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Provenance of Lower Cretaceous sediments in the Nariwa and Hokubo areas, Okayama Prefecture, deduced from detrital modes and geochemistry of sandstones

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Petrographic and geochemical study of sandstones from the Kenseki Formation have shown that the sandstones are compositionally immature. The immaturity is reflected geochemically by their low SiO_2 contents (52-66 wt%) and petrographically by low modal percents of quartz and K-feldspar, and high modal percents of plagioclase and volcanic lithic fragments. The Kenseki sandstones are, however, poor in Na_2O (up to 2.1 wt%).

Both petrography and geochemistry suggest a heterogeneous source lithologies of acidic and basic volcanics, sedimentary, and ultramafic rocks. Petrographic evidence is supplied by quartz and plagioclase of volcanic origin, acidic volcanic fragments, basic volcanic fragments, volcanic glass, serpentinite fragments and detrital spinel grains. Geochemical evidence is provided by high FeO* (total iron as FeO), MgO, TiO_2, CaO and K_2O contents.

Petrographic and geochemical study of the Kenseki sandstones indicate calc-alkaline oceanic island arc provenance. The sediments were locally derived, with Alpine-type ultramafic rocks exposed in the north and volcanic materials of the Akiyoshi Belt supplying the bulk of the detritus.

Keywords: Kenseki Formation, modal analyses, provenance

I. Introduction

The Lower Cretaceous Kenseki Formation is distributed sporadically in the western part of Okayama Prefecture and the eastern part of the neighboring Hiroshima Prefecture (Fig.1). It is composed of up to cobble-size conglomerates (rich in limestone, chert, and volcanic rock fragments), reddish and greenish gray sandstones, and brownish red shales. The Formation which reaches a maximum thickness of about 300m in the Nariwa area, can generally be divided into two parts: Lower and Upper Member. The Lower Member is dominated by conglomerate whilst the Upper Member by mudstone. The transition from the Lower to the Upper Member is, however, gradational. The paleo-morphology has been reconstructed in the Nariwa area by Suzuki et al. (in press). The basin is narrow in E-W section with an open V-shape and elongates in N-S direction. It rests with an inclined unconformity plane on the basements. Geometry of the basin is reconstructed as river valley. The valleys are one to several kilometers in width and greater than 300m in depth. Lithofacies and geometry of the Kenseki Formation suggest deposition in mountainous areas. Asiedu & Suzuki (1995) have discussed the sedimentary facies and depositional environment of the Formation. The environment of deposition was generally fluvial. The change from the Lower to Upper Member of the Formation probably corresponds to a gradual change in river morphology from a narrow to flat valley (Asiedu, 1995, Asiedu & Suzuki, 1995; Suzuki et al., in press). The occurrence of carbonate nodules in the Upper Member of the Formation,

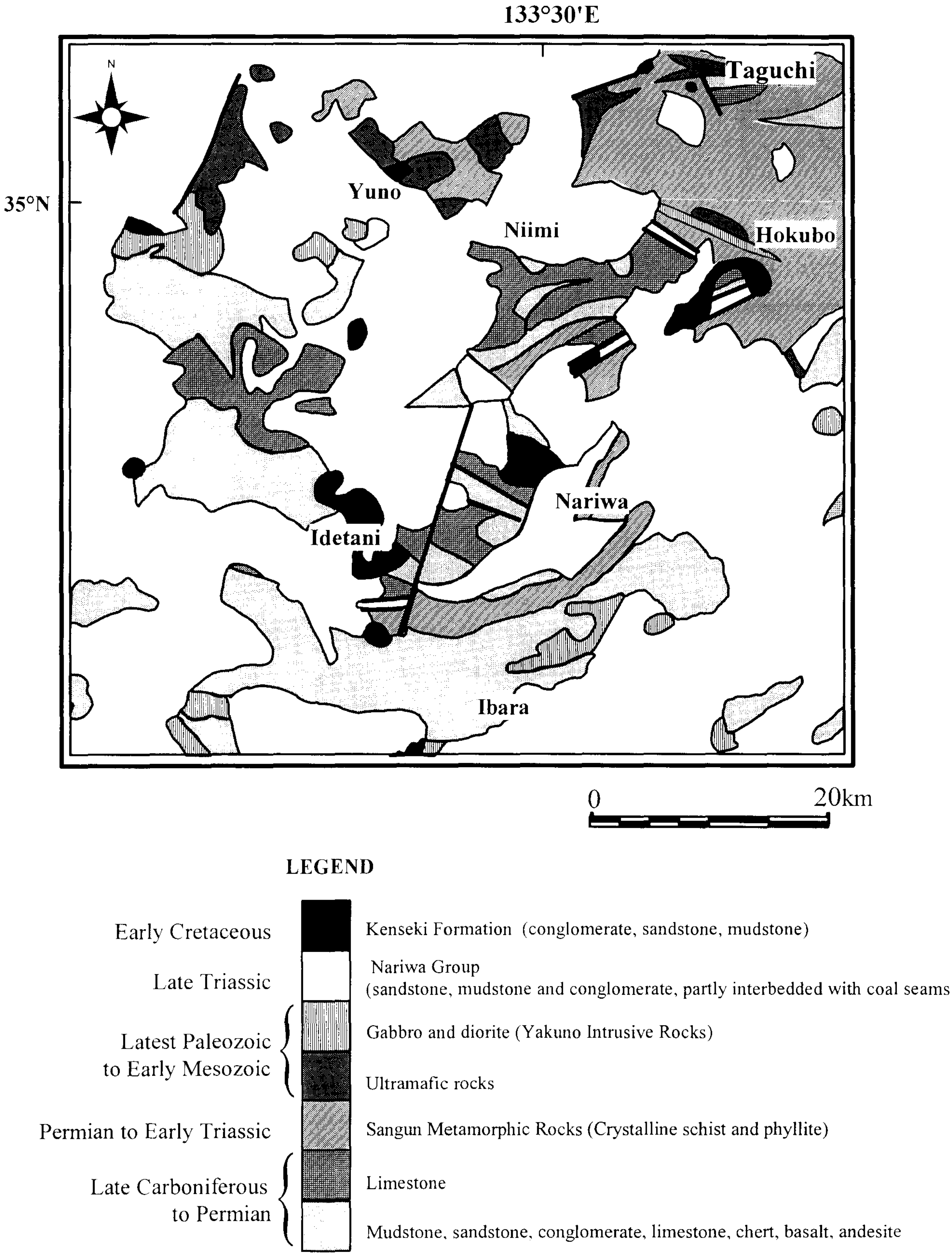

Fig. 1 Simplified geological map of the study area. Formations younger than Early Cretaceous are not shown.

coupled with the general paucity of intermediate flow sedimentary structures suggest that deposition took place in arid or semi-arid climatic conditions (Asiedu, 1995). Paleocurrent analysis suggests a southerly trending stream. The Formation is correlative to a part of the Wakino subgroup in northern Kyushu, and the Shindong Group in southeastern Korea by their non-marine fauna and non-volcanic lithology (Asiedu & Suzuki, 1995).

The sediments have undergone very minimal metamorphic reconstitution, permitting detailed petrographic and geochemical study. The purpose of this study is two-fold: first to report the petrological and geochemical characteristics of the sediments, and second to discuss their provenance.

II. Pre-Cretaceous geology of the study area

The Kenseki Formation is located in the Sangun and Akiyoshi Belts which belong to the Chugoku Zone. Pre-Cretaceous rocks in these belts include high pressure-low temperature metamorphic rocks (Sangun Metamorphic Rocks), non-metamorphosed upper Paleozoic rocks, ultramafic rocks, gabbroic and dioritic intrusives, and non-marine to shallow marine Triassic strata (Fig. 1).

The Sangun Belt is mainly composed of Sangun Metamorphic Rocks which are characterized by mineral assemblages of pumpellyite-actinolite and epidote-glaucophane. These metamorphic rocks were derived mainly from middle to upper Paleozoic strata which consist of mainly of clastic rocks and mafic volcanic rocks (Tanaka, 1977). The metamorphic ages of these rocks are assigned to about 300, 220, and 180 Ma (Shibata & Nishimura, 1989). The Akiyoshi Belt, which is a non-metamorphosed unit, is wedged into the Sangun Belt (Okada & Sakai, 1993). They are mainly Carboniferous and Permian sedimentary rocks and are composed of limestones, cherts, siliceous mudstones, acidic and basic tuffs, and basaltic lava. Sano and Kanmera (1988) reconstructed the Akiyoshi oceanic-rocks as a laterally continuous sedimentary cover on and around a seamount in an open-ocean realm. These Paleozoic rocks are unconformably covered by non-marine to shallow marine Triassic rocks.

Serpentinized Alpine-type ultramafic complexes are located in the northern part of the study area. These isolated ultramafic masses are emplaced individually in the regionally metamorphosed or unmetamorphosed Paleozoic sediments. They have been recognized as disrupted masses such as gravity-slide blocks from ophiolitic complexes uplifted by thrust (Arai, 1980).

III. Analytical techniques

We examined over 40 sandstone samples collected from the Nariwa and Hokubo areas under the microscope. We selected 17 of the least altered samples, (i.e., 10 from the Nariwa area and 7 from the Hokubo area) for modal analyses. Modal analyses were performed using both the Gazzi-Dickinson point-counting technique (see Ingersoll et al., 1984) and the traditional method. The Gazzi-Dickinson point counting method minimizes the grain size effect on composition and is thus a better method in provenance studies. The traditional method, however, has its advantages in that it provides more information about rock fragments (Kumon & Kiminami, 1994). In this paper, we have used the Gazzi-Dickinson method for provenance determination and the traditional method for the classification of the sandstones. The sandstones are very poor in coarse-grained (plutonic) lithic fragments; therefore, there is very little difference between the two point-counting results. About 500 detrital grains were point counted in each thin section. Petrographic parameters used in this study are listed in Table 1.

Whole-rock major element analyses were obtained on 16 of the sandstones using X-ray fluorescence techniques at Kusatsu-Shirane Volcano Observatory, Tokyo Institute of Technology. Compositions of selected plagioclase grains were checked by electron microprobe. Microprobe analysis on detrital chromian spinels and chlorite aggregates were also carried out to determine their origin. The microprobe analysis was carried out with a three-channel JOEL JXA-733 microprobe analyzer at the Department of Earth sciences, Okayama University. The Bence-Albee correction methods (Bence & Albee, 1968) were used

TABLE 1 Explanations of petrographic and other parameters used in this study (modified from Ahmed et al., 1994.)

Q = Qm + Qp	where:	Q = total quartzose grains
		Qp = polycrystalline quartzose grains including chert
		Qm = monocrystalline quartzose grains
F = P + K	where:	F = total feldspar grains
		P = plagioclase grains
		K = potassium feldspar grains
L = Lm + Lv + Ls	where:	L = total unstable alphanitic lithic grains excluding chert
		Lm = metamorphic lithic grains
		Lv = volcanic lithic grains including serpentinite
		Ls = sedimentary lithic grains excluding chert
Lt = L + Qp	where:	Lt = total alphanitic lithic grains
R = L + chert	where:	R = total rock fragments

to convert the raw x-ray intensity data to weight percent oxide. All Fe was first calculated as FeO for the analysis and recalculated to weight percent FeO and Fe_2O_3 following the method of Bjerg et al. (1992). Three samples were selected for X-ray powder diffraction analysis (XRD) to determine the composition of the matrix.

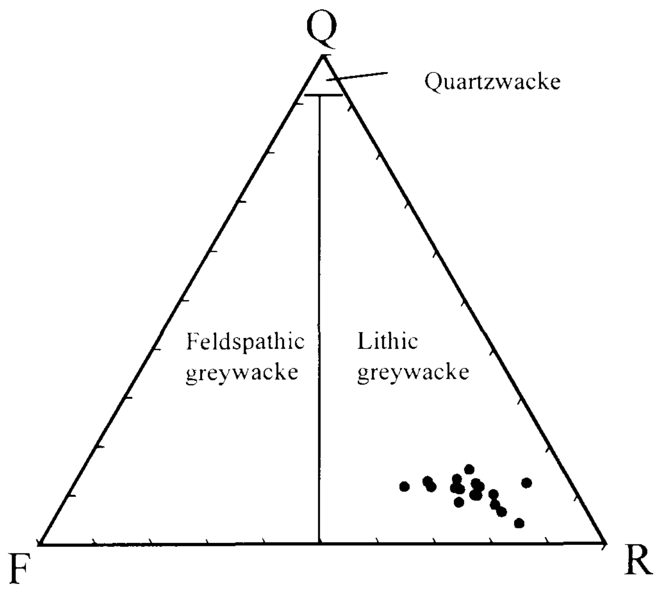

Fig.2 Petrographic classification of the sandstones (after Folk, 1974)

IV. Sandstone petrography

The sandstones generally contain more than 15% fine-grained matrix and are therefore greywackes according to Folk (1974). They plot in the lithic greywacke field of Folk (1974) (Fig. 2). XRD analyses on three samples showed quartz, albite, chlorite (chamosite) and calcite as the major constituent minerals. Representative point-counted data of the Kenseki sandstones are shown in Table 2, and are as follows:

Quartz

These constitute between 3 to 12% of the sandstones and are mostly sub-angular in shape. Monocrystalline quartz grains are relatively more abundant than polycrystalline quartz grains (Qm/Q=0.67). We infer that most monocrystalline quartz grains are of volcanic origin as these grains exhibit non-undulose extinction and are free of inclusions. Plutonic varieties, that exhibit undulose extinction, fluid inclusion trails and heavy mineral inclusions, are also present though generally rare. Polycrystalline quartz grains are mostly composed of three or more crystals with straight contact. No overgrowths were observed.

Feldspar

Plagioclase is by far the most abundant feldspar variety while K-feldspar is generally rare (P/F ranges

TABLE 2 Representative point-counted framework grains

SAMPLE NUMBER	931227(5a)	941006(1)	941006(7a)	950420 (1)	860812(4)	931214(1)	931214(4)	931227(5b)	941006(2)	941006(7b)
Monocrystalline quartz	5.3	6.3	6.9	5.5	5.0	8.6	2.3	4.6	4.7	7.9
Polycrystalline quartz	2.5	3.3	2.0	5.5	3.5	1.4	1.4	1.7	2.8	4.1
K-feldspar	-	2.9	3.0	-	0.2	0.9	-	0.4	2.4	3.0
Plagioclase	12.9	14.3	21.3	13.8	19.0	5.1	11.1	12.8	17.2	15.3
Acidic volcanic rk fgm	12.5	17.5	18.9	10.5	14.1	36.1	21.9	20.6	12.0	22.1
Basic/inter. volcanic rk fgm	8.8	12.2	1.7	8.6	5.4	3.2	6.9	4.4	4.3	2.7
Gabbroic rk fgm	1.4	0.8	0.7	1.2	0.4	0.2	0.7	1.3	1.2	1.4
Serpentinite fgm	8.8	8.4	4.0	10.2	9.1	1.0	9.1	15.4	14.6	6.0
Metamorphic rk fgm	0.7	0.2	2.0	3.4	0.2	-	0.7	1.7	1.2	1.1
Cataclastic rk fgm	0.2	-	3.3	3.4	4.6	0.2	6.0	-	2.6	2.7
Sandstone	0.4	-	1.3	0.3	-	1.4	-	-	1.6	1.1
Mudstone	3.0	3.0	2.3	3.1	-	4.3	2.2	2.7	2.4	1.4
Limestone	4.8	2.4	2.3	2.5	2.1	3.2	4.0	4.0	2.6	1.6
Chert	2.5	0.4	1.7	-	0.4	1.0	1.3	2.1	0.8	1.6
Calcite (single grains)	3.0	0.6	0.7	3.4	3.5	4.4	2.7	4.2	2.6	2.5
mica and chlorites (single grains)	1.4	0.4	-	-	0.2	1.0	0.5	1.9	-	-
Epidote	-	3.5	0.3	-	1.4	-	0.5	1.5	0.8	-
Spinel	0.4	0.2	1.0	0.3	-	-	0.2	-	0.8	0.5
Opaque minerals	2.7	3.5	1.0	1.2	1.5	0.5	2.2	2.1	2.6	1.6
Other heavy minerals	-	0.6	-	0.3	-	-	-		0.4	0.3
Other minerals (unidentified)	0.1	1.1	0.7	-	-	-	-	0.1	0.5	0.8
Cement	7.4	-	-	-	0.8	-	4.3	-	0.6	2.2
Matrix	21.2	19.4	24.9	26.8	28.6	27.5	21.9	18.5	21.3	19.9
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	99.9	100.0	100.0	99.8

from 0.8 to 1). Both twinned and untwined plagioclase varieties. Most grains have been at least partly replaced by secondary minerals including mica, chlorite and calcite, but relict twinning is still recognizable. Microprobe analyses on least altered plagioclase grains generally showed a compositional range of albite-andesine, with most being albite. Albitization of potash feldspar and calcic plagioclase by diagenesis and source area weathering can contribute to the high albite content (Dabard, 1990). However, we observed a bimodal distribution of plagioclase compositions from a single thin section: one group with lower CaO contents varying between 0.1 and 1.45% and the other group with higher CaO contents ranging from 9 to 10.5%, suggesting that the albitic composition is most probably primary (Dutta & Wheat, 1993). Representative plagioclase analyses are shown in Table 3.

Volcanic lithics.

Lithic volcanic clasts are the predominant component in all the analyzed sandstones (18 to 30%). Two broad categories were identified: (i) acidic volcanics, which is the more abundant, and (ii) basic volcanic clasts. The acidic volcanic clasts are characterized by quartzolithic chert-like grains with relict plagioclase. Vitric varieties also occur and have groundmass consisting mainly of altered glass. Relict shards and flow structures were observed in some samples. We interpret the acidic volcanic lithics as rhyolites with subordinate rhyolitic tuffs. Basic volcanic rock fragments are mainly basalt with subordinate basaltic tuff. They are mostly microlithic in texture with laths of plagioclase in an altered alphanitic groundmass. Some have crystalline components including altered mafic minerals in a glassy groundmass. Some basaltic grains have variolitic texture.

Ophiolitic lithics

They constitute up to 15% of the sandstones and include Mg-rich chlorites aggregates, serpentinites, gabbroic, and some other altered mafic-rock fragments. Serpentinite fragments consist almost completely of serpentine though some few grains have opaque minerals and chromian spinel inclusions. The gabbroic fragments are fine-grained and are composed of plagioclase and hornblende.

Sedimentary lithics

These include limestone, sandstone, mudstone, chert, and carbonate fragments. Limestone fragments often contain *fusulinid* and other Paleozoic foraminifera. Lithology and fauna are similar to that of the Paleozoic limestone distributed in the study area. Some chert fragments contain radiolarian fossils. Detrital carbonate fragments constitute up to 3% of the sandstones. Microprobe analysis indicates that they are calcite. These carbonates are also most probably derived from the Paleozoic limestone basement. Chert is either white or red. They are generally fine grained and contain rare radiolarian remains. They are sometime difficult to distinguish from rhyolite fragments. Chert was point-counted as polycrystalline quartz instead of a sedimentary fragment under the Gazzi-Dickinson point-counting method.

Cataclastic rock fragments

These contribute up to 6% of the sandstones. They consist of cataclastic granitic rocks and consolidated fault gauges and fault breccias.

Metamorphic lithics

They are generally poorly represented, up to 3.4% of the sandstones and comprise siliceous, pelitic and basic schist.

Dense Minerals

Detrital chromian spinel is the most abundant heavy mineral observed under the microscope, followed by rutile, epidote, ilmenite, zircon, and magnetite. Rutile, however, seems to be concentrated in finer-grained samples.

Pyllosilicates

White mica is the most dominant phyllosilicate mineral and occurs mainly as short plates. Many of the white mica are detrital. Few are of the micas show post-depositional deformation. Chlorite is also common, but biotite is generally rare.

Matrix

These constitute between 15 to 30% of the sandstones and include fine-grained quartz(grain size <0.03mm), clay minerals, iron oxide minerals and highly altered unstable grains (secondary matrix).

TABLE 3 Representative microprobe analyses of plagioclase grains

	1	2	3	4	5	6
SiO_2	68.27	64.2	57.04	65.23	64.78	66.58
Al_2O_3	21.37	22.86	24.31	21.91	21.41	21.55
CaO	0.72	0.12	9.51	0.7	0.41	1.31
Na_2O	9.48	11.13	9.78	9.88	11.58	9.24
K_2O	0.61	0.46	0.72	0.57	0.11	1.55
Total	100.45	98.77	101.36	98.29	98.29	100.23
Structural formula						
Si	11.83	11.412	10.302	11.604	11.572	11.668
Al	4.364	4.789	5.174	4.593	4.507	4.451
Ca	0.134	0.023	1.84	0.133	0.078	0.246
Na	3.185	3.836	3.424	3.407	4.01	3.139
K	0.135	0.104	0.166	0.129	0.025	0.346
Molecular Ratio						
Ab	92.2	96.8	63.1	92.9	97.5	84.1
An	3.9	0.6	33.9	3.6	1.9	6.6
Or	3.9	2.6	3.1	3.5	0.6	9.3

TABLE 4 Representative major element chemical compositions of the sandstones

Sample Number	1 941006(3)	2 941006(8)	3 960613(8)	4 951207(7T)	5 951207(10)	6 960613(1)
SiO_2	59.62	55.19	54.55	62.91	52.04	57.49
TiO_2	0.64	0.85	1.04	0.80	0.69	0.95
Al_2O_3	12.13	12.98	12.32	13.88	11.69	13.09
FeO*	4.94	7.15	7.28	4.48	6.32	9.30
MnO	0.10	0.11	0.09	0.07	0.14	0.09
MgO	4.41	3.38	7.26	2.30	3.64	5.48
CaO	7.47	8.33	6.27	5.36	12.14	3.90
Na_2O	1.75	1.29	1.02	1.40	0.58	2.11
K_2O	2.92	1.13	0.64	1.99	1.32	1.27
P_2O_5	0.09	0.10	0.08	0.08	0.06	0.06
Total	94.07	90.51	90.55	93.27	88.62	93.74
K_2O/Na_2O	1.67	0.88	0.63	1.42	2.28	0.60
Al_2O_3/SiO_2	0.20	0.24	0.23	0.22	0.22	0.23
$Al_2O_3/(CaO+Na_2O)$	1.32	1.35	1.69	2.05	0.92	2.18
FeO*+MgO	9.35	10.53	14.54	6.78	9.96	14.78

Pseudo-matrix described by Dickinson (1970) as representing deformation and compression of lithic fragments also occurs, but are classified whenever possible into their respective lithic categories.

V. Sandstone geochemistry

Geochemical studies on sandstones and mudstones have been used to define sediments petrographically (e.g., Blatt et al., 1980; Crook, 1974), to determine the tectonic setting of source area (e.g., Bhatia, 1983, 1985; Roser & Korsch, 1986) and to identify particular components of the sedimentary budget, for example ophiolitic input (e.g., Hiscott, 1978; Wrafter & Graham, 1989). It is in this light that we undertook a major-element geochemical study on the sandstones.

XRF analyses indicate that the sandstones are characterized by moderate to low SiO_2 concentrations (52 to 67 wt%) and high FeO* (total iron as FeO), MgO, CaO, and TiO_2 contents (Table 4). The Na_2O contents are low and erratic. Its composition is similar to a typical lithic arenite (see Pettijohn et al., 1972, p. 60) though substantially lower in SiO_2 and higher in Al_2O_3, MgO, TiO_2 and CaO probably due to the presence of mafic-rich detritus. In the chemical classification of Blatt et al. (1980), the sandstones plot in the greywacke and lithic sandstone fields. One sample, however, plot in the arkose field (Fig. 3a). Crook (1974) subdivided sandstones on the basis of SiO_2 content and the relative K_2O/Na_2O ratio into three classes: quartz-rich (average 89% SiO_2, $K_2O/Na_2O > 1$), quartz-intermediate (average 68-74% SiO_2, $K_2O/Na_2O < 1$) and quartz-poor ($SiO_2 < 68\%$, $K_2O.Na_2O < 1$). Considering the K_2O/Na_2O ratios, nine of the samples may be classified as quartz-rich and seven as quartz-intermediate (Fig. 3b). The SiO_2 contents of all the samples are, however, even less than the average of 68 wt% for quartz-intermediate proposed by Crook (1974). The reason for the higher K_2O/Na_2O ratios is the relative Na_2O depletion in the sandstones. This depletion could be due to a Na_2O-depleted source region rather than weathering processes. Evidence is supported by high CaO contents and high unstable grains in the sandstones (rock fragments), suggesting a rather weak degree of leaching during weathering of source rocks (Dabard, 1990). Also, Nesbitt & Young (1982) has established a Chemical Index of Alteration (CIA) as a general guide to the degree of weathering using molecular proportions:

$$CIA = 100 * Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$$

Highest values of CIA (76-100) indicate intense chemical weathering in the source areas or exposure and weathering immediately after deposition (Nesbitt & Young, 1982). The Kenseki sandstones show generally low to moderate CIA values (39-79, mean=57) close to those of fresh igneous rocks (50 or

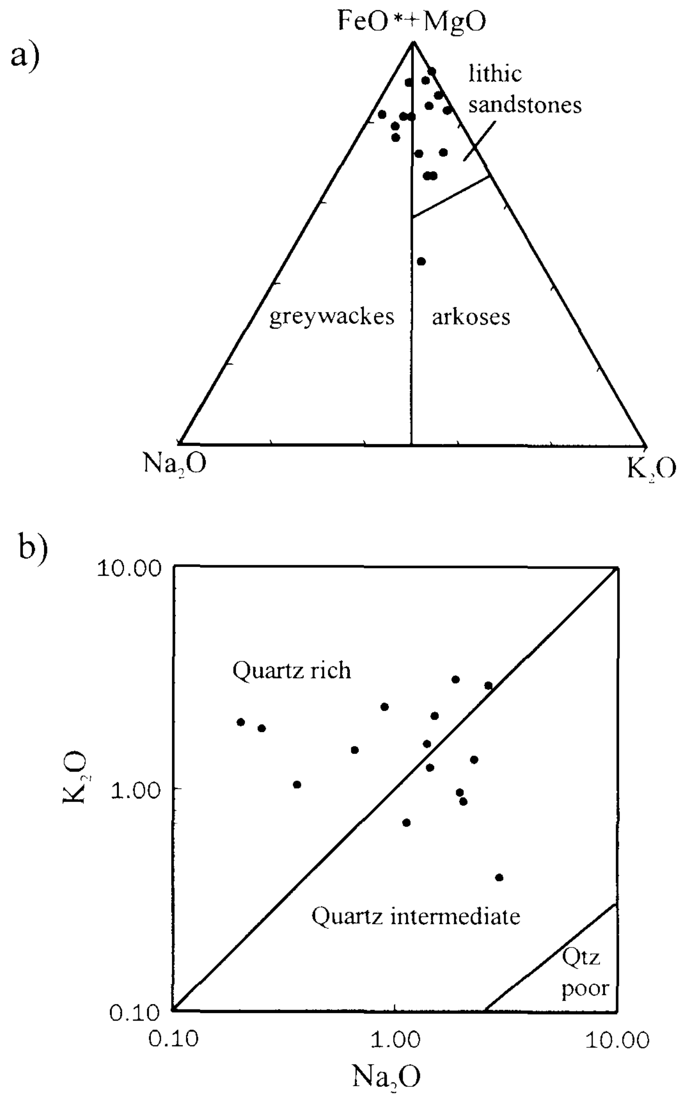

Fig. 3 Geochemical classification of the sandstones. (FeO^*+MgO)-Na_2O diagram after Blatt et al.(1972), Na_2O-K_2O diagram after Crook (1974).

below). This further confirms that source area weathering is unlikely to be the cause of general Na_2O depletion.

VI. Source areas and tectonic settings

1. Petrographic discrimination

A sediment's composition is strongly controlled by the composition of its source rocks. The source rock composition is in turn controlled to a great degree by tectonic setting. It is therefore possible to classify sand and sandstones on the basis of tectonic environment of their source terrain. Dickinson and Suczek (1979) and Dickinson et al. (1983) have shown that the mean composition of sandstone suites derived from different kinds of plate tectonic terranes tend to lie within discrete and separate fields on QFL, and QmFLt diagrams (see Table 1 for definition of parameters). Almost all data plot in a tightly constrained area within the magmatic arc field on both the QFL and QmFLt diagrams (Fig. 4). The data specifically plot in the undissected to intermediate arc fields, suggesting volcanic arc provenance.

The proportions of framework grains suggest derivation from a geologically heterogeneous source area. Input from several distinct lithologies can be identified. Volcanic source rocks with mainly acidic to subordinate basic composition are revealed by abundance of rhyolitic and volcanic glass fragments, by the presence of sodic feldspars and quartz of volcanic origin. The presence of chromian spinels, serpentinite fragments, and Mg-rich chlorite aggregates suggests contribution of ultramafic rocks (as discussed below). The erosion of sedimentary sequences is suggested by the presence of sedimentary lithic fragments. Limestone fragments together with radiolarian cherts probably represent erosional detritus of oceanic crust, an inference supported by geochemistry (see below). Minor amounts of strained quartz with inclusions, polycrystalline quartz, white mica, K-feldspar and metamorphic fragments suggest derivation from a metamorphic and plutonic source.

A synthesis of all the above informations suggests that an uplifting source area may have supplied dominantly immature first-cycle sediments into the basin. Exposed volcanic rocks may have supplied the bulk of the detritus, and ultramafic and sedimentary rocks supplied the rest. Minor granitic plutons and metamorphic rocks may have supplied the rest of the detritus. The composition of lithic clasts is similar to the heterogeneous pre-Cretaceous geology of the study area, suggesting local provenance for the sandstones. Rhyolitic and basaltic rocks are common in the non-metamorphic Paleozoic successions of the Akiyoshi

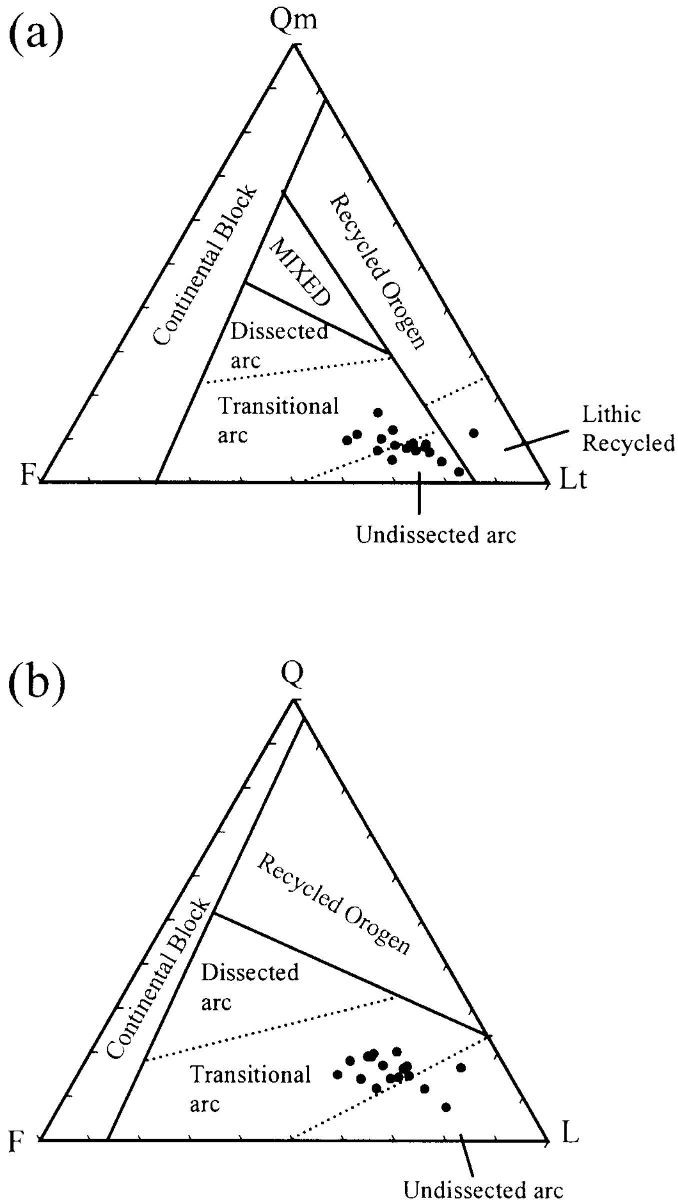

Fig. 4 Qm-F-Lt and Q-F-L provenance discriminating diagrams for the sandstones (after Dickinson et al., 1983)

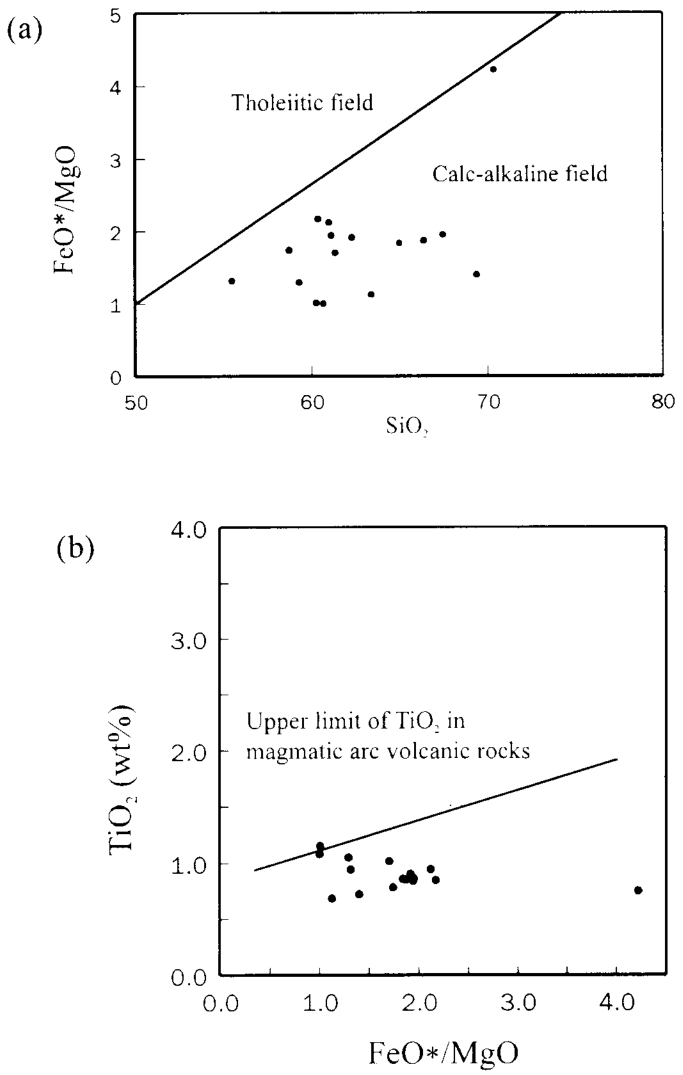

Fig. 5 Plots of (a) FeO*/MgO versus SiO_2 (after Garcia, 1978), and TiO_2 versus FeO*/MgO (after Miyashiro, 1977), for the sandstones.

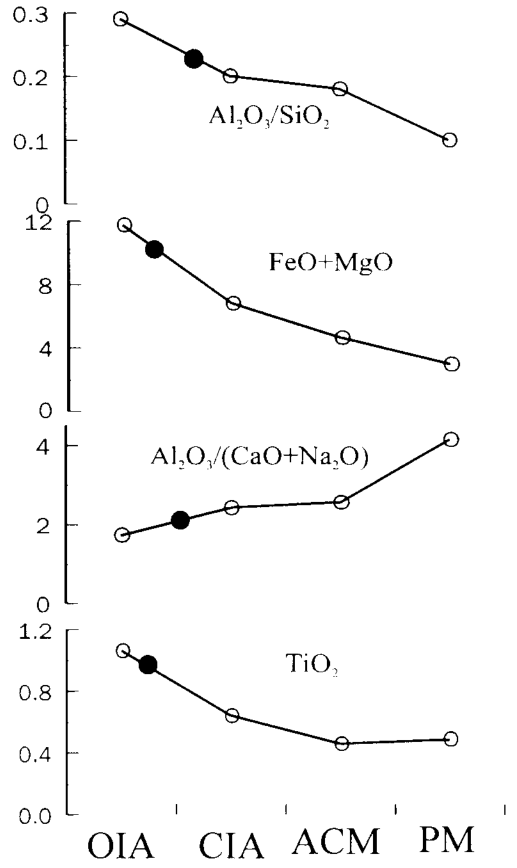

Fig. 6 Discrimination of tectonic setting of sandstones; closed circles, average Kenseki sandstones; open circles, average of sandstone from published data; OIA, oceanic island arc; CIA, continental island arc; ACM; active continental margin; PM, passive margin (after Bhatia, 1983)

Belt, and is probably the source of the volcanic lithic clasts. The sources of the serpentinite fragments are probably ultramafic complexes distributed in the study area, an inference supported by geochemistry (see below). Gabbros are found in association with these serpentinite complexes. The limestone and carbonate fragments were probably derived from the Paleozoic basement and the cataclastic rock fragments from the faulted rocks that comprise the shear zone in the Taguchi area which is located north of the Hokubo area. The presence of schist and cataclastic lithic clasts in the sandstones suggests that deformation, metamorphism and fault activities had already been completed before the Formation was deposited (Suzuki et al., in press).

2. Geochemical discrimination

The relatively high concentrations of FeO*, MgO, TiO_2 and CaO, and low concentrations of SiO_2 suggest derivation from a predominantly mafic source. However, the high K_2O concentrations suggest that the sandstones could have been derived from areas of dominantly acidic to intermediate composition. The paucity of K-feldspars (checked by microscopic study) and illite (checked by XRD) suggest that potassium is mainly concentrated in volcanic fragments of acidic composition. The FeO*, MgO and TiO_2 content are also typical of calc-alkaline magmatic arcs (Fig 5).

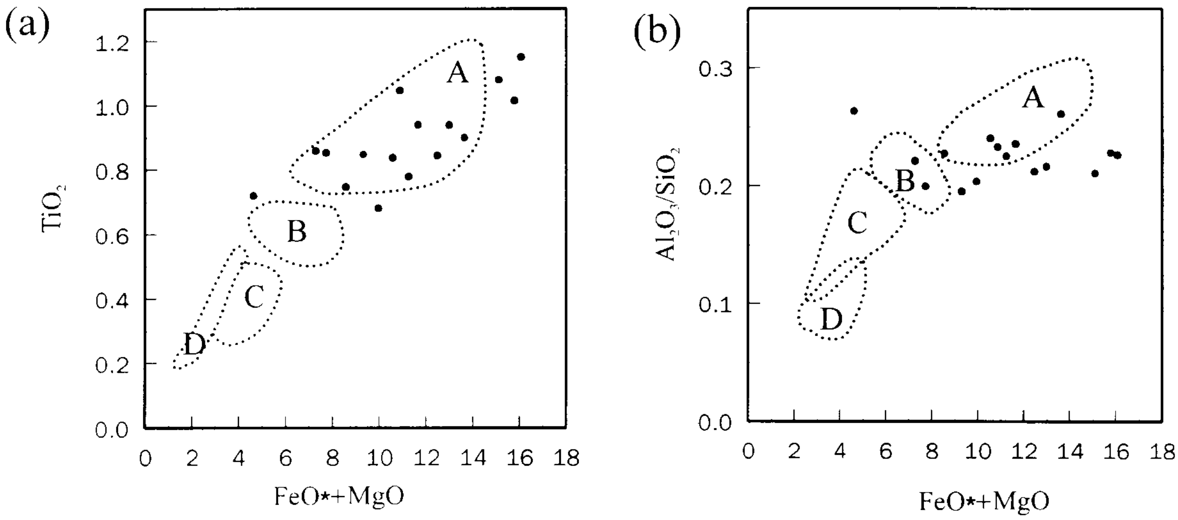

Fig.7 Bivariate plots for the discrimination of tectonic setting of the sandstones (after Bhatia, 1983). (**a**) TiO_2 versus FeO*+MgO and (**b**) Al_2O_3 versus FeO*+MgO. A, oceanic island arc; B, continental island arc; C, active continental margin; D, passive margin (after Bhatia, 1983).

These discrimination plots were, however, developed to assist the discrimination of volcanic rocks but has been successfully applied in provenance studies (Skilbeck & Cawood, 1994; Aitchison & Landis, 1990). It should be realized, however, that whole-rock analyses of sedimentary rocks are an average of all materials within the source terrane and therefore can only approximate the composition of specific igneous rock types within the provenance; the more homogeneous the source the closer the correlation.

The provenance type of a sedimentary rock is dependent on its tectonic setting. The provenance of a sandstone can therefore be deciphered by comparing it with those of sediments deposited in known tectonic settings (Bhatia, 1983; Roser & Korsch, 1986). Bhatia (1983) has shown that sandstones, by their major-element geochemistry, can be distinguished into four types of tectonic settings: (i) passive margin (PM), (ii) active continental margin (ACM), (iii) continental island arc (CIA), and (iv) oceanic island arc (OIA). The discriminant parameters are TiO_2 wt%, (FeO* + MgO) wt%, $Al_2O_3/(CaO+Na_2O)$, K_2O/Na_2O, and Al_2O_3/SiO_2 ratios. A comparison of average of the analyzed sandstones with those of published data from the above settings shows that the Kenseki sandstones have compositions in-between the oceanic and continental island arcs (Fig. 6). The K_2O/Na_2O ratio

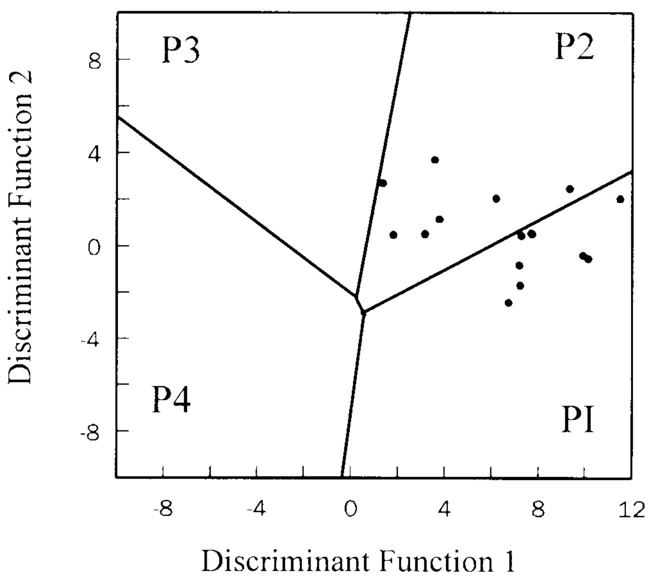

Fig. 8 Plots of first- and second- order discriminant scorescalculated using unstandardized discriminant function coefficient of Roser & Korsch (1988).

has not been used here because of the general Na_2O depletion in the Kenseki sandstones. Bhatia (1983) further showed that when the (FeO* + MgO) wt% is plotted against the other parameters mentioned above, the tectonic settings of source areas can be deciphered. Again we have avoided using plots that are dependent upon Na_2O contents. In the bivariate plots (Fig. 7), the majority of points fall within and around the oceanic island arc field (OIC) although few plots within the continental island arc field (CIA).

Roser and Korsch (1988) have classified sandstones into four provenance groups using major-element discrimination functions. The four provenance groups are mafic (P_1: first-cycle basaltic and minor andesitic detritus), intermediate (P_2: dominantly andesitic with subordinate rhyolitic and dacitic detritus), felsic (P_3: acid plutonic and volcanic detritus), and recycled (P_4: mature polycyclic quartzose detritus). Using this discrimination diagram, the Kenseki sandstones plot in the mafic and intermediate field (Fig. 8). This distribution at first glance may seem to contradict the petrographic and geochemical observations which suggest mainly acidic and mafic source lithologies. It may be expected that the data should plot mainly in the P_1 and P_3 fields (i.e., mafic and felsic, respectively) since the sandstones are rich in rhyolite and mafic/ultramafic fragments. The data plotting in the P_2 and P_1 fields suggest a thorough intra-sample provenance mixing, thus giving it a rather spurious intermediate volcanic rock composition. Such compositional trends were also observed in thin-section where the proportion of the various lithic fragments does not differ much. Anyway not all volcanic fragments are fresh enough for them to be point-counted to their correct categories so it is possible that the sandstones are also rich in intermediate volcanic fragments.

Ultramafic input

The oxide concentrations related to mafic assemblages (i.e., FeO*, MgO, and TiO_2) are distinctly high. Also, abundant detrital spinel and Mg-rich chlorite, both confirmed by microprobe analyses, were identified in thin-section. The chemical compositions of the spinels which are discussed in details elsewhere (Asiedu et al., in press) suggest derivation from the ultramafic parts of an ophiolite suite. Serpentinized dunite-harzburgite masses exposed north of the study area, particularly the Ohsa-yama and Ashidachi complexes, are the most likely sources for the detrital chromian spinels (Fig. 9). The chemistry of the chrlorite (MgO, 21.8-30%; Cr up to 2030 ppm; Ni up to 2150 ppm) also suggest a source from ultramafic rocks (Wrafter & Graham, 1989).

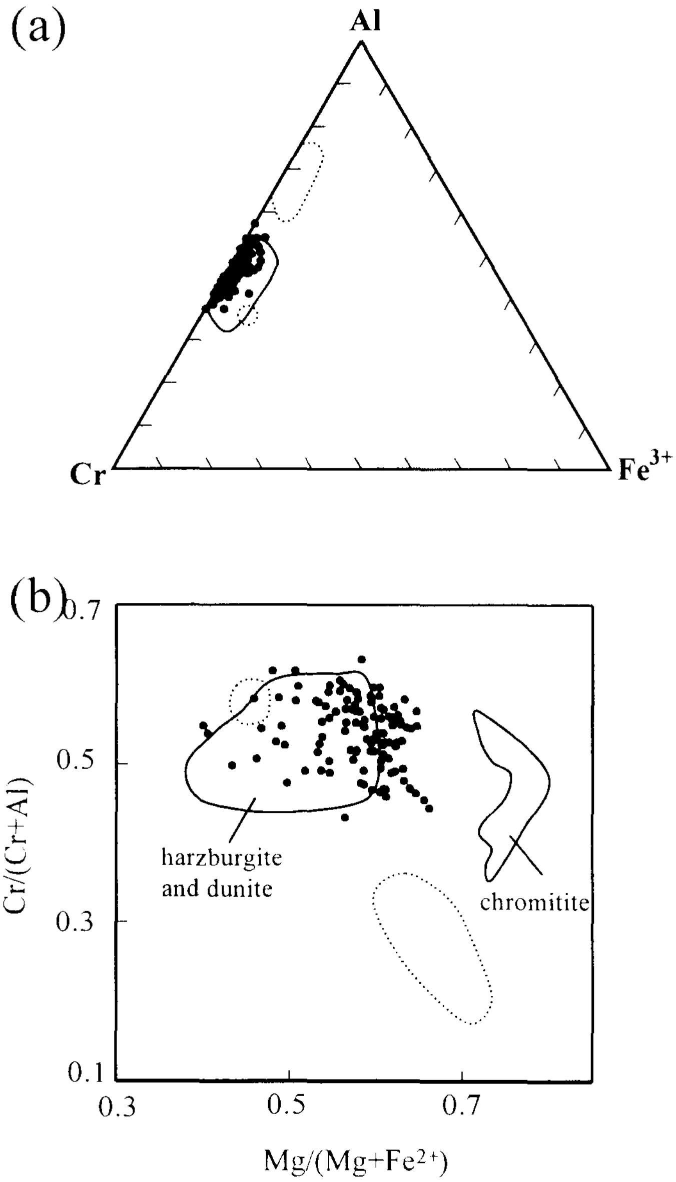

Fig. 9 Cr-Al-Fe^{3+} ternary plots and Mg/(Mg+Fe^{2+}) versus Cr/(Cr+Al) of the analysed spinels compared with spinels from the massive group (area enclosed by solid line) and layered group (area enclosed by dotted line) of ultramafic rocks from the study area (from Asiedu et al., in press).

VII. Early Cretaceous tectonism and sedimentation in Inner Zone of Southwest Japan

There were substantial strike-slip movements of tectonic zones in Southwest Japan during the Jurassic to early Cretaceous time (Taira & Tashiro, 1987; Okada & Sakai, 1993). These tectonic zones include the Nagato tectonic zone, Kurosegawa tectonic zone, and the Median Tectonic Line (Taira & Tashiro, 1987; Okada & Sakai, 1993). These strike-slip movements were responsible for reorganization of accretionary prism, uplift of metamorphic terranes and emplacement of exotic blocks together with serpentinites (Taira et al, 1983).

Formation of early Cretaceous sedimentary basins in Southwest Japan were closely related to strike-slip movements of these tectonic zones (Okada & Sakai, 1993; Hisada et al., 1995). The Inner Zone of Southwest Japan is characterized by half-graben basins covering the Hida, Sangun and Ryoke belts. These half-graben basins include the Kanmon Basin in the Sangun belt, Isumi Basin in the Ryoke Belt, and the Tetori Basin in the Hida belt. On the other hand, the Outer Zone of Southwest Japan is characterized by ridge basins related to strike-slip movement of the Kurosegawa Tectonic Zone.

The sedimentary basin of the Kenseki Formation is located in the Inner Southwest Japan and has been recognized as probably a peripheral one of the Kanmon tectonic basin (Hisada et al., 1995). However, unlike the Kanmon basin and other Lower Cretaceous basins, the Kenseki basin is not characterized by half-graben structure; at least not in the Nariwa area where the paleo-morphology of the basin has been reconstructed (see Suzuki et al, in press). Also, unlike the Kanmon basin that developed in a subsiding area, the Kenseki basin developed in an area of relative upheaval (Suzuki et al., in press). Paleocurrent analysis on the Kenseki Formation suggests that the elevated part of micro-continental block may have tilted to the south.

The strike-slip movements along tectonic zones which were prominent in early cretaceous time might have resulted in upheavals of rocks in the Akiyoshi and the Sangun terranes. The micro-continental block housing these rocks may have tilted to the south sending detritus of mainly ultramafic and volcanic composition from these terranes down-south. These detritus might have deposited on mainly Paleozoic limestone basement forming the Kenseki Formation. The basement rocks and to a minor extent the Sangun metamorphic rocks might have supplied the rest of the detritus.

VIII. Conclusions

(1) Petrographic and geochemical study of the Kenseki sandstones indicate that the source rocks were formed in a calc-alkaline oceanic island arc setting.

(2) Sandstone compositions suggest a very heterogeneous source terrain. The sediments were locally derived, with Alpine-type ultramafic rocks exposed in the north and volcanic materials of the Akiyoshi belt supplying the bulk of the detritus.

(3) The Kenseki basin was formed as a result of strike-slip movements which were prominent in early Cretaceous time.

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