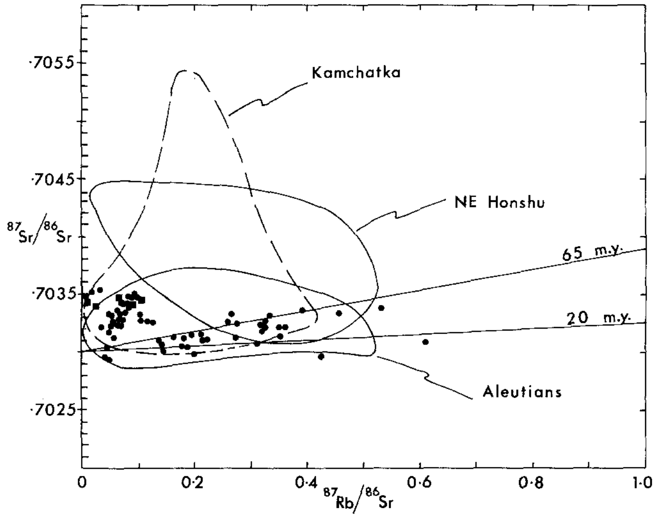

Fig. 4. $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ for basalts and andesites from Quaternary volcanics of NW Pacific arcs. *Circles* – Kuriles, *squares* – Ksudach, Kamchatka. Sources of data for other localities, same as Fig. 3. Two mantle isochrons, initial $^{87}Sr/^{86}Sr$ ratio 0.7030, ages 65 m.y. and 20 m.y. are plotted but show no relation to trends for Kurile basalts and andesites

Hypothesis (d) can be tested on Fig. 5 (Arculus and Johnson 1981). This figure shows that melting of (1) "normal" or depleted upper mantle, or (2) fresh or altered MORB would fail to produce magmas with high enough Ba/La ratios. An additional component – either seawater or ocean-floor sediments or high P–T fluids released from subducted MORB – seems required. The first two components also have high $^{87}Sr/^{86}Sr$ ratios and their addition to the source region of island-arc basalts would generate basalts with a positive correlation between $^{87}Sr/^{86}Sr$ ratios and Ba/La. It is precisely this correlation which is observed in several island arcs of the NW Pacific, including the Kuriles.

Addition of high P–T fluids released from unaltered subducted MORB, as in the model of Dupuy et al. (1982), would satisfy the need for high Ba/La but would not increase $^{87}Sr/^{86}Sr$ levels to those observed in island-arc basalts. However, mixing of these high P–T fluids with small amounts of fluids from ocean-floor sediments ± seawater is a suitable method of generating the sub-horizontal trend observed in Fig. 5 for some arcs.

If subducted ocean-floor sediments ± seawater are mixed with various proportions of altered MORB or sediments derived from radiogenic sialic crust then a range of slopes can be produced on this figure. In the case of NE Honshu the slope suggests a very high proportion of a sialic component. Some of the localities plotted by Arculus and Johnson (1981), e.g. Grenada, also appear to show a sialic influence though it cannot be reliably stated whether this is from the source region for the magmas or due to subsequent crustal contamination. The non-radiogenic end-member of the various observed trends is required to be

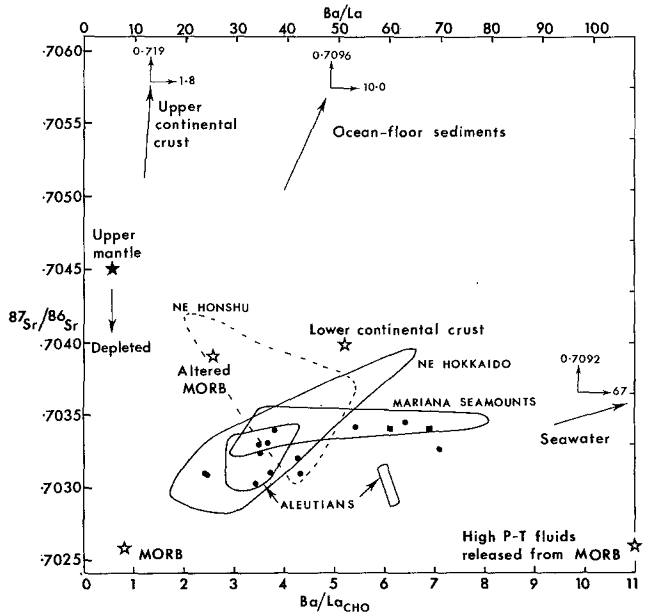

Fig. 5. ^{87}Sr/^{86}Sr versus chondrite-normalised Ba/La for island-arc basalts, and possible magma sources and contaminants. Normalization values: Ba 3.6 ppm, La 0.367 ppm (Taylor and McLennan 1981). Sources of data: Kuriles (*circles*) and Ksudach, Kamchatka (*squares*) (this paper); Aleutians and NE Hokkaido (same as Fig. 2); NE Honshu (Notsu 1983; Aramaki and Ui 1982); Marianas seamounts (Dixon and Stern 1983); upper continental crust (Taylor 1977); ocean-floor sediments and seawater (Kay 1980); primordial upper mantle and MORB (Wood et al. 1979); lower continental crust (Arculus and Johnson 1981 and references therein); altered MORB (Jahn et al. 1980; Gill 1981); high P–T fluids released from MORB (Dupuy et al. 1982)

depleted in ^{87}Sr and to possess a low Ba/La ratio; it could correspond to fresh MORB or, more likely, depleted upper mantle. The mechanics of adding Ba and ^{87}Sr/^{86}Sr to the upper mantle are discussed by Arculus and Johnson (1981). Similar modelling has been performed for Sr/La versus ^{87}Sr/^{86}Sr in Kuriles volcanics and lead to the same conclusions.

It will be seen that our foregoing discussions have dominantly considered the ability of plate-tectonic models to explain the Sr-isotopic features of island arc magmas. Comparable modelling, based on the movements of varying mantle blocks and the absence of any down-going component (Beloussov 1984), has never been performed to our knowledge. Frolova et al. (1985) have documented the evidence for high water vapour pressures during the formation of basaltic magmas of island arcs, geosynclines and orogenic zones. These magmas are always related to periods of maximum thermal and dynamic activity and the presence of Benioff zones. The ascent of deep-level heat beneath island arcs probably takes place via rising fluids. The immediate source of these fluids is thought to be the Benioff zone, with fluids being ultimately derived from even greater depths.

The high heat flow observed in the Kurile island arc suggests that its lower crust may have suffered partial melting. Derivative melts will inherit crustal geochemical features which may also be transmitted to any mantle melts they mix with. Large crustal magma chambers exist beneath several of the Kurile volcanoes and have probably undergone interaction with the surrounding crust. Geochemical data about the sub-Kuriles crust are required in order to assess these processes.

At present, we prefer a petrogenetic model whereby the primary basaltic magmas for the Kuriles were generated in an upper mantle which had suffered ^{87}Sr contamination as a result of the magma-tectonic processes associated with island-arc volcanism. Likely contaminants are ultimately ocean-floor sediments and/or seawater but in the absence of other isotopic parameters we are unable to specify further the type and proportions of contaminants. Following generation of the basaltic magmas, fractional crystallization under isotopically closed conditions lead to the formation of andesites and dacites.

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