ORIGIN OF THE IBARA METABASALTS FROM THE MAIZURU TECTONIC BELT, SOUTHWEST JAPAN

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Abstract The Ibara dismembered ophiolite of late Paleozoic age is exposed in the western part of the Maizuru Tectonic Belt and is made up mainly of metabasalts with minor amounts of slate, metagabbro and ultramafic rocks. The Ibara metabasalts are MORB-like tholeiite. Compared with MORB, however, the Ibara metabasalts are slightly rich in SiO_2 and normative plagioclase in bulk composition, and are poor in Ti content of clinopyroxene. On the basis of such chemical aspects, the Ibara metabasalts are similar to some of marginal sea basalts. The metabasalts of the Maizuru Tectonic Belt were probably derived from a MORB-like magma at a relatively deep marginal sea basin to which a muddy material was supplied.

Introduction

Greenstones are observed in four belts from the Inner Zone of the Southwest Japan; the Tamba Belt, the Maizuru and Middle Belt (called the Maizuru Tectonic Belt in this paper), the Sangun Metamorphic Belt and the Yamaguchi Belt. The greenstones in the Tamba Belt occur as olistolithes of the Jurassic olistostrome (ISHIGA, 1983). The greenstones in the Maizuru Tectonic Belt are the Early Permian(?) dismembered ophiolites and are metamorphosed up to the granulite facies of medium pressure type (ISHIWATARI, 1978, 1985a). The greenstones in the Sangun Metamorphic Belt are called the Sangun metamorphic rock proper (HASE & NISHIMURA, 1979) and are affected by the glaucophanitic metamorphism (HASHIMOTO, 1968; NISHIMURA 1971). The greenstones in the Yamaguchi Belt occur at the basements of the plateau limestones and their margins (HASE, 1964; NISHIMURA *et al.*, 1979). The greenstones of the Ibara area are in the Maizuru Tectonic Belt and are a dismembered ophiolite. The Ibara dis-

membered ophiolite is made up of metabasalts and metagabbro with small amounts of wehrlite and clinopyroxenite. The metabasalts are well exposed in this area and are weakly subjected to metamorphism.

Little have been studied on the petrochemistry of the metabasalts from the Maizuru Tectonic Belt. It is necessary to characterize the nature of magmatism of the belt so as to interpret the tectonic history of the Inner Zone of Southwest Japan in Late Paleozoic age. This paper describes the geology, petrography and petrochemistry of the metabasalts in the Ibara area with a discussion of the magmatic activity and the genesis of the metabasalts.

Geology

The Upper Paleozoic rocks in the Ibara area are called the Main Part of the Sabara Formation (HASE *et al.*, 1974, 1975). On the basis of lithofacies, HASE *et al.* (1974, 1975) divided the Main Part into Sm 1 (black slate), Sm 2 (metabasalts), Sm 3 (black slate and acidic volcanic conglomerate), and Sm 4 (metabasalts) in ascending order. The fossil age of the Main Part is Early to Middle Permian (HASE *et al.*, 1975). In the study area, Sm 2, Sm 3 and Sm 4 are observed which are called the Lower, Middle and Upper Members, re-

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Fig. 1. Location and geologic map of the Ibara area.

Abbreviations for the inset. Nz: Nagato Tectonic Zone, Sy: San-yo branch of the Sangun Belt, Si: San-in branch of the Sangun Belt, Ry: Ryoike Belt, N: North Zone of the Sangun Belt, K: Kamigori Belt, T: Tamba Belt, M: Maizuru Tectonic Belt (simplified from NISHIMURA *et al.*, 1977).

Fig. 2. Columnar section of the Sabara Formation.

spectively.

The members of this area generally trend east-west and dip homoclinally about 40° north (Fig. 1). In the southeastern margin of the area, the rocks are intruded by the Cretaceous granite and underlie the Cretaceous rhyolite. The rocks are overlain by the Pleistocene gravel beds in the northeast and are in fault contact with the slate of the Middle Member in the northwest. Many dykes of the Cretaceous andesite and granodiorite porphyry, 0.5 to 5 m in thickness with narrow contact aureoles 10 to 50 cm wide, are observed in this area.

These three members are in fault contact with each other. Fig. 2 shows a generalized column of geological succession in the Ibara area, though the stratigraphic relationships among the three members have not yet been settled.

Lower Member

The Lower Member is exposed in the south of this area, and attains 1,000 m thick. The lower part of this member is intruded by a granitic stock and is overlain by rhyolite lava flows, and the uppermost part is cut off by a fault. This member is made up dominantly of metabasalts with small amounts of hyaloclastite and black slate. Toward the lower horizon the rocks become hard and massive due to the increasing effect of contact metamorphism by the granite.

Middle Member

The Middle Member is in fault contact with both the Lower and Upper Members, and is made up dominantly of black and massive slate. This member is intercalated with a few beds of conglomerate and metabasalts. The conglomerate contains various types of subrounded to angular cobbles and pebbles such as granite, diorite, metagabbro, metabasalt, arkose sandstone, volcanic sandstone, and slate. These fragments are poorly sorted and the portion of a muddy matrix increases upward. The thickness of this member reaches about 800 m.

Upper Member

The Upper Member is composed mainly of slightly vesicular metabasalts with minor

amounts of hyaloclastite and black slate. Red shale and chert are rarely found.

The original structures of pillow lavas, dykes and hyaloclastite are well preserved. The pillow lavas which are the main constituent of the Upper Member are commonly close-packed (CARLISLE, 1963). These close-packed pillow lavas sometimes grade upward into hyaloclastite including isolated pillows. Dykes are not commonly found. The slate occurs less in the lower horizon than in the upper horizon. The red shale, a few meters thick, always overlies the metabasalts without structural gap. The chert also attains a few meters thick and is intercalated with the metabasalts. The total thickness of the Upper Member is about 2,000 m.

Yakuno Complex

The Yakuno Complex in the Ibara area consists mainly of metagabbro with subordinate amounts of serpentized ultramafic rocks and mylonitized plagiogranite (COLEMAN & PETERMAN, 1975). The Yakuno Complex is in fault contact with the Sabara Formation.

The metagabbro shows a fine- to coarse-grained gneissose texture, and is metamorphosed into amphibolite. The ultramafic rocks are composed mostly of wehrlite. Clinopyroxenite blocks, one to several meters in diameter, are sometimes found in the wehrlite. No igneous layering can be observed. The ultramafic rocks are mostly altered into serpentinite. The plagiogranite is scarcely found as mylonite in this area.

Petrography

Metabasalts

The metabasalts from the Upper Member are classified into porphyritic and non-porphyritic varieties. Based on the phenocryst abundance, the porphyritic one is further subdivided into sparsely (<2 vol.%) phyrlic and moderately (2—10%) phyrlic (MELSON *et al.*, 1979). About 70% of the metabasalts are non-porphyritic.

The non-porphyritic metabasalt of the Upper Member shows fine- to coarse-grained textures. A typical change in the textures is observed in a pillow lobe as follows; glassy,

Fig. 3. Textures of the sp-ol and pl-cpx type metabasalts.

Scale bars are 0.1 mm. sp: spinel, ol: olivine pseudomorph, pl: plagioclase, cpx: clinopyroxene.

variolitic, intersertal, intergranular, subophitic and ophitic from rim to core. The glassy part is commonly altered into fine-grained aggregates of unknown metamorphic minerals. The variolitic part is composed mainly of variolitic plagioclase, skeletal and dendritic clinopyroxenes, oxide minerals and altered glass. The intersertal and intergranular parts are made up mainly of plagioclase laths, subhedral and granular clinopyroxene, and oxide minerals and/or altered glass. The subophitic and ophitic parts consist of tabular plagioclase and anhedral clinopyroxene.

The porphyritic metabasalts of the Upper Member vary in the assemblage of phenocryst and its inclusion as follows; spinel+olivine, spinel+olivine+plagioclase+clinopyroxene, plagioclase, clinopyroxene, plagioclase+clinopyroxene, spinel+plagioclase+clinopyroxene, and olivine+plagioclase+clinopyroxene. They are essentially classified into the following three rock types; spinel-olivine (sp-ol), plagioclase-clinopyroxene (pl-cpx), and transitional types.

The sp-ol type metabasalt amounts to about 30% of the porphyritic rocks and is moderately olivine phyric. This type rarely contains plagioclase phenocrysts. The olivine phenocrysts include spinel crystals (Fig. 3). The igneous textures are preserved, though the rocks are highly altered. This type of metabasalt commonly has a glassy groundmass with dendritic clinopyroxene crystals.

The pl-cpx type metabasalt is usually sparse-

ly phyric and contains phenocrysts of plagioclase, clinopyroxene or both (Fig. 3). The plagioclase phenocrysts rarely include clinopyroxene crystals. The groundmass is similar to that of the non-porphyritic metabasalt.

The transitional type metabasalts have two phenocryst assemblages; spinel+plagioclase+clinopyroxene and olivine+plagioclase+clinopyroxene. The clinopyroxene phenocrysts are mostly euhedral but rarely anhedral and granular. The groundmass of this type is also similar to that of the non-porphyritic metabasalt.

Olivine in the metabasalts from the Upper Member is observed as a pseudomorph consisting chiefly of serpentine+spinel in holocrystalline part and of clinozoisite+serpentine in glassy part and near veins. Clinopyroxene in the metabasalts is mostly preserved, but partly recrystallized into actinolite, clinozoisite+chlorite, epidote+opaque minerals, and chlorite+spinel. Plagioclase is commonly altered into albite and partly into albite+calcite and albite+prehnite. Veins and amygdules observed in the metabasalts are composed mainly of prehnite, albite, chlorite, pumpellyite and quartz (Table 1).

The major part of the metabasalt of the Lower Member has been subjected to subsequent contact metamorphism by the Cretaceous granite. Therefore, their primary igneous textures are rarely preserved. As shown in Fig. 4, the H₂O contents of the metabasalt from the Lower Member are considerably low

Table 1. Mineral assemblages of metabasalt, metasedimentary rock, metagabbro, wehrlite and clinopyroxenite from the Ibara area.

	Primary					Secondary														
	Sp	Ol	Opx	Cpx	Pl	Ho	Act	Ab	Qz	Bt	Gar	Preh	Pump	Chl	Sph	Ep	Czo	Carb	Serp	
Upper Member																				
SO-1	R	Ps	-	Ps	Ps	-	-	-	-	-	-	-	V	M,V	M	-	M	-	M	
SO-2	R	Ps	-	Ps	Ps	-	-	M,V	-	-	-	V	-	-	M	M	M	V	M	
TR-1	R	Ps	-	Ps	Ps	-	V	M,V	-	-	-	M	V	M,V	M	-	M	V	M	
PC-6	-	-	-	R	Ps	-	-	M	-	-	-	M	M	M	-	-	-	M	-	
PC-10	-	-	-	R	Ps	-	-	M,V	-	-	-	M	V	V	-	-	-	V	-	
NP-12	-	-	-	R	Ps	-	-	M	V	-	-	V	-	M	M	-	-	V	-	
Lower Member																				
L-3	-	-	-	-	-	-	M,V	M,V	V	-	-	-	-	-	M	-	-	V	-	
L-6	-	-	-	R	-	-	M,V	M	-	-	-	V	-	M	M	-	-	-	-	
L-8	-	-	-	-	-	-	M,V	M,V	V	-	-	-	-	-	-	-	-	-	-	
metasediment	-	-	-	-	R	-	-	M	M	M	M	M	-	-	-	-	-	-	-	
Yakuno Complex																				
GB-1	-	Ps	-	R	Ps	M	-	M	-	-	-	M	M	M	M	M	-	M	M	
GB-2	-	Ps	-	R	Ps	M	M,V	M,V	-	-	-	M	M	M,V	M	M	-	-	M	
GB-3	-	Ps	-	R	Ps	M	-	M	-	-	-	M	M	M	M	-	-	-	M	
GB-4	-	Ps	-	R	Ps	M	-	M	-	-	-	-	-	M	M	-	M	M	-	
GB-5	-	Ps	-	R	Ps	M	-	M	V	-	-	M,V	-	M	M	-	-	-	M	
WH-1	R	Ps	Ps	R,M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	M	
WH-2	R	Ps	-	R,M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	M	
CP-1	R	Ps	Ps	R,M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	M	
CP-2	R,M	Ps	Ps	R,M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

Primary: igneous minerals, Secondary: altered or metamorphic minerals. Abbreviations. Sp: spinel, Ol: olivine, Opx: orthopyroxene, Cpx: clinopyroxene, Pl: plagioclase, Ho: hornblende, Act: actinolite, Ab: albite, Qz: quartz, Bt: biotite, Gar: garnet, Preh: prehnite, Pump: pumpellyite, Chl: chlorite, Sph: sphene, Ep: epidote, Czo: clinozoisite, Carb: carbonate minerals, Serp: serpentine, R: relic mineral at igneous stage, Ps: pseudomorph after primary mineral, M: metamorphic mineral, V: metamorphic mineral in veins, -: not observed.

(mostly <1.5 wt. %) compared with those from the Upper Member (average 3.1 wt. %), which is possibly ascribed to dehydration caused by the contact metamorphism. Furthermore, the H₂O contents of the rocks in the Lower Member decrease notably toward the lower horizon. Clinopyroxene from the Lower Member is recrystallized chiefly into actinolite, and plagioclase into albite+prehnite.

Metagabbro

The metagabbro from the Ibara area has been metamorphosed and shows a gneissose texture, but its primary igneous mineral assemblage of olivine, clinopyroxene and plagioclase is recognized.

Olivine is altered mainly into serpentine, with subordinate amounts of chlorite and/or sphene. Clinopyroxene is preserved, but is partly recrystallized into fine equigranular crystals of clinopyroxene and hornblende. Some crystals of clinopyroxene have exsolu-

tion lamellae of ilmenite or orthopyroxene of several tens of microns wide along cleavages and partings. Plagioclase is commonly altered into albite, prehnite, sphene and rare pumpellyite. The metamorphic hornblende is partly recrystallized into actinolite+epidote +sphene and chlorite.

Veins and veinlets have assemblages of chlorite+actinolite+albite, pumpellyite+albite+prehnite and prehnite+quartz, which are similar to those in the metabasalts.

Ultramafic rocks

The ultramafic rocks are wehrlitic and clinopyroxenitic cumulates, which are made up essentially of adcumulative crystals of clinopyroxene and olivine with accessory orthopyroxene and spinel.

Clinopyroxene is mostly recrystallized into aggregates of small granular clinopyroxene crystals, though large primary crystals of clinopyroxene are rarely preserved. The primary

clinopyroxene has exsolution lamellae of spinel (1 to 5 microns long) along cleavages and partings. Olivine is perfectly altered into serpentine. Orthopyroxene is recrystallized into bastitic serpentine and characteristically has clinopyroxene lamellae.

Rock chemistry

Major element analyses were carried out by an X-ray fluorescence analyzer (JEOL Model JSX-60S7). Table 2 lists the analytical data in this work. A new analysis of JB-1 is also shown in Table 2, which agrees with the recommended value (ANDO *et al.*, 1974).

Migration of elements

Ophiolitic metabasalts have been affected by various alteration processes, for example, ocean floor metamorphism and weathering, regional metamorphism and atmospheric weathering, through which their original chemistries may have been changed. Various attempts to determine the degree of chemical migration during alteration and metamorphism in the ophiolitic metabasalts have been conducted. Volatile contents (mainly H_2O) and altered minerals have been taken as indicators of migration degree, and comparison of chemistry between pillow rim and core has been done (HATTORI *et al.*, 1972; WOOD *et al.*, 1976; COISH, 1977; UCHIDA, 1979; GARDNER, 1980; COISH *et al.*, 1982). The results show 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 proceeding alteration and metamorphism.

Experimental studies using basaltic starting materials (BISCHOFF & DICKSON, 1975; HAJASH,

Fig. 4. H_2O contents of metabasalts and metagabbro, and their frequency.

Samples are arranged based on horizons. Average H_2O^+ content (solid triangle) of the metabasalts from the Upper Member is 3.5 wt.%, that from the Lower Member is 1.4 wt.%, and that from metagabbro is 3.3 wt.%. Cross: $H_2O \pm$ contents, solid circle: H_2O contents of the non-porphyritic metabasalt (NP), open circle: those of the pl-cpx type porphyritic metabasalt (PC), open circle with horizontal bar: those of the transitional type porphyritic metabasalt (TR), open circle with vertical bar: those of the spol type porphyritic metabasalt (SP), open triangle: those of the Lower Member metabasalt.

Table 2. Bulk rock compositions from the Ibara area and JB-1.

No.	SO-1	SO-2	SO-3	SO-4	SO-5	TR-1	TR-3	PC-1	PC-3	PC-4	PC-5	PC-6	PC-7	PC-8	PC-9	PC-10	NP-1	NP-2
SiO ₂	50.79	50.89	50.35	50.70	52.86	49.64	50.09	51.20	50.98	52.19	50.99	52.09	51.77	54.25	50.42	50.22	51.04	50.78
TiO ₂	0.73	0.81	0.72	0.72	0.75	1.10	1.30	1.30	1.58	2.21	1.45	1.56	1.61	2.02	1.40	2.79	1.27	1.49
Al ₂ O ₃	14.94	14.21	14.87	15.86	15.31	15.81	15.77	14.68	14.10	14.51	14.64	13.92	14.18	12.15	15.91	14.60	14.46	13.52
FeO*	10.18	10.91	9.58	10.31	9.91	9.26	11.51	10.89	10.81	12.10	11.92	11.76	11.28	11.45	11.04	13.48	10.06	11.85
MnO	0.25	0.16	0.13	0.27	0.07	0.16	0.20	0.21	0.20	0.24	0.24	0.09	0.19	0.24	0.16	0.17	0.18	0.28
MgO	8.58	6.87	5.70	5.34	3.68	10.70	7.32	9.13	7.31	7.27	7.12	7.12	7.00	6.92	5.75	4.02	8.94	8.81
CaO	11.86	12.22	14.17	13.08	13.96	9.42	7.77	9.09	12.04	7.93	9.61	8.61	10.27	9.19	11.66	8.37	10.32	10.26
Na ₂ O	1.92	3.59	3.77	3.43	3.11	2.29	2.49	2.59	2.65	2.61	2.68	3.05	2.74	3.75	3.23	3.82	3.12	2.80
K ₂ O	0.67	0.27	0.49	0.13	0.19	1.49	2.48	0.79	0.15	0.69	1.27	1.68	0.75	0.03	0.25	1.25	0.50	0.08
P ₂ O ₅	0.08	0.07	0.22	0.16	0.16	0.13	0.27	0.12	0.18	0.25	0.08	0.12	0.21	n.a.	0.18	0.16	0.11	0.13

No.	NP-3	NP-4	NP-6	NP-7	NP-8	NP-9	NP-10	NP-11	NP-12	NP-13	NP-14	NP-15	NP-16	NP-17	NP-18	L-1	L-2	L-3
SiO ₂	51.38	53.59	52.15	51.52	52.58	51.55	51.94	49.69	51.36	48.45	53.24	49.88	52.08	51.53	55.55	50.95	51.08	52.05
TiO ₂	1.36	1.31	1.68	1.48	1.74	1.46	1.70	2.28	2.05	2.22	2.04	2.22	1.42	1.88	1.67	1.46	1.80	1.09
Al ₂ O ₃	13.73	13.25	13.47	14.30	11.19	14.05	13.61	15.89	14.21	14.53	12.78	14.88	15.11	14.69	14.00	13.20	14.50	12.92
FeO*	11.48	10.80	12.28	10.53	12.39	10.43	11.79	10.38	13.17	14.08	12.99	11.98	11.36	12.27	11.26	11.69	11.89	11.35
MnO	0.23	0.23	0.26	0.18	0.22	0.19	0.21	0.16	0.26	0.18	0.26	0.21	0.17	0.16	0.13	0.22	0.15	0.27
MgO	8.20	8.19	8.00	7.90	7.66	7.65	7.60	7.17	7.13	6.92	6.73	6.61	6.55	5.53	4.96	8.74	7.96	7.91
CaO	11.97	9.44	8.22	10.14	11.02	11.20	9.43	9.56	8.92	10.40	8.50	10.04	8.00	8.78	8.84	11.01	10.43	11.36
Na ₂ O	1.35	2.81	3.58	3.65	3.17	3.34	3.47	3.65	2.53	3.01	3.11	2.26	4.86	4.89	3.06	2.20	1.76	2.73
K ₂ O	0.17	0.26	0.20	0.19	0.03	n.d.	0.11	0.93	0.14	n.d.	0.15	1.66	0.30	0.27	0.37	0.40	0.28	0.22
P ₂ O ₅	0.13	0.12	0.16	0.11	n.a.	0.13	0.14	0.29	0.23	0.21	0.20	0.26	0.15	n.a.	0.16	0.13	0.15	0.10

No.	L-4	L-5	L-6	L-7	L-8	GB-1	GB-2	GB-3	GB-4	GB-5	WH-1	WH-2	CP-1	CP-2	JB-1#	JB-1##
SiO ₂	51.27	51.93	49.55	50.64	49.51	48.89	48.21	46.23	50.55	51.68	46.41	48.45	50.51	50.74	53.47	53.39
TiO ₂	1.48	1.48	1.06	2.03	1.78	0.37	0.31	0.09	0.37	0.56	0.06	0.09	0.10	0.10	1.39	1.38
Al ₂ O ₃	13.30	14.29	16.51	13.89	14.83	18.26	16.54	20.02	16.44	16.21	1.89	2.78	3.71	3.63	14.93	14.83
FeO*	10.67	10.08	10.02	12.73	12.80	6.76	7.38	7.06	6.64	6.94	10.03	7.64	5.25	5.33	8.15	8.29
MnO	0.18	0.17	0.25	0.20	0.34	0.11	0.13	0.14	0.14	0.16	0.14	0.14	0.14	0.12	0.16	0.15
MgO	7.88	7.24	6.82	6.21	5.39	11.42	11.10	10.87	10.07	8.74	32.05	27.22	20.61	20.42	8.02	7.89
CaO	12.14	10.40	13.35	10.18	12.71	10.96	14.30	13.69	13.42	14.66	9.36	13.59	19.52	19.50	9.35	9.48
Na ₂ O	2.81	3.63	2.10	3.56	2.09	2.50	1.99	1.45	2.33	1.03	0.05	0.08	0.15	0.15	2.85	2.86
K ₂ O	0.14	0.64	0.26	0.39	0.39	0.71	0.01	0.44	0.01	n.d.	n.d.	n.d.	n.d.	n.d.	1.43	1.46
P ₂ O ₅	0.13	0.14	0.08	0.17	0.16	0.02	0.03	0.01	0.03	0.02	0.01	0.01	0.01	0.01	0.25	0.27

The compositions recalculated on water free basis. *: total iron as FeO, #: this work, ##: ANDO *et al.* (1974), n.d.: not detected, n.a.: not analysed. SO: sp-ol type metabasalt from the Upper Member, TR: transitional type metabasalts from the Upper Member, PC: pl-cpx type metabasalt from the Upper Member, NP: non-porphyrific metabasalts from the Upper Member, L: metabasalt from the Lower Member, GB: metagabbro, WH: werhlite, CP: clinopyroxenite.

1975; SEYFRIED & BISCHOFF, 1977, 1979, 1981; MOTTI & HOLLAND, 1978; POHL & LIOU, 1983), and studies on altered ocean floor basalts (CANN, 1969; MIYASHIRO *et al.*, 1969; HART, 1970; HEKINIAN, 1971, HART, 1973; THOMPSON, 1973; SHIDO *et al.*, 1974; HART *et al.*, 1974; RASCHKA & ECKHARDT, 1976; ANDREWS *et al.*, 1977; ROBINSON *et al.*, 1977; HUMPHRIS & THOMPSON, 1978a, 1978b; FLOYD & TARNEY, 1979; PUCHELT, 1983) resulted in a close agreement with the above tendency of chemical migration in the ophiolitic metabasalts. There is some disagreement, however, among the above results about the migration trends. Al_2O_3 , FeO and MnO decrease in the experimental studies but MnO increases in the studies of MORB's alteration and metamorphism.

The $\text{H}_2\text{O}+$ contents have been considered as a useful indicator of alteration degree (HATTORI *et al.*, 1972; HART *et al.*, 1974; PUCHELT, 1983). Fig. 4 shows a histogram of $\text{H}_2\text{O}+$ contents of the Ibara metabasalts, and Fig. 5 illustrates variation in contents of oxides versus $\text{H}_2\text{O}+$ for the metabasalts. The oxides are recalculated to 100% on an anhydrous basis. The metabasalt from the Lower Member characteristically has low $\text{H}_2\text{O}+$ contents due to the effects of contact metamorphism by the Cretaceous granite (Fig. 4).

K_2O contents of the Ibara metabasalts are concentrated in a field less than 0.6 wt.%, though some analyses disperse from this field. The dispersion may be attributed to alteration. It is well known that CaO tends to decrease with chemical migration in the case of ocean floor basalts and ophiolitic metabasalts and especially in experiments (SEYFRIED & BISCHOFF, 1977; POHL & LIOU, 1983; *etc.*) The CaO contents of the Ibara metabasalts are considered to be less than the original contents which possibly attained more than 9 wt.%. It is widely believed that TiO_2 and P_2O_5 are immobile during alteration and metamorphism. Actually, Fig. 5 shows a small dispersion in TiO_2 and P_2O_5 contents. Though P_2O_5 has been considered to add into rocks during alteration of basaltic glass or severe alteration (MIYASHIRO *et al.*, 1969;

Fig. 5. Oxides— $\text{H}_2\text{O}+$ diagrams for the Ibara metabasalts (water free).

Circle: metabasalts from the Upper Member (solid circle: non-porphyritic metabasalt, open circle: pl-cpx type porphyritic metabasalt, open circle with vertical bar: sp-ol type porphyritic metabasalt, open circle with horizontal bar: transitional type porphyritic metabasalts), triangle: metabasalt from the Lower Member.

MOORE, 1970), in the case of altered holocrystalline rocks P_2O_5 is relatively immobile.

No systematic changes in the other elements are observed with increasing $\text{H}_2\text{O}+$ contents (Fig. 5). In other words, the behavior of these elements during alteration and metamorphism is not clear. The following discussion is, therefore, developed on the basis of the assumption that the concentration fields

Fig. 6. Normative Ne-Pl-Ol-Hy-Q diagram.

Symbols are the same as in Fig. 5.
Data from MARSH *et al.* (1980) and compiled data by THOMPSON *et al.* (1972).

of these elements plotted in the discrimination diagrams should show original ones.

Rock chemistry of the Ibara metabasalts

Most analyses of the Ibara metabasalts plot in the olivine-tholeiite field of the Ne-Pl-Ol-Hy-Q diagram (YODER & TILLEY, 1962) (Fig. 6). Since the present $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios of ophiolitic metabasalts have become higher due to oxidation, their C.I.P.W. norms were recalculated using 0.15 $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio (BROOKS, 1975). Most of the recalculated analyses shift toward the Pl apex, and plot outside of the Mid-Atlantic Ridge basalt field, while they plot in the fields of the Shikoku and the Daito Basin basalts.

In the alkali-silica diagram (Fig. 7), most of the data (water free) plot in the field of non-alkaline rocks classified by MACDONALD & KATSURA (1964). Their concentration field is SiO_2 richer than the abyssal tholeiite (MIYASHIRO, 1975).

MIYASHIRO (1973) showed that the tholeiite and calc-alkali rock series can be classified by using SiO_2 -, TiO_2 - and $\text{FeO}^*/\text{FeO}^*/\text{MgO}$ diagrams (Fig. 8). As illustrated in the SiO_2 - FeO^*/MgO diagram, the Ibara metabasalts plot in the tholeiite field, but those (water free) have relatively higher SiO_2 contents than MORB. The concentration fields of the

Fig. 7. Alkali- SiO_2 diagram.

Crosses are contents including H_2O , and the other symbols are the same as in Fig. 5 (water free). Solid line: the boundary between the alkaline and non-alkaline rock series (MACDONALD & KATSURA, 1964), broken lines: the boundaries among alkali basalt, high-alumina basalt, and tholeiite (KUNO, 1966), and the rectangular field shown by solid line: the field of abyssal tholeiite (MIYASHIRO, 1973).

Ibara metabasalts in the TiO_2 - and $\text{FeO}^*/\text{FeO}^*/\text{MgO}$ diagrams are similar to those of MORB. The FeO^*/MgO ratios of the Ibara metabasalts are mostly less than 2.0 which corresponds to an average value of ophiolites (MIYASHIRO, 1975).

The fields of the Cenozoic basalts such as MORBs, ocean island basalts, island arc basalts, and plateau basalts, are shown in the AFM diagram (Fig. 9A). The Ibara metabasalts are characterized by a lower degree of fractionation than that of plateau basalts and plot in the field partly overlapping with basalts from island arcs. The tholeiites from island arcs, however, are commonly classified into quartz-tholeiite on the C.I.P.W. norm (IRVINE & BARAGAR, 1971) and are frequently

Fig. 8. SiO_2 -, TiO_2 - and FeO^* - FeO^*/MgO diagrams.

Crosses are compositions including H_2O , and the other symbols are the same as in Fig. 5 (water free). Solid line: boundary between calc-alkaline (CA) and tholeiite rock series (TH) (MIYASHIRO, 1975), broken lines: crystallization trends of abyssal tholeiite (1), liquid of Skaergaard (2), Miyake-jima (3), Tofua Island (4) and Kilauea in Hawaii Island (5) (MIYASHIRO, 1975), and trend of Kilauea in FeO^* - FeO^*/MgO diagram after ISHIWATARI (1978).

associated with more fractionated rocks. The Ibara metabasalts plot in the same fields as those from ocean ridges and ocean islands.

PEARCE *et al.* (1977) proposed a graphical discrimination of the Cenozoic subalkaline

basalt-andesite (51–56 wt.% SiO_2) using the MgO - FeO^* - Al_2O_3 diagram (Fig. 9B). The boundary between oceanic island tholeiites and oceanic island alkaline rocks is shown as a broken line in this diagram. Crystallization trends of MORBs shift from the ocean ridge and floor field to the ocean island field. The analyses of the Ibara metabasalts plot in both of the two fields. The Ibara metabasalts are similar to tholeiite from ocean regions.

PEARCE *et al.* (1975) proposed a discrimination of oceanic and non-oceanic basalts using the TiO_2 - K_2O - P_2O_5 diagram (Fig. 9C). The oceanic basalts plot in the TiO_2 rich triangle. Most of the analyzed data of the Ibara metabasalts plot in the field of oceanic basalts, but the rest plot in the K_2O rich side beyond the boundary showing a linear trend. This trend is interpreted by K_2O addition during alteration.

BASS *et al.* (1973) showed a discrimination among ocean ridge basalt, ocean island tholeiite and alkali basalt using the P_2O_5 - TiO_2 diagram (Fig. 10). Most of the Ibara metabasalts plot in the field of oceanic ridge basalts.

The TiO_2 contents of the sp-ol type metabasalt are lower than those of the other two type of metabasalts as shown in Figs. 8, 9C and 10. The TiO_2 contents of MORB increase with crystallization. The lowermost TiO_2 contents of MORB, which may be primitive, are 0.6 to 0.8 wt.% (BASALTIC VOLCANISM STUDY PROJECT, 1981) and are similar to those of the sp-ol type metabasalt from Ibara (0.7–0.8 wt.%). On the other hand, the other type metabasalts of the Upper Member have higher TiO_2 contents than the sp-ol type metabasalt as follows; pl-cpx type: 1.3–2.8 wt.%, transitional type: 1.1 and 2.1 wt.%, and non-porphyrific type: 1.3–2.3 wt.%. The metabasalt of the Lower Member contains 1.1–2.0 wt.% TiO_2 .

Mineral chemistry

Relict clinopyroxene

The Al-Si and Ti-Al diagrams of clinopyroxene proposed by KUSHIRO (1960) for discrimination of the parentage have been wide-

Fig. 9. AFM, FeO^* - MgO - Al_2O_3 and TiO_2 - P_2O_5 - K_2O diagrams.

The symbols are the same as in Fig. 5.

A: AFM diagram. The enclosed fields are MORB, tholeiite from Hawaii Islands, island arc tholeiite from Northeastern Japan and tholeiite from Deccan Plateau. Data from SUKHESWALA & POLDERVAART (1958); KAWANO & AOKI (1960); KAWANO *et al.* (1961); KATSUI *et al.* (1974); KAWABE *et al.* (1979).

B: FeO^* - MgO - Al_2O_3 diagram (after PEARCE *et al.*, 1977). Solid lines are boundaries of subalkaline volcanic rocks. C: continental, OI: ocean island, ORF: ocean ridge and floor, O: orogenic, SCI: spreading center island. Broken line is a boundary between tholeiitic (FeO^* rich side) and alkaline rock series (FeO^* poor side) from the intra-plate ocean island suite. C: TiO_2 - P_2O_5 - K_2O diagram (PEARCE *et al.*, 1975). Solid line is a boundary between non-oceanic (TiO_2 poor side) and oceanic basalts (TiO_2 rich side).

ly used (e.g., LEBAS, 1962; AOKI, 1964). MARUYAMA (1976) advocated the boundaries between tholeiitic and alkaline rock series. TAKASAWA & HIRANO (1977) also proposed the Al_2O_3 - FeO diagram to discriminate rock series. In MARUYAMA's diagrams, clinopyroxenes of the alkaline rock series plot on the low Si, high Al and high Ti sides compared with those of the tholeiitic rock series. Clinopyroxenes of abyssal tholeiites overlap between the alkalic and tholeiitic rock series. In TAKASAWA and HIRANO's diagram, Al_2O_3 contents of clinopyroxene from alkaline rock series increase with FeO, whereas Al_2O_3 contents of those from non-alkaline rock series decrease.

All of the plotted data satisfy their limitations (Table 3). As shown in MARUYAMA's

diagrams (Fig. 11A and B), clinopyroxene phenocrysts from the Ibara metabasalts plot in high Si (1.85–1.95), low Al (0.07–0.15) and low Ti (0.01–0.03) sides. As plotted in TAKASAWA and HIRANO's diagram (Fig. 11C), the clinopyroxene in groundmass shows a decreasing trend of Al_2O_3 (4 to 2 wt.%) with increasing FeO (7 to 10 wt.%). The clinopyroxene chemistries of the Ibara metabasalts show tholeiitic nature.

Relict spinel

Spinel appears as microphenocrysts in the transitional type of the Ibara metabasalts, while in the sp-ol type metabasalt it occurs either as minute crystals included in olivine phenocrysts or in the groundmass. Both spinels are found in the same thin section. No

Fig. 10. P_2O_5 - TiO_2 diagram.

The symbols are the same as in Fig. 5.
ORB: ocean ridge basalt, OIT: ocean island tholeiite, AB: alkaline basalt (after BASS *et al.*, 1973).

difference in the chemistries of both types is recognized (Table 3). As shown in Fig. 12, spinels from the Ibara metabasalts are characteristically low in Fe^{3+} contents.

Spinel chemistries from MORBs are characterized by low $Fe^{3+}/(Cr+Al+Fe^{3+})$ (less than 0.1) and $Cr/(Cr+Al)$ ratios from 0.2 to 0.6 (Fig. 12). Spinel from the Ibara metabasalts have $Fe^{3+}/(Cr+Al+Fe^{3+})$ ratios less than 0.1 and $Cr/(Cr+Al)$ ratios in a range 0.4–0.5, which are similar to those of MORBs.

Discussion

Origin of the Ibara metabasalts

The Ibara metabasalts belong to the tholeiitic rock series, judging from discrimination diagrams such as the Ne-Pl-Ol-Hy-Q (Fig. 6), alkali-silica (Fig. 7) and oxides- FeO^*/MgO (Fig. 8) diagrams. The relict clinopyroxene (Fig. 11) and spinel (Fig. 12) chemistries show the similar results.

A large volume of tholeiitic rocks in the

Table 3. Representative chemistry of the relict minerals.

Sample	SO-2		TR-1		PC-1		NP-1
Mineral	spinel	spinel	spinel	cpx	cpx	cpx	cpx
Remark	in Gm	in Ol	mPheno	Pheno	Pheno	in Gm	in Gm
SiO_2	0.11	0.11	0.33	52.09	50.68	52.39	51.89
TiO_2	0.48	0.50	0.77	0.35	0.57	0.58	0.42
Al_2O_3	24.67	24.95	21.25	3.07	3.83	3.20	2.11
$Fe_2O_3^*$	4.64	4.88	5.30	-	-	-	-
FeO^{**}	14.60	15.65	16.24	4.93	6.68	8.05	6.53
MnO	0.32	0.36	0.30	0.07	-	-	0.44
MgO	13.89	13.29	12.95	16.85	17.50	19.55	17.43
CaO	0.23	0.08	0.17	21.24	19.34	16.22	20.75
Na_2O	-	-	-	0.19	0.23	0.14	-
K_2O	-	-	0.01	-	-	0.01	-
Cr_2O_3	41.22	40.15	42.85	1.22	0.77	0.32	0.33
NiO	0.16	0.17	0.11	0.03	-	-	-
V_2O_5	-	-	0.31	-	-	-	-
Total	100.32	100.14	100.59	100.04	99.60	100.46	99.90
Oxygen	32	32	32	6	6	6	6
Si	0.026	0.026	0.082	1.905	1.868	1.903	1.915
Ti	0.088	0.092	0.143	0.010	0.016	0.016	0.012
Al	7.038	7.151	6.160	0.133	0.166	0.137	0.092
Fe^{3+}	0.845	0.893	0.981	-	-	-	-
Fe^{2+}	2.956	3.182	3.341	0.159	0.206	0.244	0.202
Mn	0.065	0.073	0.062	0.002	-	-	0.014
Mg	5.011	4.817	4.748	0.919	0.962	1.059	0.959
Ca	0.059	0.021	0.044	0.833	0.764	0.631	0.821
Na	-	-	-	0.014	0.017	0.010	-
K	-	-	0.003	-	-	0.000	-
Cr	7.889	7.719	8.333	0.035	0.022	0.009	0.010
Ni	0.024	0.025	0.017	0.001	-	-	-
V	-	-	0.050	-	-	-	-

Abbreviations. cpx: clinopyroxene, in Gm: crystal in a groundmass, in Ol: crystal included in olivine, Pheno: phenocryst, mPheno: microphenocryst, *, **: ferric and ferrous iron of spinel calculated from stoichiometry and total iron of clinopyroxene as FeO .

Fig. 11. Al-Si and Ti-Al diagrams (A, B) for clinopyroxene phenocrysts, and FeO-Al₂O₃ diagram (C) for clinopyroxene in a groundmass.

Fig. 12. Fe³⁺-Cr-Al diagram for spinel.

Spinel from MORB are plotted in the field enclosed by broken line (data taken from BRYAN, 1972; RIDLEY *et al.*, 1974; SIGURDSSON and SCHILLING, 1976).

Cenozoic tectonic regions occur in island arcs, plateau basalt regions in stable continents, ocean ridges, oceanic islands, seamounts, and marginal sea floors. The Ibara metabasalts are considerably different from plateau basalts in stable continents as illustrated in the AFM (Fig. 9A), FeO*-MgO-Al₂O₃ (Fig. 9B) and TiO₂-P₂O₅-K₂O (Fig. 9C) diagrams, from island arc tholeiites in the AFM and TiO₂-P₂O₅-K₂O diagrams, and from ocean island tholeiites also in the P₂O₅-TiO₂ diagram (Fig. 10). The Ibara metabasalts are MORB-like tholeiite similar to tholeiite occurring in mid-ocean ridges and marginal seas. This result

is supported by the petrological study by ISHIWATARI (1978, 1985b) that the metamorphosed igneous rocks in the Yakuno district may be fragments of an oceanic crust.

HART *et al.* (1972) and HAWKINS (1976) showed a similarity in chemical composition between MORBs and marginal sea basalts. The chemistries of the marginal sea basalts from different regions are more variable than those of MORBs. The tholeiites from the Lau Basin and the Mariana Trough are similar to MORBs in the K₂O-SiO₂ diagram (Fig. 13B). K₂O contents of the tholeiite from the East Scotia Sea increase with SiO₂ contents up to about 51 wt.% and decrease over 51 wt.% SiO₂.

The Ibara metabasalts contain about 51-52 wt.% SiO₂ on a water free basis. Their SiO₂ contents are 1-2 wt.% higher than those of MORB. SiO₂ is generally subtracted from ophiolitic metabasalts during alteration and metamorphism (HATTORI *et al.*, 1972; UCHIDA *et al.*, 1979; *etc.*). Accordingly, it is probably that the Ibara metabasalts originally had higher SiO₂ contents than those of MORBs. As shown in YODER and TILLEY's tetrahedron (Fig. 6), the Ibara metabasalts are richer in normative plagioclase than those of the Mid-Atlantic Ocean Ridge basalts, and are similar to the Shikoku and the Daito Basin basalts.

Fig. 13. K_2O - SiO_2 diagrams.

A: MORB (MUIR & TILLEY, 1964; MELSON *et al.*, 1968; KAY *et al.*, 1970; EWART & BRYAN, 1972; BENGE *et al.*, 1975; AYUSO *et al.*, 1976; HEKINIAN *et al.*, 1976; BRYAN & MOORE, 1977).

B: marginal sea basalt. Open circle: Lau basin (HAWKINS, 1976), solid circle: East Scotia sea (SAUNDERS & TARNEY, 1979; MUENOW *et al.*, 1980), open square: Mariana Trough (HART *et al.*, 1972; GARCIA *et al.*, 1979), open triangle: West Philippine Basin (MATTEY *et al.*, 1981).

C: Ibara. Crosses are compositions including water. The other symbols are the same as in Fig. 5 (water free).

The clinopyroxene chemistries of the Ibara metabasalts are similar to those of the tholeiitic rock series in MARUYAMA's diagram (Fig. 11), but their Ti contents are lower than those of MORBs. The chemistry of the metabasalts which are MORB-like tholeiite may indicate a variety of marginal sea basalts.

Generation environment of the metabasalts from the Maizuru Tectonic Belt

In the Yakuno area at the east of the Maizuru Tectonic Belt, the metabasalts which are the pillow lavas and hyaloclastite are intercalated with black slate beds (IGI *et al.*, 1961; ISHIWATARI, 1978, 1985b). In the Akenobe area at the center of the belt, the slate is intercalated among the metabasalts (IGI, 1976). In the Ibara area at the west of the belt, the metabasalts show the pillow structure and are accompanied with hy-

aloclastite. These geological phenomena suggest that the metabasalts of the Maizuru Tectonic Belt may be formed by the undersea volcanism in the environment supplied a muddy material. The Ibara metabasalts have only a low percentage of small vesicles, suggesting that the metabasalts have erupted in a relatively deep sea (MOORE, 1965; JONES, 1969).

The chemical features of MORB are olivine-hyperthine normative, low FeO^*/MgO ratios (average 1.40) and high TiO_2 contents (average 1.56 wt. %) in bulk, low Fe^{3+} in chromian spinel, and low Fe/Mg in clinopyroxene (SIGURDSSON & SCHILLING, 1976; BASALTIC VOLCANISM STUDY PROJECT, 1981). The metabasalts of the Maizuru Tectonic Belt show the MORB-like tholeiitic features as follows; Yakuno: olivine-hypersthene normative, low

FeO*/MgO ratios (average 1.50) and high TiO₂ contents (average 1.40 wt.%) in bulk, low Fe³⁺ in relict chromian spinel, and decreasing Al₂O₃ contents with FeO increasing in relict clinopyroxene (ISHIWATARI, 1985b); Akenobe : mainly olivine-hypersthene normative, low FeO*/MgO ratios (average 1.74) and high TiO₂ contents (average 1.48 wt.%) in bulk, and low Al and high Si in relict clinopyroxene (IGI, 1976). The Ibara metabasalts show also the MORB-like tholeiitic features and are furthermore similar to marginal sea basalts.

The Ibara dismembered ophiolite resembles the Yakuno ophiolite reported by ISHIWATARI (1978, 1985a) which shows a typical ophiolite sequence in the Maizuru Tectonic Belt. The metabasalts, metagabbro and ultramafic rocks of the Ibara dismembered ophiolite can be correlated to the upper and middle zones of the metavolcanics, the transition zone and the lower zone of the metacumulates, respectively, based on lithofacies and petrography (ISHIWATARI, 1985a). The Ibara dismembered ophiolite may originally have a similar succession to the Yakuno ophiolite. Furthermore, the Ibara dismembered ophiolite may be considered to have been generated in a similar geological setting from a similar magma to those of the Yakuno ophiolite. In contrast to typical ophiolites (COLEMAN, 1977), those in the Maizuru Tectonic Belt (the Ibara and Yakuno ophiolites) contain rare chert, limestone and shale, and no dyke swarms.

The above characteristics suggest that the metabasalts of the Maizuru Tectonic Belt may not be formed at the typical oceanic ridge estimated by the other typical ophiolites, but may be generated by a MORB-like magma in a relative deep marginal sea basin supplied a muddy material.

Conclusions

1. The Ibara dismembered ophiolite is made up mainly of metabasalts with minor amounts of metagabbro and ultramafic rocks. These rocks are in fault contact with each other.

2. The Ibara dismembered ophiolite con-

sists of similar rock assemblage to the Yakuno ophiolite which shows a ophiolite sequence. Compared with typical ophiolites, the Ibara dismembered ophiolite comprises rare pelagic sediments and no dyke swarm.

3. The Ibara metabasalts formed in a relatively deep sea as inferred from their scarce and small vesicles. The Ibara metabasalts are MORB-like tholeiite in bulk, relict clinopyroxene and relict spinel chemistries.

4. The chemistries of MORB are relatively homogeneous in comparison with those of marginal sea basalt, the latter of which slightly varies with marginal seas. The Ibara metabasalts have higher SiO₂ and normative plagioclase contents in bulk, low Ti in relict clinopyroxene than those of typical MORB. These differences may be interpreted by a chemical variation of the marginal sea basalts.

5. The metabasalts of the Maizuru Tectonic Belt (Yakuno, Akenobe and Ibara) may be formed by the undersea volcanism in the environment supplied a muddy material. They show the MORB-like tholeiitic features in bulk and relict mineral chemistries.

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- *: In Japanese with English abstract.
- **: In Japanese.

〈地名〉

Akenobe	明延	Maizuru	舞鶴	San-in	山陰
Chugoku	中国	Nagato	長門	San-yo	山陽
Daito	大東	Ryoke	領家	Shikoku	四国
Ibara	井原	Sabara	佐原	Tamba	丹波
Kamigori	上郡	Sangun	三郡	Yakuno	夜久野

(要旨)

KOIDE, Y., 1986: Origin of the Ibara metabasalts from the Maizuru Tectonic Belt, Southwest Japan. *Jour. Geol. Soc. Japan*, **92**, 329–348. (小出良幸, 1986: 西南日本, 舞鶴構造帯の井原変玄武岩類の起源. 地質雑, **92**, 329–348.)

後期古生代の井原ディスメンバード・オフィオライトは, 舞鶴構造帯の西部に産し, 変玄武岩類と少量の粘板岩, 変斑れい岩と超苦鉄質岩類よりなる. 井原変玄武岩類は, 中央海嶺玄武岩 (MORB) 類似のソレライトである. しかし, MORB と比較して, 井原変玄武岩類は, 全岩組成の SiO_2 とノルム斜長石にやや富み, 単斜輝石の Ti 含有量が乏しい. このような差異に注目すれば, 井原変玄武岩類はある種の縁海玄武岩類に類似する. また, 舞鶴構造帯の変玄武岩類は, 泥質物の供給されるやや深い縁海盆で, MORB 類似のマグマから由来したと考えられる.