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Author(s)	Koide, Yoshiyuki; Sano, Sakae; Ishiwatari, Akira; Kagami, Hiroo
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GEOCHEMISTRY OF THE YAKUNO OPHIOLITE IN SOUTHWEST JAPAN

by

Yoshiyuki Koide, Sakae Sano*, Akira Ishiwatari**
and Hiroo Kagami*

(with 13 text-figures and 3 plates)

Abstract

The Yakuno ophiolite is exposed in the eastern part of the Maizuru Tectonic Belt which consists of ophiolitic rocks. The Yakuno ophiolite is made up of ultramafic, mafic, intermediate, and felsic rocks which are regarded as the fragments of an ancient oceanic crust. Major element analyses (23 samples) and Sr isotope determinations (12 samples) were made for the representative rocks of the Yakuno ophiolite. The chemical features of the rocks and relict clinopyroxenes indicate that the ophiolite belongs to the tholeiitic rock series and shows a similarity to MORB in discrimination diagrams. However, the Yakuno ophiolite is much thicker than normal oceanic crust, and is associated with evolved rocks such as quartz diorite, granophyre and trondhjemite, but not with typical sheeted dyke complex. The Yakuno ophiolite is higher in normative plagioclase content and initial Sr isotope ratio (0.705092) than typical MORB. Hence, the Yakuno ophiolite resembles both ocean ridge and oceanic island basalts in magmatic nature, which suggests that it has been generated by oceanic island magmatism at an ocean ridge. The Rb-Sr isochron age of the Yakuno ophiolite was determined as 285 Ma, which is almost identical with those of other ophiolites from the Maizuru Tectonic Belt. So far as the available chemical data are concerned, the ophiolites from the Maizuru Tectonic Belt seem to have originated at various tectonic settings, i.e. oceanic island at ocean ridge, ocean ridge, island arc and marginal sea from east to west.

Introduction

Upper Paleozoic greenstones from the Inner Zone of Southwest Japan occur in four belts; Tamba Belt (Hashimoto et al., 1970; Hashimoto and Saito, 1970; Hashimoto, 1972; Sano, 1986), North Zone of Sangun-Chugoku Belt (Hase and Nishimura, 1979; Nishimura et al., 1979), Sangun Metamorphic Belt (Ishiwatari, 1978; Koide, 1984), and Maizuru Tectonic Belt (including both so-called Maizuru Belt and Middle Zone of the Sangun-Chugoku Belt, Koide, 1986). The greenstones from the Maizuru Tectonic Belt have been regarded as dismembered ophiolites of 280 ~ 300 Ma (Koide et al., 1987).

The Yakuno ophiolite is exposed in the eastern part of the Maizuru Tectonic Belt. In the Yakuno area, the rocks show a typical ophiolite sequence though dyke swarm and pelagic sediments are scarce, and they are similar to MORB in chemistry. Ishiwatari (1985a) showed that the Yakuno ophiolite was affected by relatively higher pressure metamorphism than the typical ocean floor metamorphism. He, therefore, concluded that the Yakuno ophiolite was derived from an unusually thick oceanic crust (15 ~ 30 km thick).

In this paper, the authors discuss magmatic property of the Yakuno ophiolite based

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Contribution from the Department of Geology and Mineralogy, Faculty of Science, Hokkaido University, No. 1926

* Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori 682-02, Japan.
** Department of Earth Sciences, Kanazawa University, Kanazawa 920, Japan.

on the new data of major element chemical analyses and Sr isotope ratios.

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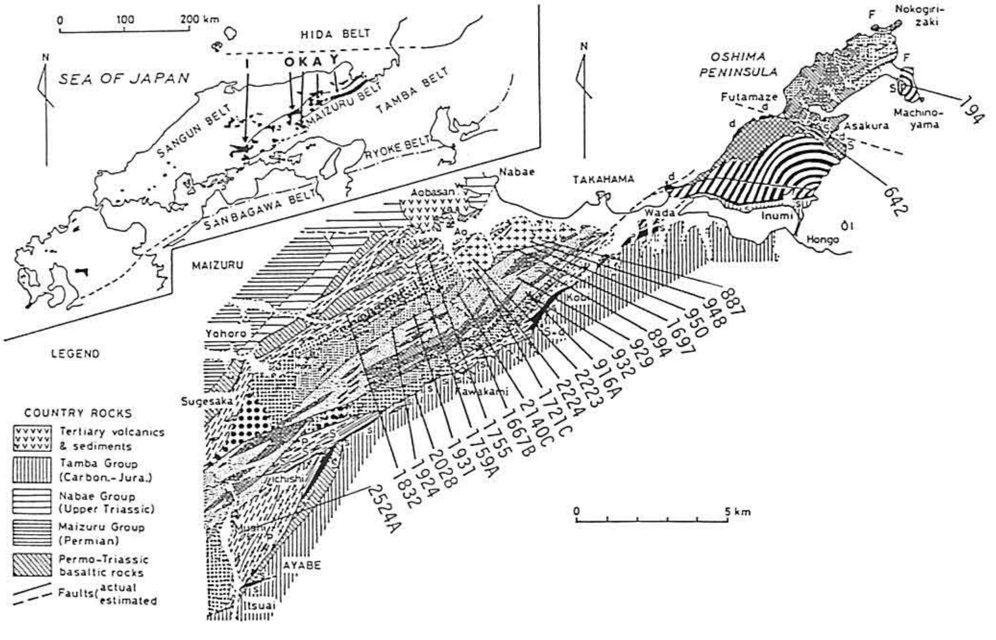
Outline of Geology and Petrography

The Yakuno ophiolite and its equivalents extend from Oshima Peninsula to Ibara in a WSW direction (Text-fig. 1). The ophiolite massif is thrust over the Tamba Belt on the south, while on the north it is in high angle fault contact with the Nabae Group (Upper Triassic) and the Maizuru Group (Permian). The massif consists of many tectonic slices, each of which contains only a part of the ophiolite succession (Text-fig. 2).

Ishiwatari (1985a and b) divided the Yakuno ophiolite into three members based on lithofacies; metavolcanics, metacumulates and metaresidua members (Text-fig. 2).

The metavolcanics member is made up mainly of massive basalt flows with small amounts of pillow lavas, hyaloclastites and reworked volcaniclastic rocks. They often intercalate thin layers of black slate. Numerous dolerite dykes and sheets are observed in this area, but they do not form a typical "sheeted dyke complex".

Between the metavolcanics and the metacumulates, there is a transitional zone which is composed of fine-grained pyroxene amphibolite and coarse-grained hornblende metagabbro. The former is basaltic (Fe-rich) in composition, whereas the latter



Text-fig. 1 Geological map of the Yakuno ophiolite (Ishiwatari, 1985a) and sample localities. The legend of lithology of the ophiolite is shown in Text-fig. 2. Insert shows the distribution of the ophiolitic rocks in the Inner Zone of Southwest Japan. Y: Yakuno, K: Kamigori, O: Ohara, I: Ibara.

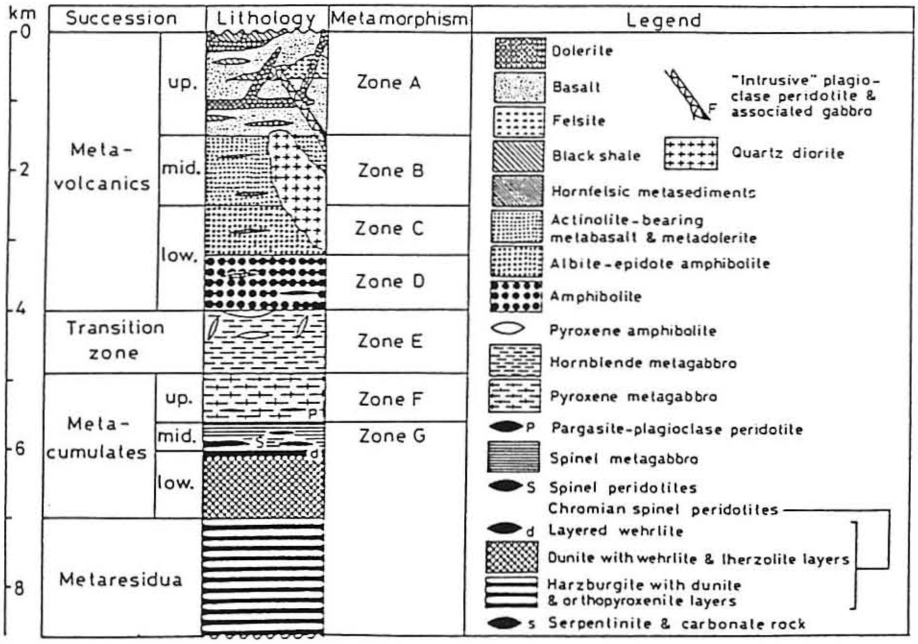
resembles the underlying mafic metacumulate rocks in chemistry.

The metacumulate member is divided into three zones based on lithology. The upper zone is made up mainly of layered pargasite-two pyroxene metagabbro with some layers of pargasite-plagioclase wehrlite and pargasite-clinopyroxenite. This zone grades upward into the transition zone. The middle zone is composed of alternating layers of two-pyroxene metagabbro, pyroxenite (mainly clinopyroxene rich olivine websterite), and peridotite (lherzolite and wehrlite). The lower zone is dominated by massive dunite with some layers of wehrlite, lherzolite, harzburgite and chromitite. Rhythmic layering is developed in the uppermost section.

The metaresidua member is composed wholly of chromian spinel peridotite, in which harzburgite is dominant.

The associated complexes in this area are hornblende-quartz diorite, which was intruded into the metavolcanics, porphyrite, granophyre, trondhjemite and quartz keratophyre. The quartz diorite was affected by the same metamorphism as the country metavolcanics. The ultramafic, mafic and evolved rocks are regarded as the products of the same magmatism.

The Yakuno ophiolite has been extensively subjected to metamorphism ranging from prehnite-pumpellyite facies to granulite facies (Ishiwatari, 1985a). Based on the metamorphic mineral assemblage of mafic rocks, the ophiolite can be divided into seven metamorphic zones from A to G and become progressively higher grades toward



Text-fig. 2 Schematic columnar section of the Yakuno ophiolite (Ishiwatari, 1985a).

the lower succession in the following order of metamorphic facies; prehnite-pumpellyite, greenschist, epidote amphibolite, amphibolite, hornblende granulite and pyroxene granulite facies.

The metamorphic facies series, including prehnite-pumpellyite and epidote amphibolite facies, suggests a low geothermal gradient and a high pressure compared with the normal metamorphic conditions of ocean floor metamorphism. Such metamorphic conditions of the Yakuno ophiolite require an unusually thick oceanic crust, 15~30 km (Ishiwatari, 1985a). The actual thickness of the ophiolite is about 7 km. Therefore, it is likely that the Yakuno ophiolite has become considerably thin due to tectonic slice.

Table 1 Rock chemistry and C.I.P.W. norm of the Yakuno ophiolite

Chemical compositions are recalculated on water free basis. mBas: metabasalt, mDol: metadolerite, mGb: metagabbro, Amph: amphibolite, Grn: granulite, spWbs: spinel websterite, qz-Di: quartz diorite,

Sample No	950	929	894	1949	916A	887	1721C	932	2140C	1667B	1924	1931
Rock Name	mBas	mBas	mBas	mBas	mDol	mBas	mDol	mDol	mBas	mDol	mBas	mBas
Meta.Zone	A	A	A	A	A	A	A	B	B	B	B	B
SiO_2	53.71	52.66	50.14	50.30	51.10	52.20	51.77	50.32	52.71	50.44	53.45	51.44
TiO_2	1.19	1.23	1.24	1.35	1.43	1.64	1.97	0.83	0.97	1.41	1.45	2.12
Al_2O_3	15.33	16.09	17.63	15.00	16.40	16.26	15.67	17.46	15.52	16.19	15.32	15.32
FeO*	8.67	8.96	9.93	10.87	9.81	9.04	10.72	8.43	10.09	10.19	10.35	10.21
MnO	0.19	0.14	0.64	0.16	0.18	0.18	0.19	0.15	0.29	0.26	0.22	0.22
MgO	7.71	6.67	6.17	7.75	8.37	7.70	6.75	10.07	8.00	7.63	7.04	5.97
CaO	7.50	8.23	9.41	10.39	8.88	9.58	8.75	8.85	8.04	9.72	7.36	10.09
Na_2O	4.07	5.34	4.27	4.10	6.51	2.18	3.53	2.46	4.16	2.72	4.12	4.29
K_2O	1.63	0.69	0.56	0.07	0.12	1.22	0.75	1.33	0.23	1.44	0.68	0.35
P_2O_5	n.a.	n.a.	n.a.	n.a.	0.20	n.a.	0.25	0.10	n.a.	n.a.	n.a.	n.a.
CIPW Norm**												
Q	-	-	-	-	-	1.29	-	-	-	-	-	-
Or	9.62	4.07	3.31	0.41	0.71	7.20	4.49	7.85	1.36	8.50	4.01	2.07
Pl	53.13	54.62	57.40	52.59	58.23	49.37	54.46	53.43	58.11	50.66	56.09	56.32
Ab	34.40	36.74	30.15	30.30	29.66	18.43	29.83	20.79	35.15	22.99	34.82	34.83
An	18.72	17.87	27.25	22.29	28.60	30.94	24.63	32.64	22.96	27.68	21.27	21.48
Ne	-	4.54	3.22	2.36	-	-	-	-	-	-	-	0.76
Di	13.64	18.74	15.98	23.92	10.56	12.60	11.44	12.51	7.95	15.07	11.35	23.44
Wo	7.70	9.56	8.09	12.19	5.88	6.90	6.39	7.04	4.41	8.55	6.34	11.90
En	4.58	5.37	4.12	6.71	3.47	4.12	3.45	3.95	0.72	4.79	3.45	6.31
Fs	1.36	3.80	3.78	5.03	1.21	1.58	1.60	1.52	9.99	1.73	1.56	5.22
Hy	4.06	-	-	-	12.70	20.78	14.22	9.12	7.97	5.08	13.41	-
En	3.13	-	-	-	9.42	15.03	9.71	6.59	2.03	3.74	9.23	-
Fs	0.93	-	-	-	3.29	5.75	4.51	2.54	12.12	1.35	4.18	-
Ol	9.91	13.99	15.84	16.08	7.23	-	3.58	8.65	10.00	9.39	4.72	11.44
Fo	8.05	7.86	7.87	8.81	5.56	-	2.55	6.56	2.12	7.32	3.39	5.98
Fa	1.86	6.12	7.97	7.27	1.66	-	1.04	2.09	0.96	2.07	1.33	5.46
Mt	1.19	1.71	1.90	2.08	1.42	1.39	1.57	1.43	1.20	1.40	1.51	1.95
Il	1.27	2.33	2.35	2.56	1.70	2.17	2.40	1.11	0.96	1.53	1.75	4.02
Ap	-	-	-	-	0.46	-	0.58	-	-	-	-	-

Rock and Mineral Chemistries

Major element chemical analyses of 23 representative rocks were carried out by the X-ray fluorescence analyser. The localities of analysed samples are shown in Text-fig. 1. The analysed samples comprise nearly all of the metamorphic zones and rock types. Table 1 lists the analysed data which are recalculated on water free basis. C.I.P.W. norm is calculated using the ratio of $Fe_2O_3/FeO = 0.15$ (Brooks, 1975). New analyses of the reference samples, JB-1 and JG-1, were also made by the same method, and the results are listed in Table 2, which show close agree with the recommended values (Ando et al., 1974).

Gphy: granophyre, Trnj: trondhjemite, FeO*: total iron as FeO, C.I.P.W. norm**: calculated on the basis of Fe_2O_3/FeO ratio = 0.15. Sample localities are shown in Text-fig. 1. Data of 950, 929, 894, 1949, 887, 1931, 2140C, 1924, 1667B and 642 after Ishiwatari (1980MS, 1985a and b).

Sample No	1832	2524A	2028	1755	1759A	642	194	2223	2224	948	1697
Rock Name	mGb	Amph	Amph	mGb	mGb	Grn	spWbs	qz-Di	qz-Di	Gphy	Trnj
Meta.Zone	E	E	E	F	F	G					
SiO_2	45.11	51.39	48.62	44.34	48.93	49.28	49.64	57.80	68.33	78.05	75.74
TiO_2	1.37	1.98	3.71	1.31	1.55	0.18	0.09	2.27	0.68	0.36	0.30
Al_2O_3	15.93	14.85	13.57	19.44	15.19	16.67	6.45	15.04	15.30	12.08	12.73
FeO*	11.71	9.60	15.10	12.62	11.11	5.59	7.71	10.44	6.81	2.74	4.04
MnO	0.22	0.15	0.22	0.18	0.27	0.11	0.15	0.26	0.16	0.04	0.08
MgO	10.08	5.36	5.62	6.19	8.57	11.80	25.31	2.86	0.68	0.62	0.35
CaO	12.65	12.05	8.77	14.23	11.27	14.88	10.32	5.77	2.32	1.13	2.21
Na_2O	2.73	4.25	3.05	1.65	2.93	1.48	0.27	3.93	4.51	4.64	4.52
K_2O	0.20	0.16	0.69	0.04	0.10	n.d.	0.05	0.79	1.07	0.33	n.d.
P_2O_5	n.a.	0.23	0.65	n.d.	0.09	n.a.	0.02	0.84	0.14	0.02	0.03
CIPW Norm**											
Q	-	-	-	-	-	-	-	12.41	28.08	44.84	41.64
C	-	-	-	-	-	-	-	-	2.84	2.08	1.35
Or	1.18	0.94	4.07	0.24	0.59	-	0.30	4.66	6.32	1.95	-
Pl	39.94	53.15	47.01	55.62	52.71	51.33	18.51	54.24	48.71	44.72	48.99
Ab	9.37	32.21	25.76	10.17	24.75	12.52	2.28	33.21	38.13	39.24	38.23
An	30.58	20.94	21.26	45.44	27.96	38.82	16.22	21.04	10.59	5.47	10.76
Ne	7.42	2.01	-	2.04	-	-	-	-	-	-	-
Di	26.15	30.67	13.31	20.76	19.97	26.43	26.74	1.68	-	-	-
Wo	13.40	15.56	7.49	10.45	11.39	14.60	14.53	0.87	-	-	-
En	7.83	8.12	3.36	4.89	6.46	10.37	11.00	0.32	-	-	-
Fs	4.93	6.99	2.46	5.45	2.12	1.46	1.21	0.49	-	-	-
Hy	-	-	15.44	-	2.39	5.85	26.10	17.19	11.48	5.57	7.14
En	-	-	8.90	-	1.80	5.13	23.51	6.79	1.69	1.54	0.87
Fs	-	-	6.53	-	0.59	0.72	2.59	10.39	9.79	4.02	6.27
Ol	20.47	7.11	1.98	16.42	11.39	10.78	21.88	-	-	-	-
Fo	12.08	3.65	1.20	7.36	9.15	9.72	19.95	-	-	-	-
Fa	8.38	3.46	0.78	9.06	2.25	1.06	1.93	-	-	-	-
Mt	2.24	1.84	2.23	2.41	1.49	0.76	1.13	1.85	1.33	0.56	0.81
Il	2.60	3.76	4.60	2.48	1.60	0.19	0.11	3.83	1.33	0.75	0.62
Ap	-	0.53	1.50	-	0.21	-	0.05	1.94	0.32	0.05	0.07

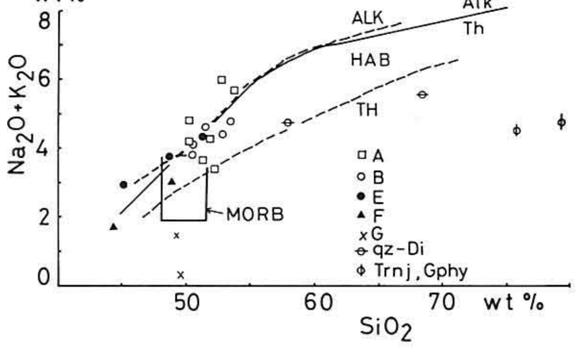
Table 2 Analyses of JB-1 and JG-1
XRF: new analyses (this work), Recom: recommended values (Ando et al., 1974). FeO*: total iron as FeO.

Sample No. Rock Name	JB-1 XRF	 Recom	JG-1 XRF	 Recom
SiO_2	53.13	53.39	73.23	72.87
TiO_2	1.38	1.38	0.25	0.26
Al_2O_3	14.60	14.83	14.39	14.35
FeO*	8.45	8.29	1.92	1.99
MnO	0.16	0.15	0.06	0.06
MgO	8.16	7.89	0.78	0.75
CaO	9.53	9.48	2.15	2.22
Na_2O	2.88	2.86	3.26	3.41
K_2O	1.46	1.46	3.88	3.99
P_2O_5	0.26	0.27	0.08	0.10

In the alkali-silica diagram (Text-fig. 3), the data of the Yakuno ophiolite plot mostly in the tholeiitic field classified by Macdonald and Katsura (1964). The SiO_2 contents range widely from 44 to 78 wt%. The variation trend of the ophiolite ranges from the alkaline to the tholeiite fields through the high alumina basalt field (Kuno, 1966). Most of the mafic rocks are apparently higher in alkali than MORB (Miyashiro, 1975).

Text-fig. 4 shows the Ne-Pl-Ol-Hy-Q diagram of C.I.P.W. norm (Yoder and Tilley, 1962). Rock chemistry of the metabasalt and metadolerite widely,ranges from nepheline-normative to quartz-normative field, but most of them are olivine-hypersthene-normative (i.e. olivine tholeiite). The evolved rocks, such as, quartz diorite, trondhjemite and granophyre, trend to quartz tholeiite. The Yakuno metabasalts together with the Ibara metabasalts are apparently higher in plagioclase than MORB.

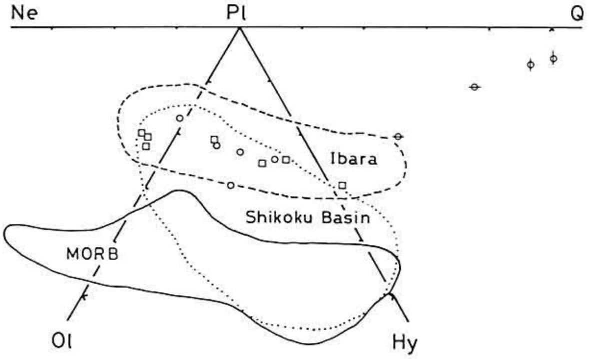
Miyashiro (1973) showed that the tholeiitic and calcalkalic rock series can be classified by using of the SiO_2, TiO_2 and FeO* versus FeO*/MgO diagrams (Text-fig. 5). In these diagrams, the Yakuno ophiolite mostly plots in the tholeiitic field and shows



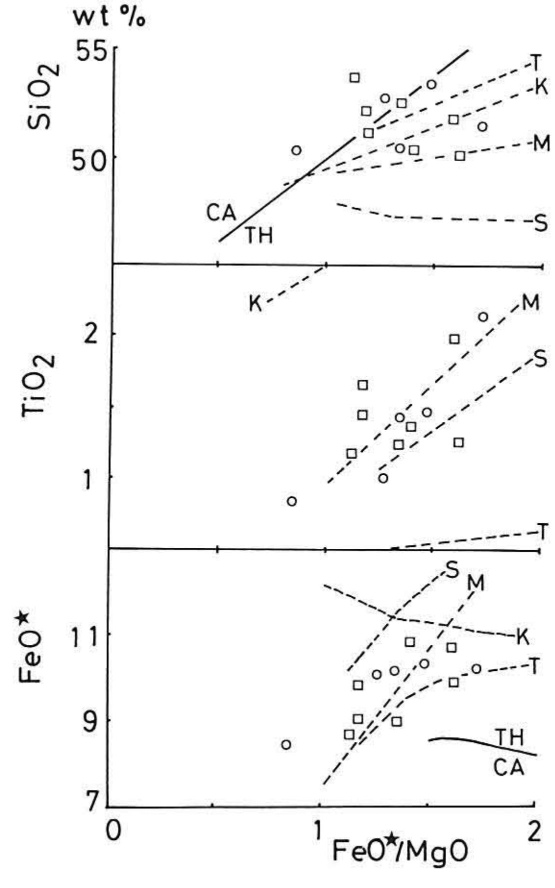
Text-fig. 3 Na_2O+K_2O — SiO_2 diagram
Solid line is the boundary between the alkalic (Alk) and tholeiitic (Th) rock suites (Macdonald and Katsura, 1964). Broken lines are the boundaries among the alkali (ALK), high-alumina basalt (HAB) and tholeiite (TH) rock series (Kuno, 1966). Rectangular field represents MORB (Miyashiro, 1973). Symbols with A to G: ultramafic and mafic rocks of the metamorphic zones A to G. qz-Di: quartz diorite, Trnj: trondhjemite, Gphy: granophyre.

a similarity to MORB (M). The FeO*/MgO ratios are less than 2.0, which are nearly comparable with the general range of ophiolites (Miyashiro, 1975).

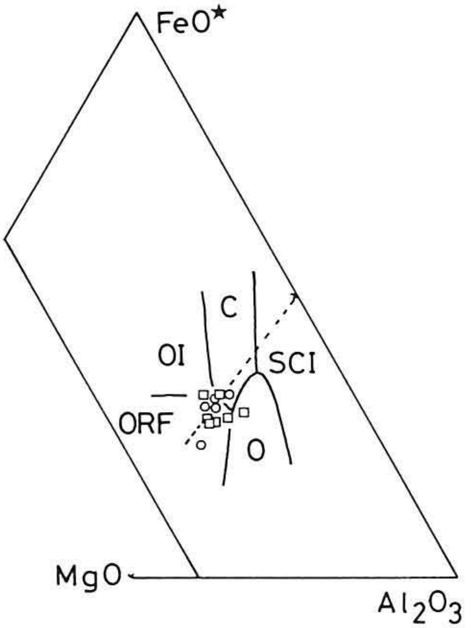
Pearce et al. (1977) proposed a graphical discrimination by using the MgO-FeO*-Al_2O_3 diagram (Text-fig. 6) for subalkaline basalt-andesite (51 ~ 56 wt% SiO_2).



Text-fig. 4 Ne-Pl-Ol-Hy-Q diagram of C.I.P.W. norm
Solid line area: MORB (Thompson et al., 1972), broken line area: Ibara metabasalts (Koide, 1986), dotted line area: Shikoku basin (Marsh et al., 1980). Symbols are same as in Text-fig. 3.



Text-fig. 5 SiO_2, TiO_2 and FeO* versus FeO*/MgO diagrams
Solid line boundary between calc-alkaline (CA) and tholeiite rock series (TH) (Miyashiro, 1975), broken lines: crystallization trends of abyssal tholeiite (M), liquid of Skaergaard (S), Tofua Island (T) and Kilauea in Hawaii Islands (K) (Miyashiro, 1975). Symbols are same as in Text-fig. 3.

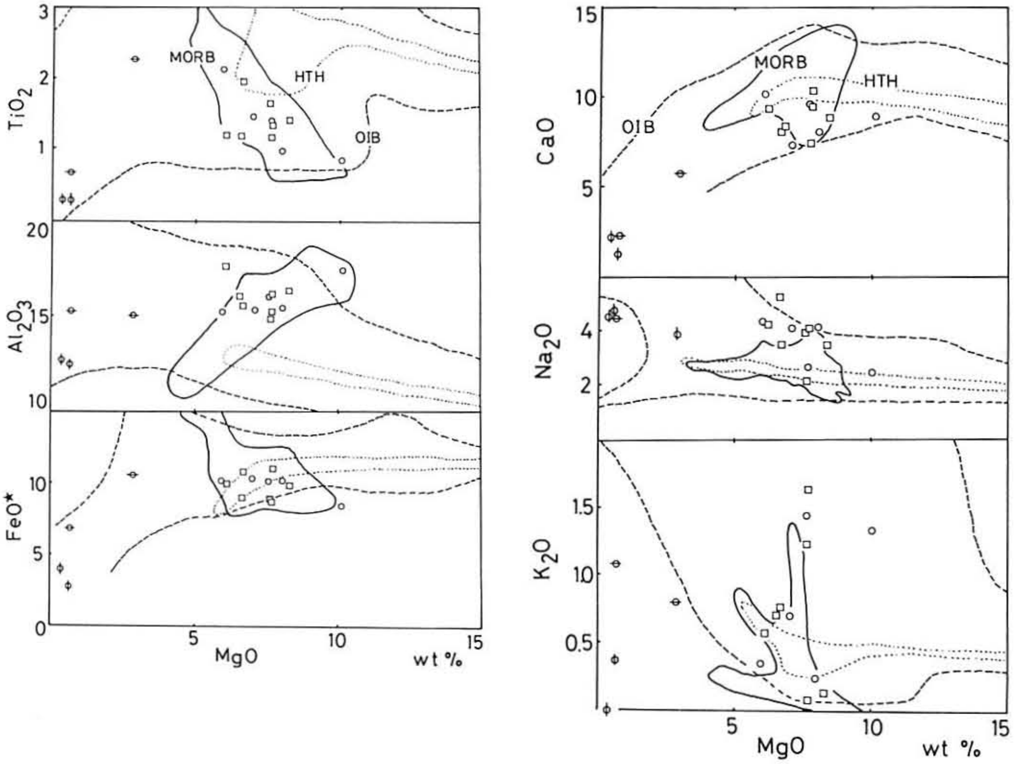


Text-fig. 6 FeO*-MgO-Al_2O_3 diagram
The discriminant boundaries (solid lines) are shown after Pearce et at. (1977); C: continental, OI: ocean island, ORF: ocean ridge and floor, O: orogenic, and SCI: spreading center island. Broken line is the boundary between tholeiitic (FeO*-rich side) and alkaline rock series (FeO*-poor side) from intra-plate ocean islands. Symbols are same as in Text-fig. 3.

They also define the boundary between oceanic island tholeiites and oceanic island alkaline rocks in the same diagram. The analyses of the Yakuno ophiolite plot in a small area near the boundaries between the ocean ridge and floor (ORF) and the ocean island rocks (OI) and between the ocean island tholeiite and alkaline rocks.

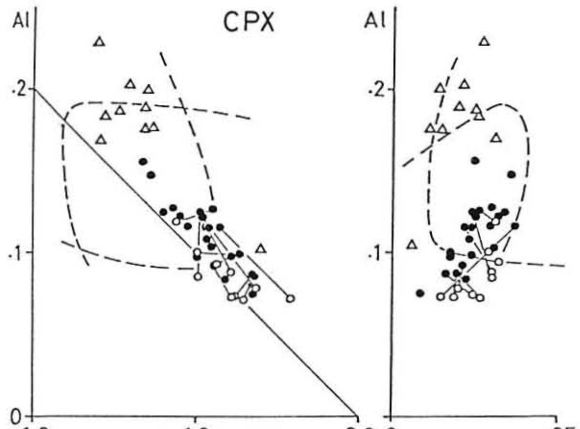
Text-fig. 7 shows the diagrams of TiO_2, Al_2O_3, FeO*, CaO, Na_2O and K_2O versus MgO. In these diagrams, the metabasalt and metadolerite of the Yakuno ophiolite plot in the field of the MORB glass (Basaltic Volcanism Study Project, 1981), while the evolved rocks plot in the field of those of the oceanic island basalt (OIB).

The magmatic parentage of ophiolites can be identified in terms of the chemistries of relict minerals. Clinopyroxenes are commonly preserved in the metabasalt and metadolerite of the Yakuno ophiolite. The Al-Si and Ti-Al diagrams of clinopyroxene proposed by Kushiro (1960) have been widely used for discrimination of the magmatic parentage (e.g. LeBas, 1962; Aoki, 1964). Maruyama (1976) advocated the boundaries between the tholeiitic and alkaline rock series. The relict clinopyroxene analyses of some Yakuno metabasalts and metadolerites plot in the high Si (1.80 ~ 1.95), low Al (0.08 ~ 0.20) and low Ti (0.01 ~ 0.03) sides (Text-fig. 8). The plotted field of the relict clinopyroxenes coincides mostly with the tholeiitic field and the overlapped field of the tholeiitic and alkalic clinopyroxenes, in which those from abyssal tholeiite plot (Maruyama, 1976). However, some of the metabasalt carry relict clinopyroxenes rich in Al.



Text-fig. 7 Oxides-MgO diagrams

The fields enclosed by the solid (MORB), dotted (HTH) and broken lines (OIB) are of abyssal basalt glasses, Hawaiian tholeiite suite, and oceanic island basalts, respectively (Basaltic Volcanism Study Project, 1981). Symbols are same as in Text-fig. 3.



Text-fig. 8 Al-Si and Al-Ti diagrams for relict clinopyroxenes

Circles: clinopyroxenes from the metadolerites (solid circle: core, open circle: rim, tie-line: same crystal), triangles: those from metabasalts. Broken lines are the boundaries between alkalic (Al-rich sides) and tholeiitic (Al-poor sides) pyroxenes (Maruyama, 1976).

Sr Isotope Geochemistry

Sr isotope determinations of 12 samples were carried out by using a full automatic thermal ionization mass spectrometer ("MAT 261" of Finnigan MAT LTD) of Institute for study of the Earth's Interior, Okayama University. Rb and Sr concentrations were measured by isotope dilution method. The analytical procedure was followed by Kagami et al. (1982). During the work the $^{87}Sr/^{86}Sr$ ratio of NBS 987 was determined as 0.710239±05 (normalized to the $^{86}Sr/^{88}Sr$ ratio of 0.1194) and BCR-1 as 0.705009±16. The Rb and Sr concentrations of standard samples were obtained as follows; Rb 184.8 ppm and Sr 185.5 ppm for JG-1, Rb 41.5 ppm and Sr 448.4 ppm for JB-1, and Rb 46.5 ppm and Sr 327.8 ppm for BCR-1.

Table 3 lists the newly obtained Sr isotope ratios and Sr and Rb concentrations. Text-fig. 9 shows the Rb and Sr concentration diagram. The Rb and Sr concentrations of MORB are characteristically lower than those of the basalts from other tectonic regions (Kurasawa, 1975). Koide et al. (1987) reported that basalts from both ocean ridge and marginal sea are similar to each other in Rb and Sr concentrations. The Yakuno ophiolite has Rb and Sr concentrations similar to MORB and marginal sea basalt.

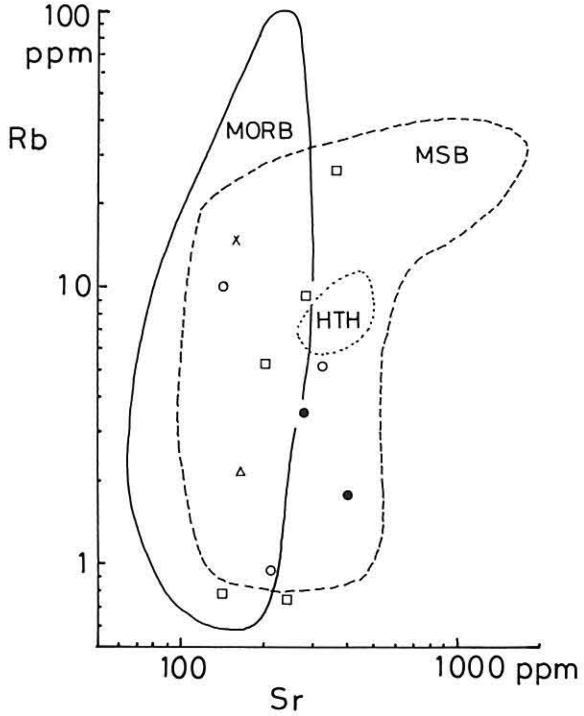
The $^{87}Sr/^{86}Sr$ — $^{87}Rb/^{86}Sr$ diagram (isochron diagram) for the Yakuno ophiolite is shown in Text-fig. 10. The Yakuno ophiolite does not form a clear isochron, and the plotted data are scattered. Except for the granulite, however, the rest 11 data indicate a positive correlation. Hence an isochron age of 285 Ma and the initial $^{87}Sr/^{86}Sr$ ratio (SrI) of 0.705092±157 are obtained by the use of the least squares method (York, 1966) and decay constant $1.42 \times 10^{-11} y^{-1}$ for ^{87}Rb (Steiger and Jäger, 1977). The SrI of each sample calculated on the basis of the isochron age 285 Ma is also shown in Table 3.

Text-fig. 11 shows an isotopic exchange diagram during rock and sea water interaction. Tazaki (1985) reported that the SrIs of the Slide Mountain ophiolite from the Canadian Cordillera are plotted on the isotopic exchange line of MORB and sea water. If Sr isotopic exchange occurred in the Yakuno ophiolite, the data are expected to plot on a line conecting MORB and sea water at 285 Ma. The plots of the ophiolite,

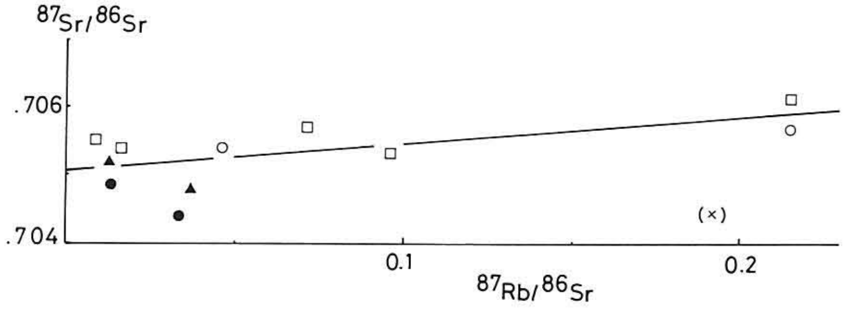
Table 3 Sr isotope ratios and Rb and Sr concentrations of the Yakuno ophiolite

$^{87}Sr/^{86}Sr$ ratios are normalized to the $^{86}Sr/^{88}Sr$ ratio of 0.1194. SrIs are calculated based on the isochron age (285 Ma). Sample localities are shown in Text-fig. 1.

Sample No	Rock	Meta.Zone	$^{87}Sr/^{86}Sr$	2 sigma	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	SrI(285Ma)
929	metabasalt	A	0.705733	0.000031	5.39	199.89	0.071	0.705446
894	"	"	0.705332	0.000035	9.31	281.03	0.096	0.704944
1949	"	"	0.705395	0.000014	0.78	140.45	0.016	0.705330
887	"	"	0.706176	0.000034	27.35	368.70	0.215	0.705306
916A	metadolerite	"	0.705519	0.000025	0.74	241.11	0.009	0.705483
1931	metabasalt	B	0.705425	0.000020	5.09	319.23	0.046	0.705238
1924	"	B	0.705705	0.000052	10.39	139.68	0.215	0.704832
1832	metagabbro	E	0.704381	0.000026	3.25	280.36	0.033	0.704245
2524A	amphibolite	"	0.704877	0.000021	1.89	405.88	0.013	0.704823
1755	metagabbro	F	0.704772	0.000026	2.15	167.39	0.037	0.704622
1759A	"	"	0.705196	0.000045	0.94	217.95	0.013	0.705145
642	granulite	G	0.704453	0.000041	10.50	158.03	0.192	0.703673



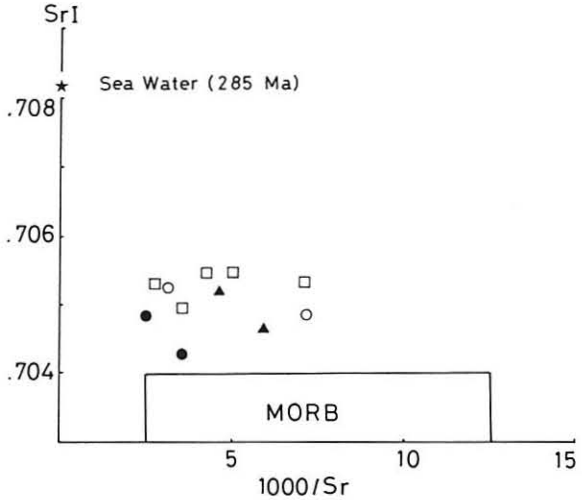
Text-fig. 9 Rb-Sr diagram
The fields enclosed by solid (MORB), broken (MSB) and dotted lines (HTH) are of MORB, marginal sea basalt (Koide et al., 1987) and Hawaiian tholeiite (Kurasawa, 1975; Koide et al., 1987), respectively. Symbols are same as in Text-fig. 3.



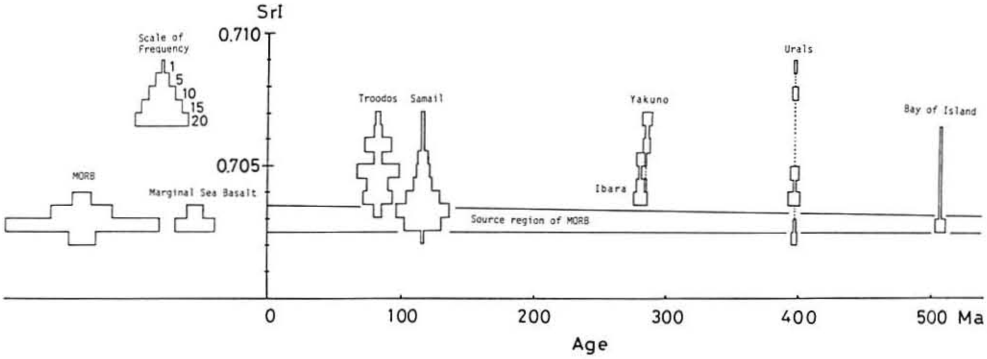
Text-fig. 10 Isochron diagram
The isochron obtained from 11 samples except a granulite (X) shows Sr initial ratio 0.705092 ± 157 and 285 Ma.

however, are scattered, which suggests that the Yakuno ophiolite was not simply affected by rock and seawater interaction.

When the SrIs of old ophiolites are compared with $^{87}Sr/^{86}Sr$ ratios of modern MORB, the isotopic evolution of the source region of MORB should be taken into consideration. The isotopic evolution of the source region of MORB in Text-fig. 12 is based on 1600 Ma and SrI 0.7023 which are determined by the mantle isochron (Brooks et al., 1976). The midline of each histogram represents the age of the respective ophiolite. As shown in this diagram, the Yakuno ophiolite has higher SrI ratios than the source region of MORB. On the basis of SrIs, Koide et al. (1987) classified ophiolites into two types of high and low SrIs. The Yakuno ophiolite belongs to the high SrI type. The high SrI can be interpreted either by secondary addition of radiogen-

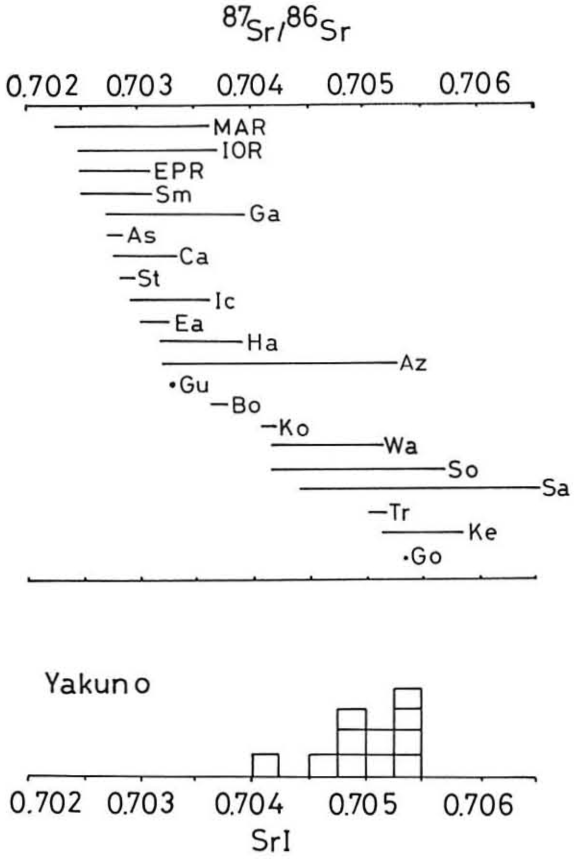


Text-fig. 11 SrI vs. 1000/Sr diagram
SrI of sea water at 285 Ma is shown by star (Burke et al., 1980). The field enclosed by solid line is of MORB (Koide et al., 1987). Symbols are same as in Text-fig. 3



Text-fig. 12 SrI histograms of ophiolites vs. their age
SrIs of ophiolites are calculated on the basis of their magmatic age (Koide et al., 1987). The source region of MORB is determined by the mantle isochorn (1600 Ma, SrI = 0.7023; Brooks et al., 1976) and the SrI range of the modern MORB and marginal sea basalts (0.7025 ~ 0.7035).

ic Sr during alteration and metamorphism, or by derivation from the source material having higher Sr isotope ratio. In the latter case, the originally high Sr isotope ratio may be derived from enriched mantle, such as the rocks from Kerguelen, Tristan da Cunha, Society, and Gough islands (Text-fig. 13; Zindler et al., 1984).



Text-fig. 13 Range of present $^{87}Sr/^{86}Sr$ ratios from seamounts, islands and ridges and SrI histogram of the Yakuno ophiolite
MAR: Mid-Atlantic Ridge, IOR: Indian Ocean Ridge, EPR: East Pacific Rise, Sm: East Pacific Rise Small Seamounts, Ga: Galapagos Islands, As: Ascension Island, Ca: Canary Islands, St: St. Helena, Ic: Iceland, Ea: Easter Island, Ha: Hawaiian Islands, Az: Azores, Gu: Guadalupe, Bo: Bouvet Island, Ko: Koolau, Wa: Walvis Ridge, So: Society Islands, Sa: Samoan Island, Tr: Tristan da Cunha, Ke: Kerguelen, Go: Gough Island (Zindler et al., 1984).

Discussion

The Yakuno ophiolite is considered to represent the fragments of oceanic crust as inferred from the rock facies and their succession (Text-fig. 1 and 2). However, the maximum metamorphic grade (granulite facies) indicates that the Yakuno ophiolite is much thicker than normal oceanic crust. No typical sheeted dyke complex has been found, but evolved rocks such as quartz diorite, granophyre and trondhjemite are associated. The metamorphic facies series including the prehnite-pumpellyite and the epidote amphibolite facies suggests a geothermal gradient lower than that of ocean floor metamorphism.

The Yakuno ophiolite belongs to the tholeiitic rock series and its chemistry shows a similarity to MORB, judging from various discrimination diagrams such as the Na_2O+K_2O—SiO_2 (Text-fig. 3), Ne-Pl-Ol-Hy-Q (Text-fig. 4) and oxides—FeO/MgO (Text-fig. 5), and oxides — MgO (Text-fig. 7) diagrams.

Ophiolites have been affected by various alteration processes, e.g. ocean floor metamorphism and weathering, regional metamorphism, and atmospheric weathering, through which their original compositions may have been changed. In ophiolitic metabasalts, it shows a general tendency that FeO* (total iron as FeO), K_2O and H_2O increase, while CaO and SiO_2 decrease, but TiO_2 and P_2O_5 remain unchanged with progress of alteration and metamorphism (Hattori et al., 1972; Wood et al., 1976; Coish, 1977; Uchida, 1979; Gardner, 1980; Coish et al., 1982). Therefore, the major element compositions of the Yakuno ophiolite may have been subjected to such secondary effects.

The chemistry of the relict minerals in ophiolites can be used for identification of their magmatic parentage (Kushiro, 1960; LeBas, 1962; Aoki, 1964; Maruyama, 1976). The Al-Si and Ti-Al diagrams for the relict clinopyroxene chemistry of the Yakuno metabasalt and metadolerite show a tholeiitic affinity (Text-fig. 8). This relict clinopyroxene data indicate that most of the Yakuno ophiolite has not been subjected to change in composition to an appreciable extent qualitatively different.

Although most of the Yakuno ophiolite belongs to the tholeiitic rock series, a few data of the ophiolite show an alkaline affinity. In the Ne-Pl-Ol-Hy-Q diagram (Text-fig. 4), the Yakuno ophiolite has higher normative plagioclase than MORB. The variation trend of the evolved rocks such as quartz diorite, granophyre and trondhjemite shows a tholeiitic trend and resembles that of oceanic island basalt (Text-fig. 7). The SrI of the Yakuno ophiolite (0.705092) is higher than those of typical MORB (0.7025 ~0.7035, Text-fig. 13). Therefore, the Yakuno ophiolite shows chemical nature similar to both MORB and oceanic island basalt, which suggests that it was generated by oceanic island magmatism at an ocean ridge.

The isochron age (285 Ma) of the Yakuno ophiolite, which was newly obtained here, is similar to those of other ophiolites from the Maizuru Tectonic Belt (Koide et al., 1987). The Ibara ophiolite which is located in the western part of the belt has been considered to be formed by the marginal sea volcanism on the basis of the rock and relict clinopyroxene chemistries and Sr isotope (Koide, 1986; Koide et al., 1987). The Kamigori and Ohara complexes may represent the products of arc magmatism as inferred from the plagioclase and clinopyroxene chemistries (Ishiwatari, 1986). The ophiolitic rocks in the Akenobe area show the MORB-like nature in the rock and relict clinopyroxene chemistries (Igi, 1976; Koide, 1984). As discussed above, the Yakuno ophiolite is cosidered to be the products of oceanic island volcanism on an oceanic ridge. The arrangement of these ophiolites suggests that the Maizuru Tectonic Belt may represent an original geologic construction consisting of oceanic island at ocean ridge, ocean ridge, island arc and marginal sea from east to west along the belt. Accordingly, if this suggestion is valid, the Maizuru Tectonic Belt preserves a geotectonic configuration across the plate boundary between ocean and island arc at the Late Paleozoic.

Conclusions

1. The Yakuno ophiolite which is exposed in the eastern part of the Maizuru Tectonic Belt, is composed of ultramafic, mafic, intermediate and felsic rocks. The ophiolite is much thicker than normal oceanic crust, and is not associated typical sheeted dyke complex but with evolved rocks.

2. The Yakuno ophiolite shows magmatic nature similar to both ocean ridge and oceanic island rocks in rock and mineral chemistries and Sr isotope ratio, which suggests that it was generated by oceanic island magmatism at an oceanic ridge.

3. The arrangement of various types of ophiolites of the Maizuru Tectonic Belt suggests that the belt may represent an original geologic construction consisting of oceanic island at an ocean ridge, ocean ridge, island arc and marginal sea from east to west at the Late Paleozoic.

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