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Mafic rocks from the Ryoke Belt, southwest Japan: implications for Cretaceous Ryoke/San-yo granitic magma genesis

Takashi Nakajima, Hiroyuki Kamiyama, Ian S. Williams and Kenichiro Tani

ABSTRACT: Mafic rocks in the Ryoke belt, the Cretaceous granitic province in Southwest Japan, occur in two modes: (1) as mafic dykes and pillow-shaped enclaves, and (2) as isolated kilometre-sized bodies of gabbroic cumulate. The dykes and pillows have fine-grained textures with thin radiating plagioclase laths, indicative of quenching. The gabbroic cumulates are predominantly coarse-grained and commonly lithologically layered.

SHRIMP zircon U-Pb ages of both types of mafic rocks are in the range 71–86 Ma, late Cretaceous. The mafic rocks become younger eastwards, matching the along-arc age trend of the associated Cretaceous granites (Nakajima *et al.* 1990). Both types of mafic rocks were apparently generated during the same magmatic event that produced the Ryoke/San-yo granites. The mafic dykes and pillows are aphyric basaltic-andesites to andesites (SiO_2 54–60 wt.%), with microphenocrysts of biotite and hornblende. They have a composition which is similar to mafic rocks from the northern Sierra Nevada, and also to medium-K calc-alkaline rocks from present-day arc volcanics. The gabbroic cumulates are mostly pyroxene-hornblende gabbros (SiO_2 43–52 wt.%). Their bulk-rock chemical compositions are mostly unlike any magma compositions.

Both types of mafic rocks from the Ryoke belt have relatively high $^{87}Sr/^{86}Sr$ initial ratios (SrI), 0·7071–0·7097, which are similar to those of the associated granites. The granites were formed either by fractional crystallisation of the mafic magmas, or by partial melting of newly formed mafic rocks at depth. The high SrI indicates that the mafic magmas were derived from enriched mantle or mixed with enriched crustal materials. Even if the mixing occurred between primitive basaltic magma and metasedimentary rocks, then the basaltic andesite–andesite magmas must have contained more than 60% mantle-derived components. The Cretaceous magmatism in Southwest Japan represents a major episode of crustal growth by additions from the upper mantle in an arc setting.

KEY WORDS: continental arc, crustal evolution, granites, magma source, SHRIMP U-Pb age, Sr isotope.

The late Mesozoic Circum-Pacific granitic provinces comprise the largest Phanerozoic granitic province on earth. The granitic arcs occur at continental margins, having formed by Cordilleran-type orogeny related to the subduction of oceanic plates rather than by continental collision. Cordilleran-type orogeny is one of the major processes by which Phanerozoic continental crust was produced, thus the understanding of the generation of subduction-related granitic magmas is essential to understanding global crustal growth.

The Cretaceous granitic province of southwest Japan is a part of the Circum-Pacific granitic province. It is of similar size to the Sierra Nevada and Peninsular Range Batholiths in the western United States. The province formed in a continental arc setting at the eastern Eurasian continental margin prior to separation of the Japanese Islands from the continent during the Miocene (Otofuji & Matsuda 1984). The granites form three arc-parallel zones; from back-arc to fore-arc the San-in, San-yo and Ryoke zones respectively (Fig. 1). It has been suggested that a transect from the San-yo to the Ryoke zone represents a crustal cross section through the eastern margin of the Eurasian continent down to mid-crustal depths (12–14 km; Nakajima 1994, 1996). The granites of the San-yo and Ryoke zones are mostly of I-type and ilmenite-series (Takahashi *et al.* 1980) and are classified as VAG (volcanic arc granite) by their Y, Nb and Rb contents (Nakajima 1996).

Large granitic provinces commonly contain some associated mafic rocks. These can provide important clues to the genesis of the granitic magmas and their tectonic setting (e.g. Sisson *et al.* 1996; Ducea & Saleeby 1998; Collins 2002). In the granitic province of SW Japan, mafic rocks are most abundant in the Ryoke belt, where they occur sporadically but ubiquitously throughout the whole area. This paper presents a geological, petrographical and geochemical description of the mafic rocks from the Ryoke belt, and discusses their petrogenesis in relation to the generation of the associated granitic magmas.

1. Mafic rocks from the Ryoke Belt

1.1. Occurrence of the mafic rocks

The exposed area of mafic rocks in the Ryoke belt is about 1–2% of the exposed area of granitic rocks (Fig. 1). The former occur either as fine-grained dykes and pillows closely associated with granitic rocks at the outcrop scale, or as discrete bodies of medium- to coarse-grained gabbroic cumulate.

1.2. Dykes and pillows

The mafic dykes range in thickness from ∼0·3 to 3 m. Although some apparently intruded after complete solidification

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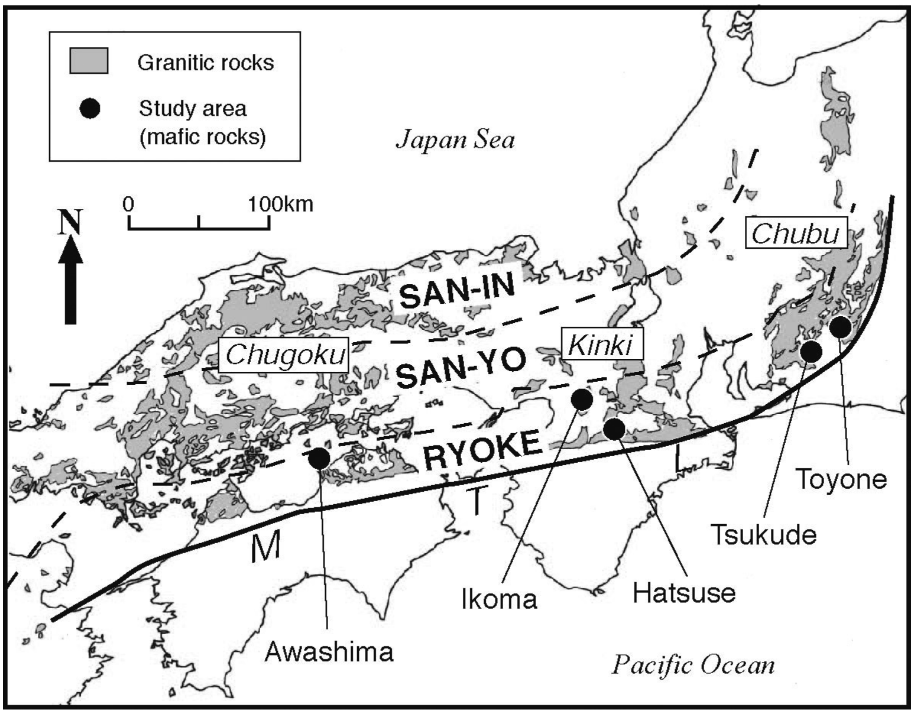

Figure 1 Cretaceous granitic province of SW Japan, showing the distribution of mafic rocks associated with the granitoids of the present study. MTL denotes the Median Tectonic Line, an arc-parallel active fault.

of the granitic host rocks, others are sharply cut by veins indistinguishable from the host granite, consistent with syn-plutonic dyke emplacement while the granite was partially molten (Fig. 2a). The mafic pillows are generally 0·1–0·5 m diameter, and commonly have crenulate chilled margins with convex-outward lobes separated by sharp, inward-pointing cusps. The volume of mafic pillows relative to granitic matrix within an outcrop varies. The layer of granite separating pillows can be as thin as a few millimetres. In such cases, some pillows are moulded against one another and appear to have been mutually deformed (Fig. 2b). These occurrences strongly indicate that both mafic and granitic magmas coexisted in a partially-molten state. Similar occurrences of mafic dykes and pillows have been reported from other bimodal magmatic provinces (e.g., Wiebe 1973; Mattson *et al.* 1986; Falkner *et al.* 1995; Snyder *et al.* 1997; Wiebe *et al.* 2001; Kapp *et al.* 2002).

The dykes and pillows have similar textures and, using the nomenclature of Streckeisen (1976), range in composition from diorite to quartz diorite. They are fine-grained, and characterised by thin radiating laths of plagioclase (Fig. 2c). Average grain size is commonly <0·1 mm. Most of the rocks are aphyric, but some are porphyritic, with large euhedral crystals of plagioclase (~2 mm) set in a fine-grained matrix. The mafic minerals are dominated by subhedral brown to greenish-brown hornblende, with subordinate biotite and opaque oxides. Some rocks contain small amounts of interstitial quartz.

1.3. Gabbroic cumulates

The gabbroic cumulates are medium- to coarse-grained, and occur as isolated bodies up to several kilometres in diameter. Although they are closely associated with granitic rocks on a regional scale, their intrusion relationships to the granites remain unclear. The gabbroic rocks are commonly layered, the relative proportions of plagioclase and brown hornblende varying regularly on a scale of tens of millimetres (Fig. 2d).

Hornblende gabbro (Fig. 2e), with approximately equal amounts of plagioclase and mafic minerals, is the dominant rock type, but anorthositic rocks are also common. Plagioclase, hornblende, and minor opaque oxides are ubiquitous. The plagioclase crystals mostly consist of euhedral homogeneous cores surrounded by thin, strongly zoned rims. Hornblende occurs either as small crystals interstitial to euhedral to subhedral plagioclase, or as large poikilitic crystals up to ~0·1 m. Both clinopyroxene and orthopyroxene are common, but they only occur in small amounts as corroded cores in large poikilitic crystals of hornblende. Olivine is rare and only occurs as small crystals included in hornblende.

2. Magmatic ages of the mafic rocks

2.1. Various ages and various stories

Before discussing the petrogenetic relationships between the mafic and granitic rocks, two facts need to be established: (1) that the mafic and granitic rocks are contemporaneous; and (2) that the chemical composition of each rock type, especially of the mafic rocks, could be the composition of a magma.

As mentioned above, there is strong field evidence that the mafic magmas that formed the pillows and at least some of the dykes were contemporaneous with the host granitic magma. However, field observations have not been able to determine the temporal relationships between the isolated bodies of gabbroic cumulates and the associated granitic rocks. Recently, several workers have measured pre-Cretaceous Sm-Nd mineral ages of 180–240 Ma on those gabbroic cumulates and concluded that they represent older basement to SW Japan (Kagami *et al.* 1995; Okano *et al.* 2000). However, Rb-Sr ages measured on the same samples are much younger (<120 Ma), thus the emplacement ages of the gabbros have remained a subject of debate. Zircon U-Pb age measurements are less ambiguous.

2.2. SHRIMP U-Pb ages

Zircon for SHRIMP U-Pb age measurement was separated from six Ryoke mafic rocks. The zircon occurs as fine elongate to needle-like grains in the fine-grained pillows and dykes, and

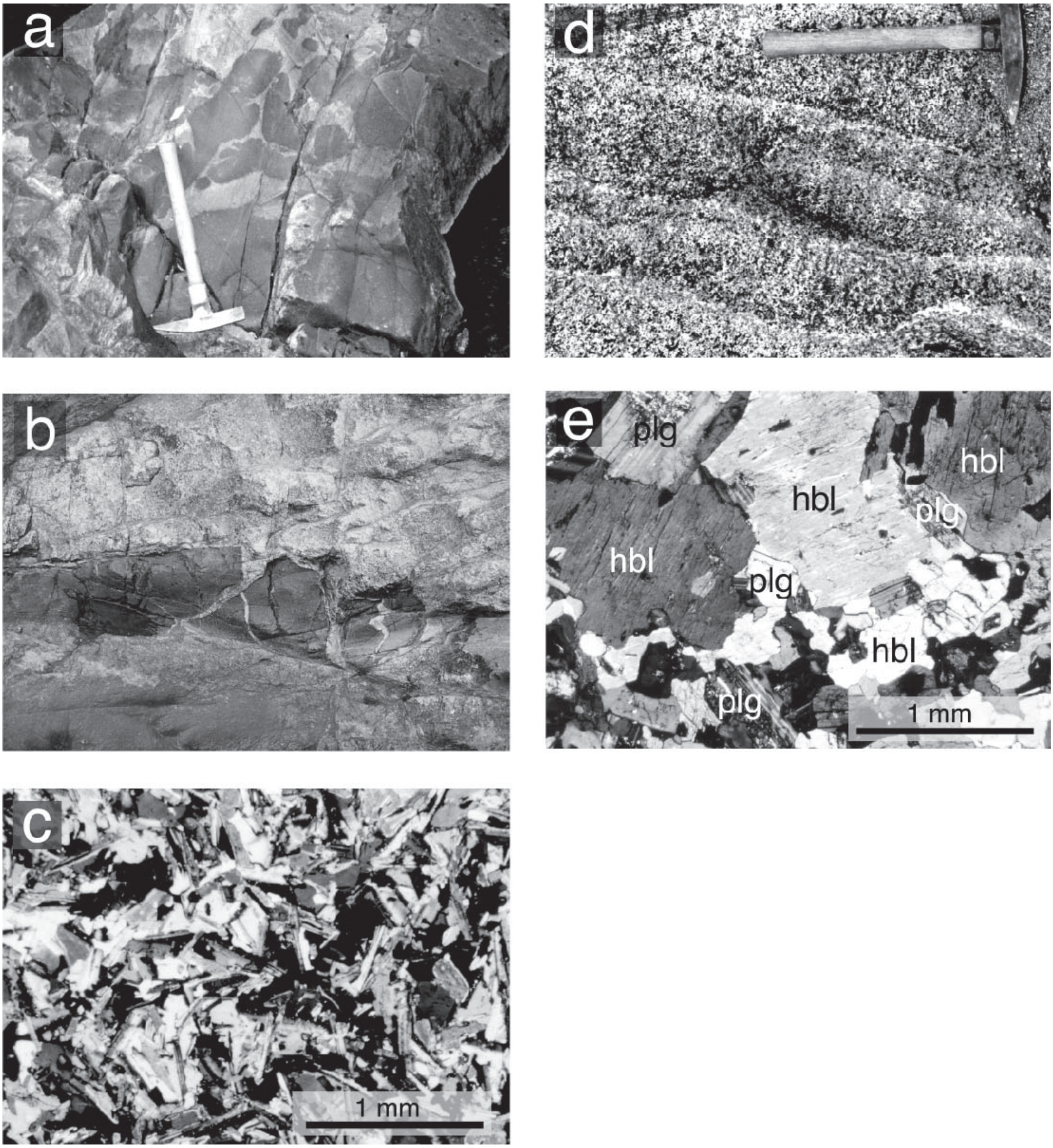

Figure 2 (a) Pillow-shaped mafic enclave swarm in granitic rocks, Toyone village, Chubu district. (b) Mafic synplutonic dyke with granitic back veins, Hatsuse village, Kinki district. Width of the dyke is approximately 30 cm. (c) Photomicrograph of a mafic enclave. (d) Layered gabbro, Awashima Island, Chugoku district. (e) Photomicrograph of hornblende gabbro. Abbreviations: (plg) plagioclase; (hbl) hornblende.

as coarse blocky to moderately elongate grains in the coarse-grained gabbros. In common with zircon from most other mafic rocks, the zircon zoning structures (as revealed by cathodoluminescence imaging) are relatively simple; broad prism-parallel zones in the elongate grains, broad concentric and sector zones in the blocky grains (Fig. 3). This contrasts with the fine oscillatory zoning common in zircon from granitic rocks. Also in contrast to granites, because mafic magmas are initially strongly zircon undersaturated, older inherited zircon is relatively rare.

Six mafic rocks (a pillow, a dyke and four cumulate gabbro-type rocks) were collected from a wide area over a distance of 500 km between the Chubu and Chugoku districts in SW Japan, and their Zircon U-Pb ages were measured using the SHRIMP II at the Australian National University. Some of the samples were collected from the same bodies on which pre-Cretaceous (∼200 Ma) Sm-Nd mineral ages had previously been measured (Kagami *et al.* 1995; Okano *et al.* 2000). Sample preparation, analysis and data processing followed procedures based on those described by Williams *et al.* (1996).

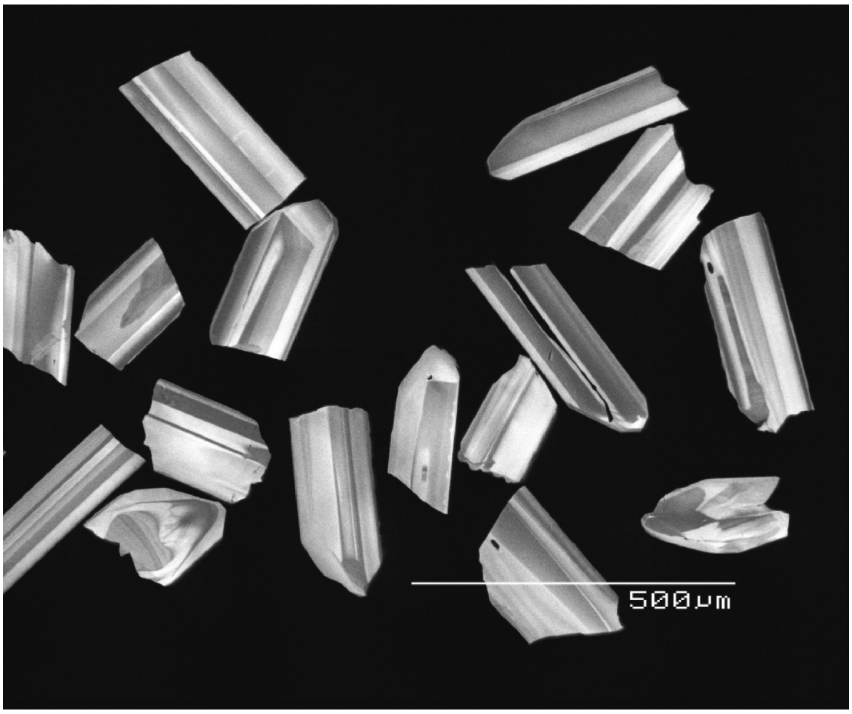

Figure 3 A cathodoluminescence image of zircon from Ryoke hornblende gabbro 99120203 showing strongly elongated, needle-like shapes with the simple broad zonation characteristic of most zircon from mafic rocks.

Pb/U ratios were determined relative to Palaeozoic reference zircon Temora 1 (417 Ma; Black *et al.* 2003). Ages were calculated using the constants recommended by the IUGS Subcommission on Geochronology (Steiger & Jäger 1977). Uncertainties in the ages are cited as 95% confidence limits, and include allowance for uncertainty in the Pb/U calibration (0·30–0·34%).

The zircon analyses are listed in Table 1 and plotted on Tera-Wasserberg concordia diagrams in Figure 4. To minimise the effects of calibration errors, some of the samples were run together in the same analytical session. These sessions also included analyses of zircon from some Ryoke granites, which will be reported elsewhere. With a few exceptions, the analyses from each sample cluster around a mixing line between common Pb and a single Cretaceous radiogenic end member, consistent with most of the zircon in each sample being the same age and having suffered little or no radiogenic Pb loss. The zircon in all samples is characterised by moderate to high U contents (150–1870 ppm) and generally moderate to high Th/U (0·5–2·6), although the low Th in some grains results in a few Th/U values being very low (<0·1).

99120101A: Fine-grained basaltic andesite from a mafic pillow in a synplutonic composite dyke, Toyone village, Mikawa area, Chubu district. Eight zircons and 2 zircon cores analysed (Fig. 4a). Six of the zircons have equal radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, equivalent to a weighted mean age of 71·5 ± 1·1 Ma. One grain ~93 Ma, cores ~166 Ma and ~1·85 Ga.

00021701A: Fine-grained mafic synplutonic dyke, Hatsuse village, Kinki district. Ten zircons analysed (Fig. 4b). Nine zircons have almost equal radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, equivalent to a weighted mean age of 75·5 ± 0·8 Ma. One grain ~89 Ma.

99120203: Coarse-grained hornblende gabbro, Tsukude village, Mikawa area, Chubu district. Eleven zircons analysed (Fig. 4c). All have almost equal radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, equivalent to a weighted mean age of 72·4 ± 1·2 Ma.

01012103: Coarse-grained hornblende gabbro, Awashima Island, Setouchi area, eastern Chugoku district. Ten zircons analysed (Fig. 4d). All have equal radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, equivalent to a weighted mean age of 86·0 ± 1·2 Ma.

00021401A: Coarse-grained layered gabbro, Ikoma Mountain, Kinki district. Ten zircons analysed (Fig. 4e). All have equal radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, equivalent to a weighted mean age of 82·0 ± 0·9 Ma.

00021504: Coarse-grained anorthositic gabbro, Ikoma Mountain, Kinki district. Ten zircons analysed (Fig. 4f). The scatter is beyond analytical uncertainty, even if the analysis with lowest $^{206}Pb/^{238}U$ is omitted. The weighted mean radiogenic $^{206}Pb/^{238}U$ of the other nine analyses is equivalent to an age of 83·2 ± 1·3 Ma.

There is no systematic difference between the zircon ages of the pillow, dyke, and cumulate gabbros and all measured ages are in the range 71 to 86 Ma, Late Cretaceous. There is no zircon evidence to support the suggestion that some of the mafic rocks are Jurassic or older. The few grains and cores of older zircon in the dyke and pillow samples (~89 Ma, ~93 Ma, ~166 Ma, ~1·85 Ga) are probably inherited from the host granites, many of which contain a small amount of older zircon thought to be contributed by a sediment-derived component in the magmas. No inherited zircon was found in the cumulate gabbro samples.

2.3. Contemporaneous magmatism with the Ryoke/San-yo granitoids

The zircon U-Pb ages of the Ryoke mafic rocks seem to be independent of rock type, but related to sample locality. The rocks are older in the west (86 Ma in the Chugoku district), younger in the east (71–72 Ma in the Chubu district), and intermediate in between (75–83 Ma in the Kinki district) (Fig. 5). This eastward younging of the Ryoke mafic rocks seems to match the along-arc variation in granite ages documented by Nakajima *et al.* (1990) and Nakajima (1994) (Fig. 6). Namely,

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Table 1 SHRIMP zircon U-Pb isotopic analyses of zircon from Ryoke mafic rocks

	Pb* ppm	U ppm	Th ppm	Th/U	% ^{206}Pb† comm.	^{207}Pb/ ^{206}Pbm	Å}	^{238}U/ ^{206}Pbm	Å}	^{208}Pb*/ ^{206}Pb	Å}	^{208}Pb*/ ^{232}Th	Å}	^{206}Pb*/ ^{238}U	Å}	Apparent ages (Ma) 208/232	Å}	206/238	Å}
Grain spot gabbros																			
99120203																			
1·1	12	806	1182	1·47	0·83	0·0551	13	85·02	86	0·4506	98	0·00358	9	0·01166	12	72·3	1·8	74·7	0·8
2·1	10	678	1027	1·51	0·68	0·0537	12	87·87	99	0·4839	83	0·00361	8	0·01130	13	72·9	1·5	72·5	0·8
3·1	9	672	804	1·20	1·19	0·0583	20	89·58	96	0·3837	93	0·00354	10	0·01103	12	71·4	1·9	70·7	0·8
5·1	8	623	664	1·07	0·67	0·0535	23	89·62	103	0·3442	100	0·00358	11	0·01108	13	72·2	2·3	71·1	0·8
7·1	9	611	976	1·60	0·45	0·0516	17	89·90	155	0·5164	139	0·00358	12	0·01107	19	72·2	2·4	71·0	1·2
10·1	6	487	456	0·94	1·09	0·0574	17	86·41	86	0·2762	93	0·00337	12	0·01145	12	68·1	2·4	73·4	0·7
9·1	6	429	419	0·98	1·24	0·0588	24	85·75	108	0·3033	121	0·00358	15	0·01152	15	72·2	3·0	73·8	0·9
11·1	3	325	6	0·02	1·63	0·0624	23	86·07	147	0·0082	80	0·00540	531	0·01143	20	108·9	106·9	73·3	1·3
4·1	3	242	172	0·71	2·04	0·0661	27	88·28	135	0·2466	143	0·00385	23	0·01110	17	77·7	4·7	71·1	1·1
6·1	2	210	145	0·69	3·19	0·0767	59	89·80	239	0·2136	268	0·00334	43	0·01078	30	67·4	8·7	69·1	1·9
8·1	3	207	141	0·68	1·78	0·0637	45	86·53	216	0·2104	202	0·00352	35	0·01135	29	71·0	7·1	72·8	1·8
00021401A																			
6·1	16	958	1301	1·36	0·11	0·0486	9	78·14	85	0·4399	63	0·00414	8	0·01278	14	83·5	1·6	81·9	0·9
5·1	10	633	703	1·11	0·49	0·0521	15	77·97	69	0·3520	72	0·00404	9	0·01276	12	81·5	1·9	81·8	0·7
1·1	9	544	726	1·34	0·79	0·0549	12	77·40	49	0·4295	78	0·00412	8	0·01282	8	83·2	1·7	82·1	0·5
2·1	9	529	837	1·58	0·56	0·0527	14	78·40	57	0·4991	95	0·00400	10	0·01268	9	80·7	1·9	81·3	0·6
3·1	9	436	1151	2·64	0·77	0·0547	15	78·39	72	0·8324	154	0·00399	8	0·01266	12	80·5	1·7	81·1	0·8
4·1	4	257	426	1·66	1·25	0·0591	20	77·83	124	0·5229	179	0·00399	15	0·01269	20	80·6	3·1	81·3	1·3
10·1	4	235	420	1·79	1·38	0·0603	21	75·26	77	0·5468	142	0·00401	13	0·01310	14	80·9	2·6	83·9	0·9
9·1	3	217	9	0·04	1·45	0·0609	22	77·07	138	0·0129	64	0·00393	195	0·01279	23	79·3	39·3	81·9	1·5
7·1	3	211	28	0·13	1·50	0·0614	22	74·89	140	0·0390	70	0·00384	70	0·01315	25	77·4	14·1	84·2	1·6
8·1	2	207	19	0·09	1·56	0·0619	38	75·49	130	0·0200	101	0·00280	142	0·01304	23	56·5	28·6	83·5	1·5
00021504																			
3·1	24	1724	1299	0·75	0·19	0·0494	14	78·08	64	0·2413	51	0·00409	9	0·01278	11	82·6	1·9	81·9	0·7
2·1	22	1507	1181	0·78	0·31	0·0505	13	76·66	72	0·2447	53	0·00406	10	0·01300	12	81·9	2·0	83·3	0·8
9·1	12	925	369	0·40	0·20	0·0495	9	75·81	77	0·1333	37	0·00440	13	0·01317	14	88·8	2·7	84·3	0·9
10·1	10	776	417	0·54	0·44	0·0516	12	79·34	78	0·1706	78	0·00398	19	0·01255	12	80·3	3·8	80·4	0·8
5·1	7	530	301	0·57	0·84	0·0553	14	78·08	109	0·1747	61	0·00391	15	0·01270	18	78·8	3·0	81·3	1·1
7·1	8	520	415	0·80	0·63	0·0535	14	75·77	100	0·2545	68	0·00418	13	0·01311	17	84·3	2·6	84·0	1·1
1·1	7	491	386	0·79	0·47	0·0520	14	74·44	87	0·2515	68	0·00428	13	0·01337	16	86·3	2·6	85·6	1·0
6·1	6	440	377	0·86	0·60	0·0531	15	78·23	79	0·2689	74	0·00399	12	0·01271	13	80·4	2·4	81·4	0·8
8·1	6	423	329	0·78	0·57	0·0529	18	74·89	88	0·2471	107	0·00422	19	0·01328	16	85·1	3·8	85·0	1·0
4·1	6	411	314	0·76	0·95	0·0563	21	76·31	93	0·2235	91	0·00380	16	0·01298	16	76·6	3·3	83·1	1·0
01012103																			
10·1	10	638	683	1·07	0·39	0·0513	13	74·46	72	0·3485	78	0·00436	11	0·01338	13	87·9	2·2	85·7	0·8
8·1	8	448	571	1·27	1·10	0·0578	23	71·80	117	0·3888	106	0·00421	14	0·01377	23	84·8	2·8	88·2	1·4
5·1	6	352	419	1·19	1·87	0·0648	29	73·91	87	0·3625	155	0·00405	18	0·01328	16	81·6	3·7	85·0	1·0
6·1	5	295	270	0·91	0·70	0·0541	26	74·29	117	0·3105	139	0·00454	22	0·01337	21	91·5	4·4	85·6	1·4
7·1	4	250	363	1·45	0·10	0·0486	30	73·65	213	0·4624	169	0·00432	21	0·01356	40	87·2	4·3	86·9	2·5
9·1	4	228	216	0·95	2·15	0·0674	33	70·83	117	0·2872	134	0·00419	21	0·01382	23	84·4	4·3	88·5	1·5
1·1	3	193	168	0·87	3·59	0·0806	73	72·49	190	0·2771	240	0·00422	39	0·01330	37	85·1	7·8	85·2	2·3
4·1	3	187	169	0·90	2·34	0·0691	38	73·15	128	0·2776	166	0·00410	26	0·01335	24	82·8	5·2	85·5	1·5
2·1	2	175	140	0·80	3·67	0·0812	36	76·54	156	0·2361	150	0·00371	25	0·01259	26	74·8	5·0	80·6	1·7
3·1	2	153	130	0·85	0·76	0·0546	22	74·37	152	0·2861	212	0·00447	35	0·01335	28	90·2	7·0	85·5	1·8
Syn-plutonic dykes																			
99120101A																			
7·1	23	1867	1396	0·75	0·25	0·0497	7	90·05	81	0·2370	35	0·00351	6	0·01108	10	70·8	1·2	71·0	0·6
2·1	18	1260	315	0·25	0·22	0·0498	11	68·72	59	0·0764	33	0·00444	20	0·01452	13	89·5	4·0	92·9	0·8
3·1	10	763	833	1·09	0·65	0·0534	12	88·98	97	0·3554	93	0·00363	10	0·01116	12	73·3	2·1	71·6	0·8
4·1	20	685	512	0·75	0·27	0·0518	8	38·32	35	0·2265	48	0·00789	19	0·02603	24	158·8	3·7	165·6	1·5
10·1	221	670	228	0·34	0·02	0·1132	11	3·16	4	0·0994	32	0·09233	329	0·31639	432	1785·0	60·9	1772·1	21·2
6·1	8	639	558	0·87	0·53	0·0522	13	94·01	104	0·2771	69	0·00335	10	0·01058	12	67·7	2·0	67·8	0·8
1·1	7	561	518	0·92	0·95	0·0562	13	88·65	118	0·2835	76	0·00343	11	0·01117	15	69·2	2·1	71·6	1·0
9·1	6	492	278	0·57	0·53	0·0523	16	88·10	114	0·1838	66	0·00367	14	0·01129	15	74·1	2·9	72·4	0·9
5·1	5	353	396	1·12	1·03	0·0568	18	90·17	149	0·3546	102	0·00347	12	0·01098	18	70·0	2·4	70·4	1·2
8·1	4	342	205	0·60	0·89	0·0556	17	88·19	120	0·1899	96	0·00355	19	0·01124	15	71·7	3·8	72·0	1·0

Continued on next page

Table 1 *Continued*

	Pb* ppm	U ppm	Th ppm	Th/U	% ^{206}Pb† comm.	^{207}Pb/^{206}Pbm	Å}	^{238}U/^{206}Pbm	Å}	^{208}Pb*/^{206}Pb	Å}	^{208}Pb*/^{232}Th	Å}	^{206}Pb*/^{238}U	Å}	Apparent ages (Ma) 208/232	Å}	206/238	Å}
00021701A																			
10·1	21	1465	1774	1·21	–	0·0474	7	85·17	31	0·3785	41	0·00367	6	0·01174	4	74·0	1·1	75·3	0·3
6·1	20	1211	2111	1·74	–	0·0470	8	84·88	55	0·5477	83	0·00370	6	0·01179	8	74·7	1·2	75·6	0·5
7·1	16	1155	1253	1·08	0·08	0·0483	11	85·97	59	0·3396	52	0·00364	6	0·01162	8	73·5	1·3	74·5	0·5
9·1	15	1108	1229	1·11	0·03	0·0478	8	86·40	69	0·3447	55	0·00360	7	0·01157	9	72·6	1·3	74·2	0·6
5·1	14	1031	979	0·95	0·24	0·0497	7	83·50	33	0·2969	41	0·00374	9	0·01195	5	75·4	1·7	76·6	0·3
1·1	14	1027	769	0·75	0·13	0·0487	16	83·41	83	0·2366	55	0·00378	10	0·01197	12	76·3	2·0	76·7	0·8
4·1	17	1024	1751	1·71	0·16	0·0490	9	84·82	52	0·5418	86	0·00373	6	0·01177	7	75·2	1·3	75·4	0·5
2·1	13	957	960	1·00	0·20	0·0494	9	84·77	82	0·3200	52	0·00376	7	0·01177	11	75·8	1·5	75·4	0·7
8·1	12	897	209	0·23	0·08	0·0486	10	71·61	52	0·0743	32	0·00445	19	0·01395	10	89·8	3·9	89·3	0·6
3·1	9	666	601	0·90	0·05	0·0480	14	84·54	78	0·2934	63	0·00384	9	0·01182	11	77·6	1·8	75·8	0·7

*Corrected for common Pb of Broken Hill galena composition using ^{207}Pb/^{206}Pb
Measured value not corrected for common Pb
†Percentage of total ^{206}Pb that is common ^{206}Pb.

at any given site in SW Japan, the granitic and mafic magmatism appears to have been synchronous, implying that the two types of magmatism are genetically related.

3. Magmatic composition of the mafic rocks

3.1. Cumulate gabbros versus dykes and pillows

Field observations and petrography show that the dykes and pillows are quenched liquids, whereas the cumulate gabbros are accumulations of minerals precipitated from magma. The dyke and pillow chemical compositions probably correspond to magma compositions, but the gabbro compositions do not. Representative whole rock chemical analyses of the Ryoke mafic rocks and some Ryoke granites and metasediments are listed in Table 2.

The dykes and pillows analysed so far are mostly basaltic andesites to andesites (53–60% SiO_2), whereas the gabbroic cumulates are more mafic (43–52% SiO_2). Some of the latter contain very high Al_2O_3 (25–29%) and could not have been magmas. Plotted on Harker variation diagrams, the Al_2O_3, MgO and CaO contents of the gabbroic cumulates deviate markedly from the magmatic trend defined by the dykes, pillows and granitic rocks (Fig. 7a, b, c). Co-linearity on Harker diagrams does not necessarily prove that rocks are comagmatic, so it is not yet possible to establish whether the Ryoke granitic rocks, dykes and pillows constitute a single magma series. The diagrams do indicate, however, that the compositions of the gabbroic cumulates cannot be used as magma compositions in any petrogenetic discussion.

3.2. Arc affinities of the mafic magma compositions

In contrast to the large range in chemical composition of the gabbroic cumulates, the dykes and pillows are all basaltic andesites and andesites (SiO_2 53–60%; K_2O 1·3–1·8%; TiO_2 0·8–1·1%; Rb 36–58 ppm; Sr 370–500 ppm; Nb 6–10 ppm and FeO*/MgO ratio 2·0–2·5: Table 1), similar to primitive mafic rocks from the northern Sierra Nevada (Tani 2002), and to medium-K series calc-alkaline rocks from modern volcanic arcs (Fig. 8a). The dykes and pillows have compositions near the boundary between Miyashiro's tholeiite and calc-alkaline fields on a SiO_2-FeO*/MgO diagram, a common feature of arc volcanics, whereas the cumulate gabbros mostly plot deep in the tholeiite field (Fig. 8b). Recent claims that the Ryoke mafic rocks are mostly tholeiitic continental flood basalt (Kagami *et al.* 2000) are possibly based on a misinterpretation of gabbro compositions as magma compositions, as the supporting analyses are mostly of gabbros and granulites. Our analyses (Table 2) show that the Ryoke mafic magmas were characterised by high Sr and Zr and moderately low Nb contents, features of arc rocks, especially the volcanic rocks from continental arcs (Table 3).

The basaltic andesite–andesite of the dykes and pillows has low Ni and Cr contents and a relatively high FeO*/MgO ratio, consistent with moderate fractionation of a primary magma composition.

3.3. Sr isotopes

There is commonly a strong negative correlation between εNd and SrI in arc magmas. The Cretaceous granites from SW Japan are a typical example of this behaviour (Okudaira *et al.* 2003, fig. 6). In such a case, SrI alone (without ε_{Nd}) is a useful petrogenetic indicator. Furthermore, the isotopic evolution line on a SrI-ε_{Nd} diagram is concave upward, making SrI a more sensitive parameter than ε_{Nd} in the study of isotopically evolved magmas. Here we have measured SrI as a tracer of the processes of mafic and granitic magma generation.

In the Chugoku district, in western SW Japan, the SrI of the Cretaceous granites increases across the arc, being higher in the Ryoke zone than in the San-yo zone (Nakajima 1996). It remains unclear whether the variation is continuous, or if there are several isotopically discrete crustal segments as proposed by Kagami *et al.* (1992). The same across-arc SrI gradient is not found everywhere in SW Japan. In eastern SW Japan, for example, SrI is lower in the Ryoke zone than in the San-yo zone (Nakajima 1996, fig. 9). The changes in the across-arc SrI trends are principally due to along-arc changes in the SrI of the San-yo granites, the SrI of the Ryoke granites along-arc being on average almost constant (Nakajima 1996).

All the Ryoke mafic rocks – dykes, pillows and cumulate gabbros – have relatively high SrI, 0·7071–0·7097, higher than most Quaternary subduction-related basaltic rocks. The SrI of most of the granitic rocks is in the same range (0·707–0·709), although some are even higher, up to 0·712 (Fig. 9). In any given region, the SrI of the mafic and granitic rocks is similar. The SrI of the Ryoke metasediments is much higher, 0·714–0·721.

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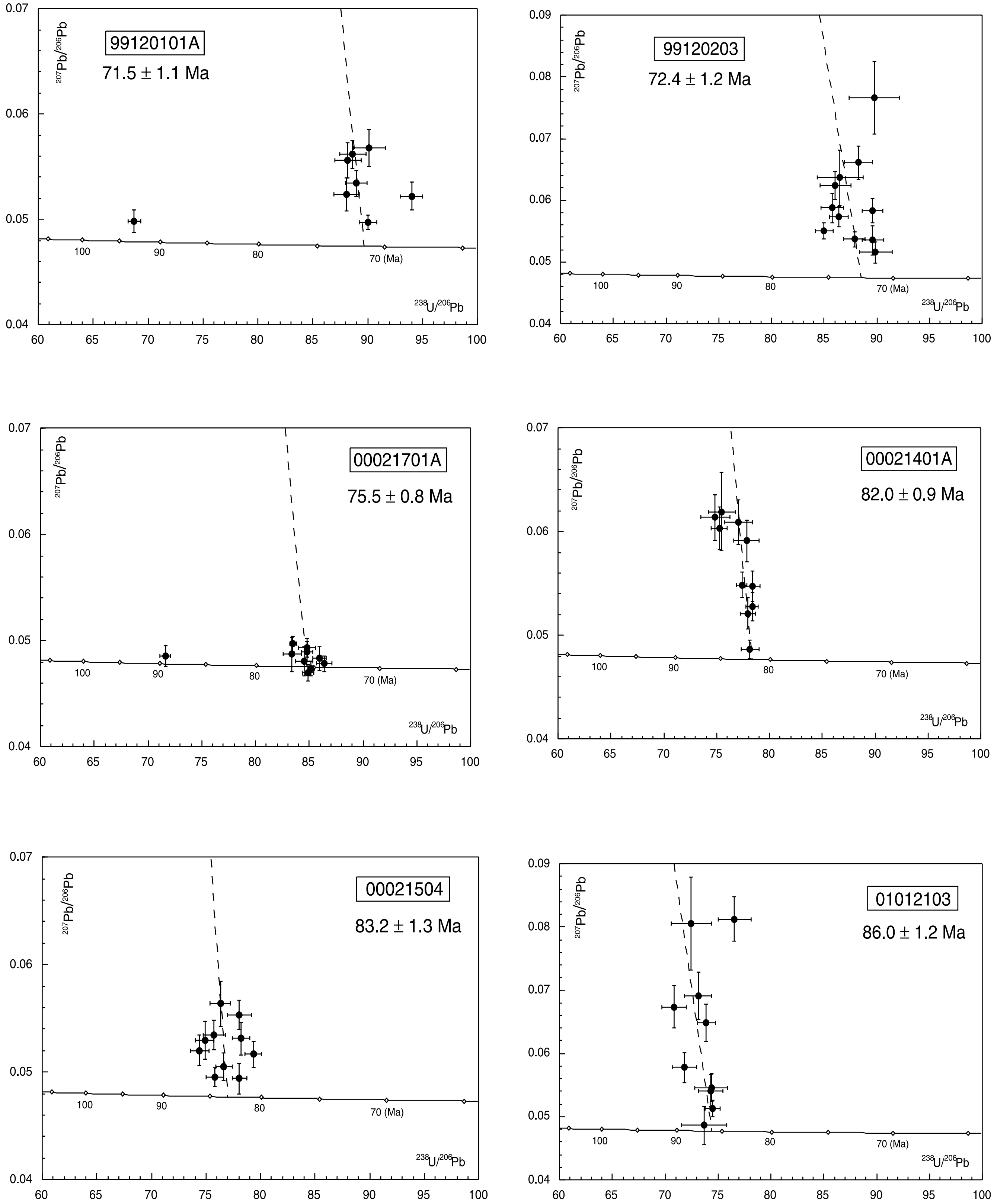

Figure 4 Concordia plots of SHRIMP U-Pb isotopic analyses of zircon from Ryoke mafic rocks before correction for common Pb. Dashed lines show the locus of mixing with common Pb. Analytical uncertainties one standard error, age uncertainties 95% confidence limits.

4. Discussion

4.1. Magma sources

4.1.1. Mantle-derived component versus crustal component. The most striking aspect of the geochemical data for the Cretaceous plutonic rocks in Southwest Japan is the rather small variation in initial Sr isotopic composition over the entire range of rock types. This suggests that all the plutonic rocks were derived from similar source materials. The presence of mafic rocks in close spatial and temporal association with the granitic rocks implies an involvement of mantle-derived juvenile material in the latter's petrogenesis.

The mafic dykes and pillows, which approximate melt compositions, have high FeO*/MgO ratios and low Ni and Cr

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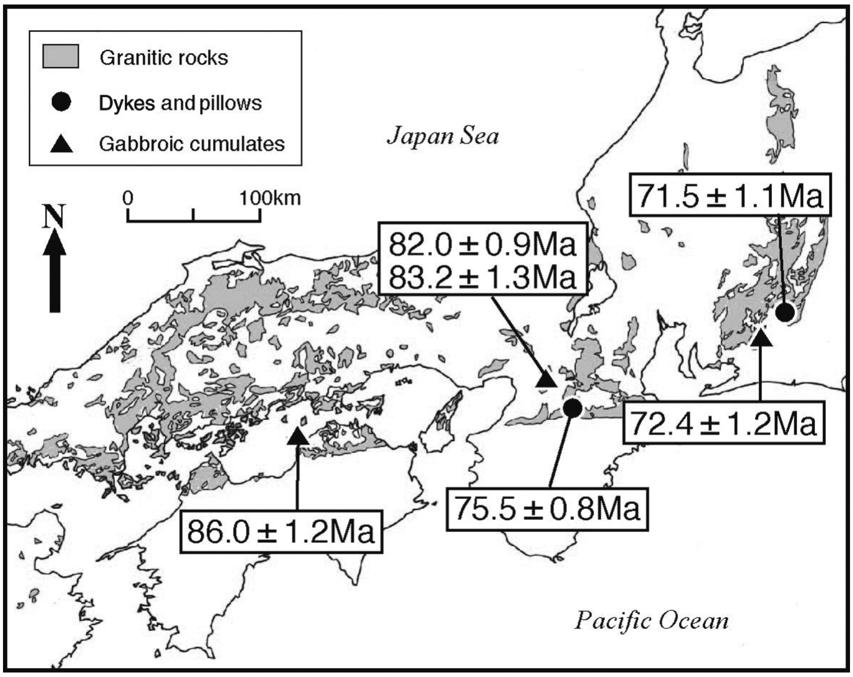

Figure 5 Sample localities and SHRIMP zircon U-Pb ages of the analysed Ryoke mafic rocks.

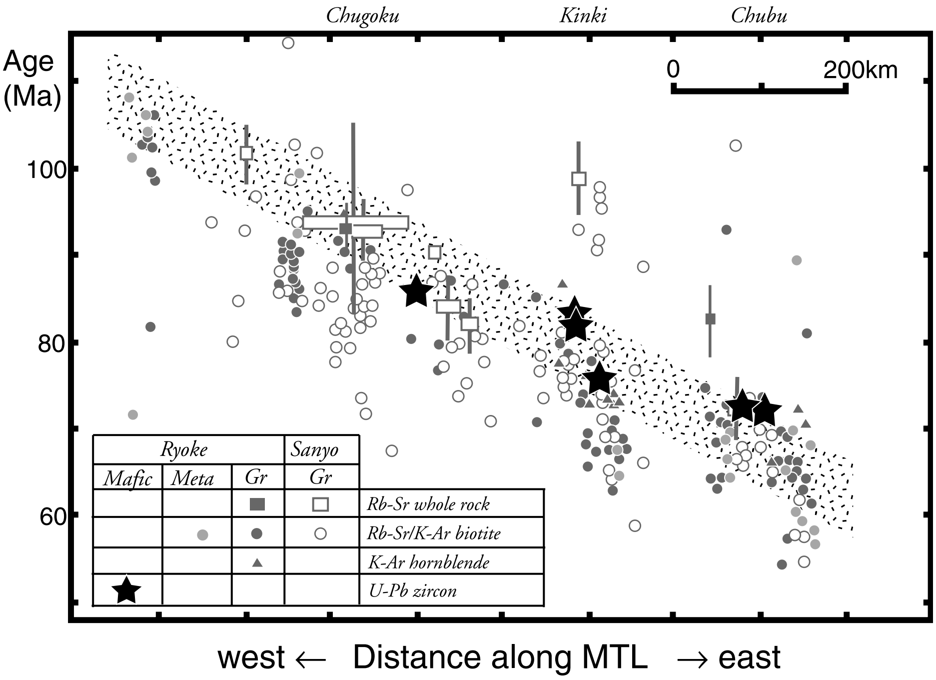

Figure 6 Along-arc variation of SHRIMP zircon ages of mafic rocks plotted with the ages of granitoids and metamorphic rocks from SW Japan. The along-arc position of each point is defined as the normal projection from the sample locality onto the Median Tectonic Line. The stippled band is a trace of the along-arc variation trend of the Rb-Sr whole rock isochron ages of the granitoids after Nakajima *et al.* (1990).

contents. Such evolved compositions argue against equilibration of the melts with mantle peridotite. The mafic magmas must have evolved from mantle-derived primitive magmas in the deep crust.

Another important fact is that none of the mafic rocks in the Ryoke belt have isotope signatures of depleted mantle. The high SrI could be interpreted in two different ways. Either the mafic rocks were produced from primitive basaltic magma with a high SrI (~0·7075) derived directly from enriched mantle, or the SrI of the magmas has been elevated by the incorporation of a crustal component. Although the mantle- and crust-derived end members cannot be directly identified, validity of crustal contamination as an explanation for the enriched isotopic signature of the Ryoke mafic rocks can be evaluated for possible ranges of mantle- and crust-derived end member compositions. In the following discussions, the SiO_2 and Sr contents and the SrI are used as key parameters.

4.1.2. Characterisation of the mantle-derived component. The outcome of any calculation assuming mixing between crust- and mantle-derived components depends heavily on the SrI, Sr and SiO_2 assumed for the mantle-derived basaltic magma. If, for example, the SrI of the basaltic magma is 0·708, no crustal component need be involved. The modern arc basalts show considerable chemical variation. We will give

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Table 2 Representative analyses of the Ryoke mafic and granitic rocks, and metasediments

	95101702 Gr	91030804 Gr	99112902A Gr	99112902B D/P	99120101A D/P	99120203 G.C.	00021402 G.C.	01012103 G.C.	99120201 Gn	95101602B Gn	95101801B Gn
%											
SiO_2	71·76	71·19	69·85	54·95	59·92	50·81	46·31	48·71	65·50	67·04	68·40
TiO_2	0·34	0·38	0·43	1·13	0·82	1·08	0·85	0·25	0·74	0·74	0·66
Al_2O_3	14·36	14·72	15·22	17·68	17·74	17·86	18·78	24·71	17·46	17·25	15·98
Fe_2O_3	2·56	3·13	4·11	9·04	6·42	10·37	10·69	4·73	5·57	5·53	5·19
MnO	0·04	0·04	0·08	0·16	0·11	0·17	0·19	0·08	0·09	0·07	0·09
MgO	0·72	0·61	1·28	4·91	2·98	6·33	8·53	5·14	2·07	1·99	1·88
CaO	1·77	2·41	3·49	7·56	6·48	10·36	13·24	14·69	1·33	1·44	1·25
Na_2O	2·77	3·23	3·93	3·00	3·60	2·23	1·22	1·41	2·47	2·21	2·00
K_2O	5·55	4·17	1·46	1·40	1·77	0·68	0·17	0·23	4·59	3·61	4·24
P_2O_5	0·14	0·11	0·13	0·16	0·17	0·12	0·03	0·05	0·16	0·12	0·10
Total	100·01	100·00	99·99	100·00	100·00	100·01	100·00	100·00	99·99	100·00	100·00
ppm											
Zr	168	251	179	82	103	84	15	19	182	186	158
Y	21	23	19	21	15	27	11	6	30	24	18
Sr	125	218	343	368	471	351	511	442	189	177	140
Rb	258	128	51	40	58	17	<1	6	168	143	165
Ba	460	814	374	275	499	192	65	71	858	587	779
Zn	55	42	71	102	92	107	80	38	100	89	94
Cu	3	3	3	43	7	26	11	10	24	16	35
Ni	5	<2	5	14	6	15	15	18	24	18	19
Cr	13	6	11	89	34	61	87	156	60	73	64
V	29	14	25	214	124	206	288	150	99	127	85
Nb	18	13	10	7	8	7	2	4	14	13	16
SrI	0·70892	0·70813	0·70807	0·70806	0·70734	0·70951	0·70751	0·70726	0·71775	0·71616	0·71565

(Gr) granitic rocks; (D/P) dykes and pillows type mafic rocks; (G.C.) Gabbroic cumulates; (Gn) gneisses.

some constraints on these chemical parameters and then evaluate the mantle/crust contributions with the various values in possible range of the chemistry.

First, the SiO_2 content of mantle-derived primitive basalt is controlled by phase equilibria. The SiO_2 content of a basaltic melt in equilibrium with mantle peridotite (ol+opx ± cpx ± spinel) is relatively insensitive to the melting temperature, but can be changed significantly by varying pressure and the amount of dissolved water (e.g. Hirose and Kushiro 1993; Hirose and Kawamoto 1995; Gaetani and Grove 1998). Melts generated in the presence of H_2O have significantly higher SiO_2 than those produced under dry conditions. Decreasing pressure increases the SiO_2 content of the melt. The final equilibration site of ascending basaltic melts and mantle peridotite is near the asthenosphere/lithosphere boundary, where ascent of the basaltic melts changes from porous flow to crack-dominated melt flow (Tatsumi and Eggins 1995, pp. 134–138). Consequently, if a very thick lithosphere and dry conditions for partial melting are assumed, a lower limit for the SiO_2 content of the mantle-derived primitive basalt can be obtained. Melting experiments on dry peridotites by Hirose and Kushiro (1993) have shown that the SiO_2 content of a dry partial melt decreases with increasing pressure from ~51 wt.% at 10 kbar to ~46 wt.% at 30 kbar. A pressure of 30 kbar corresponds to the base of a thick lithosphere. It is therefore reasonable to assume that the primitive arc basalts, which normally contain substantial amounts of dissolved water, would have SiO_2 contents of 46–51 wt.% or higher.

On the other hand, Sr content and SrI are much harder to constrain. Actually, they have remarkably wide ranges in modern arc basalts. It is nevertheless possible to make an informed evaluation of the alternative 'enriched mantle model' and 'crustal contamination model' for the production of the Ryoke mafic rocks.

4.1.3. Enriched mantle model. Present-day arc basalts have a variety of isotopic compositions. Most intraoceanic arc basalts have a relatively low SrI of ~0·7035 (e.g. Dixon & Batiza 1979; Tatsumi *et al.* 1991; Taylor & Nesbitt 1995; Ewart *et al.* 1998), while continental arc basalts commonly are slightly more enriched, SrI >0·704 (e.g., Kimura *et al.* 2002). Some parts of the mantle beneath continental arcs are especially enriched. Mukhopadhyay & Manton (1994) reported mantle xenoliths from beneath the Sierra Nevada batholith with SrI ranging from 0·7044 to 0·7082, concluding that those xenoliths represent old subcontinental lithospheric mantle. Many mafic rocks from continental arcs also have enriched isotopic signatures, consistent with their derivation, at least in part, from enriched mantle. This might be either old subcontinental lithospheric mantle (e.g. Young *et al.* 1992; Sisson *et al.* 1996; Ratajeski *et al.* 2001; Lucassen *et al.* 2002) or less enriched mantle contaminated by recycling of old continental material via a subduction zone (Tommasini *et al.* 1995).

If the source of magmas beneath SW Japan during the Cretaceous is assumed to be highly enriched mantle (SrI=0·7073–0·7083), then the petrogenetic model is simple (Fig. 10a). The magmas which formed the dykes and pillows could be derived from mantle-derived primitive basalt (SiO_2=48 wt.%) by moderate fractionation. The gabbroic cumulates and Ryoke granites could have been formed from those magmas in turn by crystal accumulation and further fractionation or partial melting, respectively (Fig. 10a). No crustal component need be involved. Although there is no direct evidence for such enriched mantle peridotite beneath SW Japan during the Cretaceous, namely beneath the Eurasian

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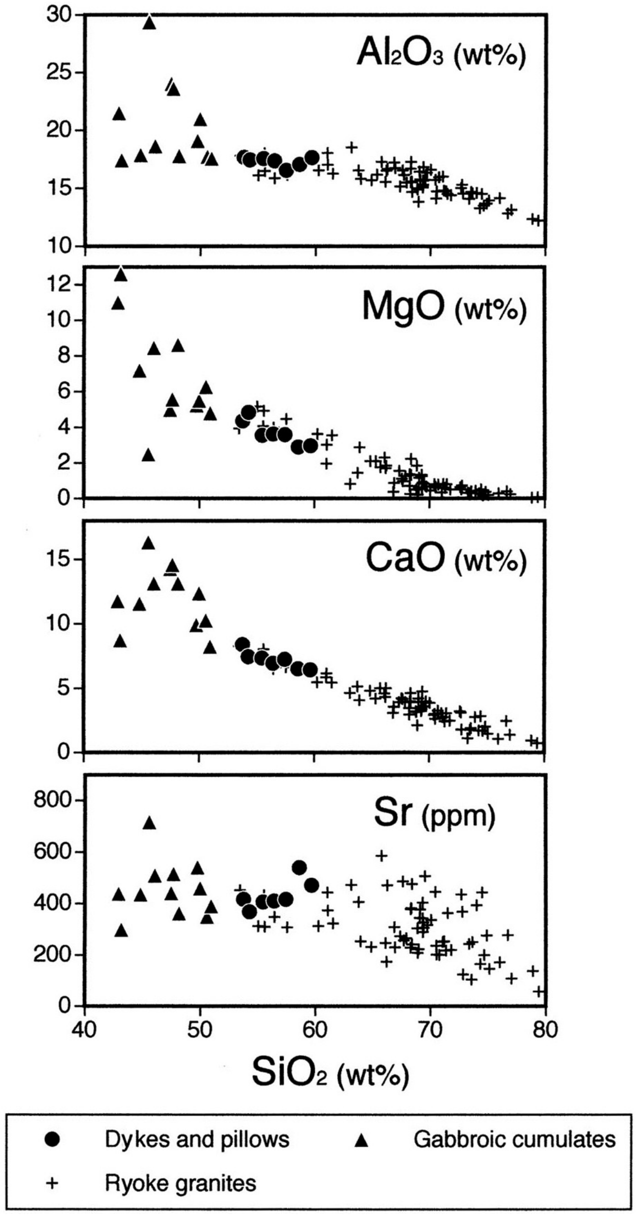

Figure 7 Harker variation diagrams for the Ryoke mafic and granitic rocks: (a) SiO_2-Al_2O_3; (b) SiO_2-MgO; (c) SiO_2-CaO; (d) SiO_2-Sr.

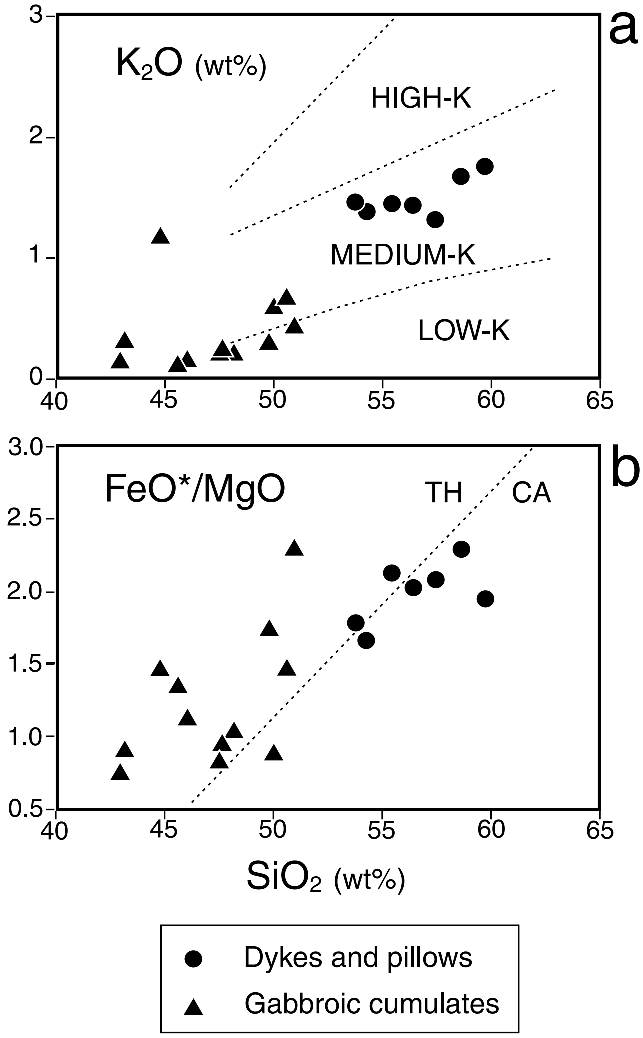

Figure 8 (a) SiO_2-K_2O diagram. Field boundaries are from Tatsumi and Eggins (1995). Ryoke mafic dykes and pillows belong to the medium-K series. (b) SiO_2-FeO*/MgO diagram. Ryoke mafic dykes and pillows plot close to the tholeiite/calc-alkali boundary of Miyashiro (1974), whereas the gabbro cumulates plot mostly in the tholeiite field.

continental margin, in some respects this model accords with reality.

The proposed enriched mantle beneath the Eurasian continental margin might be old subcontinental lithospheric mantle related to the South China craton, along the margin of which the Cretaceous accretional orogen of SW Japan developed. However, involvement of isotopically enriched sedimentary components sinking with the subducting oceanic plate could also raise the SrI of the overlying mantle wedge. If the eastward-younging trend of the Cretaceous granitic rocks in SW Japan (Fig. 6) was caused by the eastward migration of the RTT (ridge–trench–trench) junction as Nakajima *et al.* (1990) suggested, then the subducting plate would be young and hot, causing the overlying sediments to melt at some depth, isotopically enriching the Sr-poor peridotite of the mantle wedge above.

4.1.4. Crustal contamination model. Most of the mafic rocks and mantle xenoliths from continental arcs have much lower SrI than the Ryoke mafic rocks. The few that do not have mostly been affected by crustal contamination. Furthermore, the high $\delta^{18}O$ of the Ryoke mafic rocks (8·5–9·9‰; Ishihara & Matsuhisa 2002) can also be interpreted to indicate involvement of sedimentary components in the deep crust, rather than in the mantle source region.

If the mantle-derived primitive basaltic magmas were less enriched than the Ryoke mafic rocks, then they must have incorporated some enriched crustal material in order to form the hybrid parental magma (SrI = ~0·7075). The 'dykes and pillows' magma and the gabbroic cumulates would have been generated from this parental magma by fractionation, so the crustal component must have been incorporated, and the magma homogenised at deep in the lower crust.

A possible enriched crustal component in the lower crust is restitic metasediment. This is the metamorphosed equivalent of the Middle to Late Jurassic accretionary complex of the Mino–Tanba–Kuga belt in Southwest Japan. They are mainly pelitic and psammitic rocks, originated from the mountain ranges formed by the collision of the North China and South China blocks, so have isotopic compositions much more enriched (SrI = 0·714–0·721) than the Ryoke mafic rocks.

Some possible SrI–SiO_2 mixing relationships between metasediment and mantle-derived primitive basalt to form hybrid parental magmas are illustrated in Fig. 10b. The primitive basalt is assumed to have 46 wt.% SiO_2 (the minimum likely value given by phase equlibria), SrI = 0·705 and

Table 3 Compositional ranges for selected elements from mafic rocks in various tectonic settings

	SiO_2 (%)	Nb (ppm)	Sr (ppm)	Zr (ppm)
Southwest Japan				
MME	54–60	6·3–7·9	370–480	82–103
Gabbro	45–55	2·1–2·4	300–700	6–7
Continental arc				
Andes (Quat)	51–54	2·3–12	480–650	50–170
Sierra Nevada	52–57	8–9	350–750	169–700
New England FB	54–58	13–22	450–630	270–380
Oceanic island arc				
Sunda	50–55	2–4	400–460	82–134
Izu	50–55	<1	170–420	40–80
Continental(?) island arc				
NE Japan				
Nekoma	55–60	4·0–5·9	300–360	84–130
Bandai	60–61	5·6–5·9	200–320	120–130
Continental flood basalt				
Decan, Snake River	46–51	15–37	220–370	170–400
N-MORB	48–51	2–3	90–125	70–85

Data from Thompson *et al.* (1983), Kimura *et al.* (2002), Taylor & Nesbitt (1998), Foden (1983), Thorpe *et al.* (1984), Marriner & Milward (1984), Hickey *et al.* (1986), Schilling *et al.* (1983), Feeley & Davidson (1994), Tani (2002) and Sisson *et al.* (1996).

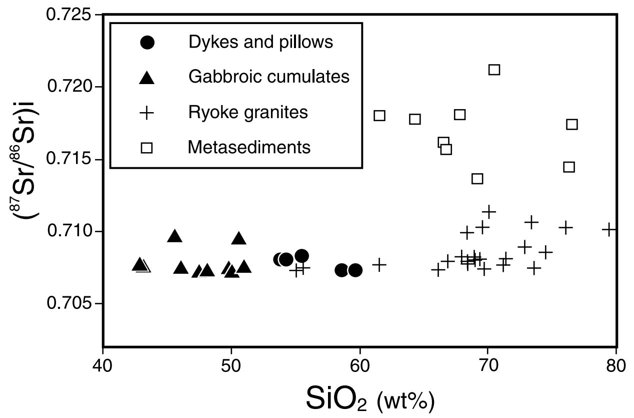

Figure 9 SiO_2-SrI systematics of the two types of Ryoke mafic rocks, Ryoke granites and metasediments.

Sr = 350 ppm (as is common in continental arc basalts). Two model metasediments are considered, the first with 67 wt.% SiO_2, SrI = 0·717 and Sr = 170 ppm (based on the average of the Ryoke high-grade pelitic gneisses) (Table 2), and the second with 60 wt.% SiO_2 such as the melt-depleted lower crustal restitic metasediments from the Ivrea–Verbano zone (Sinigoi *et al.* 1995, 1996). The SiO_2 contents of the lower crustal materials involved in producing the hybrid magmas are likely to be within this range. It is shown that the proportion of crustal material required to produce the SrI observed in the Ryoke mafic magmas is 30–40%, producing a hybrid magma with 51 and 53 wt.% SiO_2, respectively, which can fractionate to form the 'dykes and pillows' magma.

However, the crustal contamination model is only possible for a limited composition range of the assumed mixing end members. Figure 11 shows the SiO_2 versus Sr mixing relationships for the same crustal contamination model system as illustrated in Figure 10b. The assumed SiO_2 content of the crustal metasedimentary component is 67 wt.% in Figure 11a, 60 wt.% in Figure 11b. The bold lines trace the composition of hybrid magmas with SrI = 0·7075 (similar to the dykes and pillows), formed by mixing with mantle-derived primitive basalts with different Sr contents.

The Sr content of the parental basalt magma cannot be as low as 100–200 ppm because no realistic olivine-pyroxene fractionation of the resultant hybrid could produce the high Sr content of the dykes and pillows. An Sr-content of 350–400 ppm in the parental magma is much more likely. The SiO_2 content of the primitive basalt is constrained to be as low as 46 wt.%, because if it is much higher, the hybrid magma becomes too SiO_2-rich to produce the 'dykes and pillows' magma by fractionation (Fig. 10b). Similarly, higher SiO_2 contents of the crustal metasediment component would make the hybrid magma more Si-rich.

This modelling shows that it would be possible to produce the Ryoke mafic rocks by crustal contamination of primitive basaltic magmas without involving a highly-enriched mantle source. However, only a limited range of end member compositions is permitted if the model is to be realistic. Even assuming the basaltic end member to be derived from primitive mantle (SrI = 0·705), the maximum likely crustal contribution to the hybrid magma is ∼40% (Fig. 10b). It is concluded, therefore, that the major component of the Ryoke mafic magmas is mantle-derived.

4.2. Granitic magmatism and crustal evolution

4.2.1. Generation of granitic magma in the Ryoke belt. The broad isotopic similarity between the mafic and granitic rocks in the Ryoke belt suggests that the two rock types are genetically related. One possibility, which is consistent with the synchroneity of the mafic and granitic magmatism, is that the granitic magmas were produced by fractional crystallisation of the successive batches of mafic magma represented by the dykes and pillows. If so, then the isolated bodies of gabbroic cumulate might be some of the solid residue complementary to the granitic magmas (Fig. 11). Another possibility is that the granitic magmas were produced by partial melting of the mafic rocks in the lower crust. Because the granitic rocks are closely associated with the mafic rocks in space and time, it is conceivable that the intrusion of successive batches of mafic magma induced partial melting of mafic rocks formed just beforehand. In either case, the mafic magmatism has played both a thermal and a material role in the extensive Cretaceous granitic magmatism in SW Japan.

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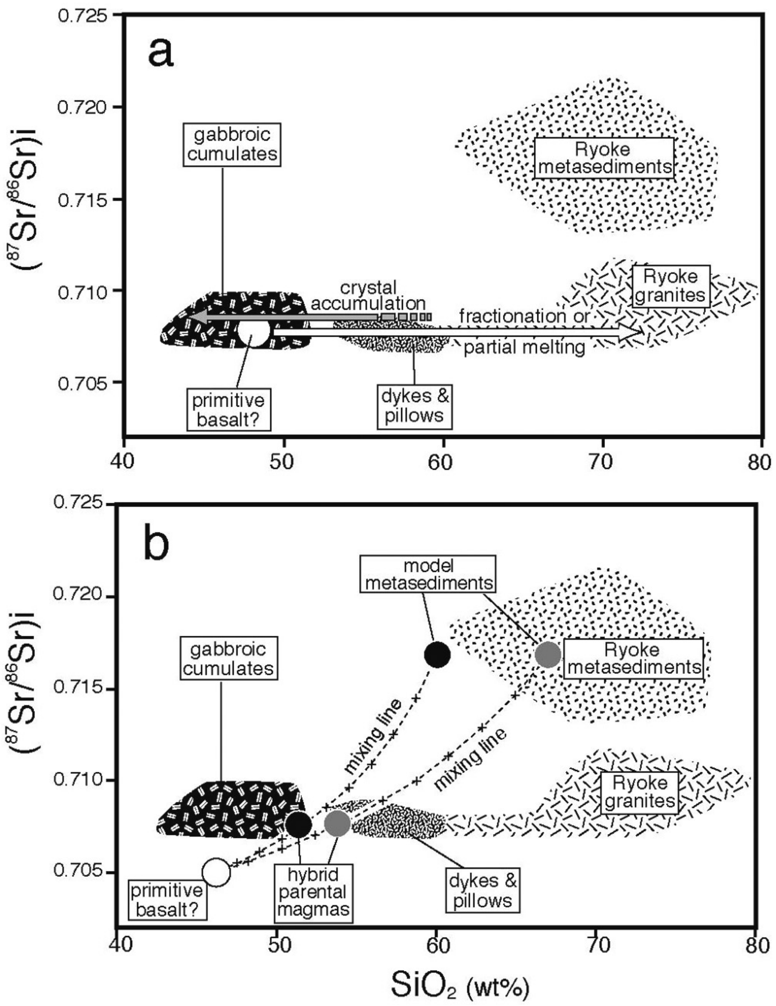

Figure 10 Generation models for the Ryoke mafic and granitic rocks on a SiO_2-SrI system: (a) Enriched mantle model assuming the source mantle of SrI = ~0·7075, which generates a mantle-derived enriched primitive basaltic magma, which generates the 'dykes and pillows' magma only with fractionation; (b) crust contamination model assuming less enriched source mantle and mixing with the crustal components to form hybrid parental magmas. Two cases of mixing involving high-grade Ryoke metapelite (SiO_2=67 wt.%) and more SiO_2-depleted model metasediments (SiO_2=60 wt.%), respectively, are shown.

It is argued above that the mafic rocks in the Ryoke belt are derived predominantly from the mantle. This in turn means that the majority of the granitic rocks are also composed mostly of mantle-derived components. Only a few of the more felsic granites have SrI slightly higher than the mafic rocks, which can be ascribed to minor assimilation of additional metasediment. S-type granites are generated mostly from recycled upper crust, so do not contribute to the growth of continental crust. Most of the Ryoke granites are I-type, although they include some two mica- or garnet-bearing varieties (Nakajima 1996). The predominance of I-type granites accords with a large proportion of juvenile material being derived from mantle. The Cretaceous granitic rocks in SW Japan therefore provide a record of crustal growth by addition of predominantly mantle-derived material during arc magmatism.

4.2.2. The Cretaceous lower crust of SW Japan. As discussed above, the granitic rocks of SW Japan were probably formed from mafic rocks by either fractional crystallisation or partial melting. Because mafic rock produces only small amounts of granitic magma by either process, the amount of mafic to ultramafic cumulate or residue remaining must have been an order of magnitude greater than the volume of the resultant granites. However, the volume of mafic rock exposed in SW Japan is negligibly small, compared to the huge volumes of granite. This suggests that the mafic lower crust was thicker by an order of magnitude than the newly-formed granitic upper crust. If the newly-formed granitic upper crust were 5 km thick, then a mafic lower crust 50 km thick would be required. There is no evidence now for such a thick mafic layer under SW Japan, so much of it must have been recycled back into the mantle by delamination (Rudnick 1995). However, in the Cretaceous, judging from the inferred P–T conditions of the Ryoke metamorphism, the geothermal gradient beneath SW Japan was high, 45–60°C/km (Nakajima 1996). Although this high geotherm is estimated from metamorphic petrology on the middle to upper crustal rocks, a high geotherm is presumed to also have prevailed in the lower crust, because it would have originated from the active underplating of basaltic magma from mantle to the lowermost crust. Such a high gradient would shift the garnet stability field to higher pressure, increasing the depth at which the crust would be sufficiently dense to delaminate, thereby possibly allowing a relatively thick mafic underplate to develop.

5. Conclusions

Although mafic rocks are volumetrically a minor component of the Ryoke belt, they provide important clues to the granitic

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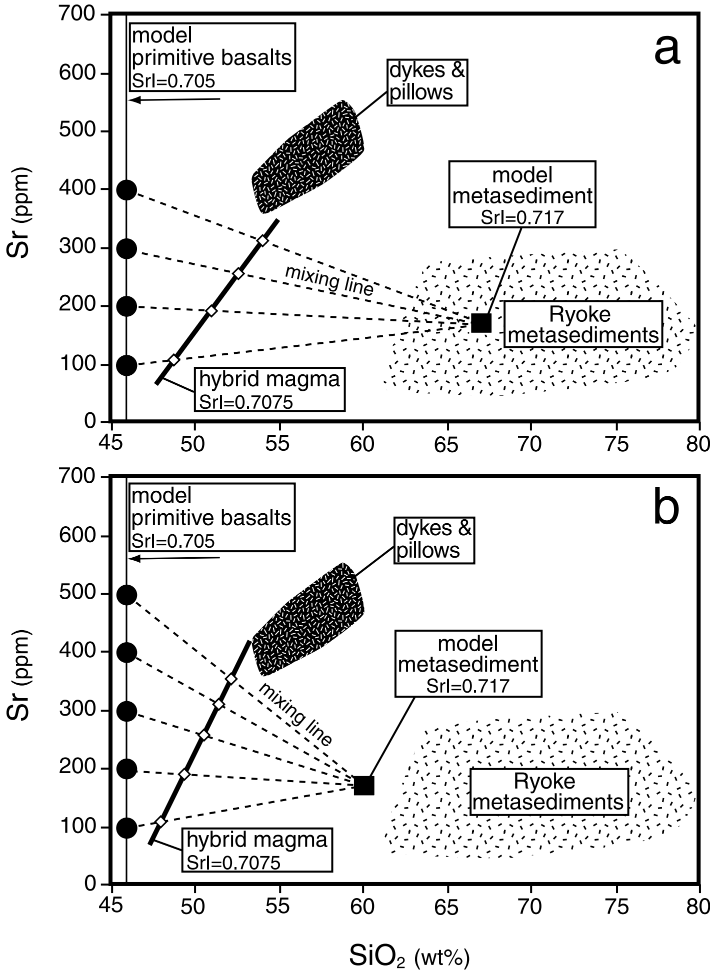

Figure 11 SiO_2-Sr systematics showing the mixing relationships of the crust contamination model. Mixing between possible mantle-derived primitive basalts with 46 wt.% SiO_2 and SrI=0·705 and (a) representative high-grade Ryoke metasediments (SiO_2=67 wt.%, Sr=170 ppm and SrI=0·717) and (b) model lower crustal metasediments (SiO_2=60 wt.%, Sr=170 ppm and SrI=0·717). Each of the broken lines represents a mixing line joining the metasediments and the primitive basalt with different Sr content. Bold lines show the compositions of the hybrid magma with SrI=0·7075, produced by mixing between the metasediments and the primitive basalts with varying Sr content. In both cases, the primitive basaltic magma with limit ranges of Sr content can generate the 'dykes and pillows' magma through olivine-pyroxene fractionation. See text for discussion.

magmatism and crustal evolution in Cretaceous SW Japan. The mafic rocks occur either as dykes and pillows set in granitic matrix or as separate bodies of gabbroic cumulate. The gabbroic cumulates do not have the composition of magmas, whereas the dykes and pillows have the composition of arc-related basaltic andesite or andesite. SHRIMP zircon U-Pb ages confirm that throughout the Ryoke belt, the mafic rocks formed contemporaneously with the associated granitic rocks, becoming younger eastward along the arc. The broad isotopic similarity between the mafic and granitic rocks suggests that the granitic rocks were produced either by fractional crystallisation of mafic magmas or by partial melting of newly-formed mafic rocks at depth. The close spatial and temporal association of the mafic and granitic rocks, together with their Sr isotopic similarity, points to thermal and material roles for the mafic magmatism in the extensive granitic magmatism.

The enriched Sr isotopic signature of the Ryoke mafic rocks could indicate either of two possible petrogenesis: (1) Derivation of the magmas from a highly-enriched mantle source that might be either subcontinental lithospheric mantle or less enriched mantle contaminated by addition of melt derived from subducting sediment; or (2) Deep crustal sedimentary contamination of primitive basaltic magma derived from a less enriched mantle source. Regardless of the mechanism of enrichment, it is concluded that the Cretaceous magmatism in Southwest Japan represents a major episode of crustal growth by additions from the upper mantle during arc magmatism.

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