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Provenance of Early Cretaceous Hayama Formation, Okayama Prefecture, Inner Zone of Southwest Japan: constraints from modal mineralogy and mineral chemistry of derived detrital grains

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Petrographic and phase chemistry studies of detrital grains were carried out on sandstones from the Lower Cretaceous Hayama Formation, Inner Zone of Southwest Japan, to determine their provenance and the tectonic setting during the early Cretaceous. The results of the modal mineralogy suggest that the Hayama Formation has magmatic arc provenance and that deposition of the sediments took place in the back-arc areas with detritus mostly derived from the magmatic arc and rifted continental margins. The chemical compositions of chromian spinel, chlorite and sphene indicate that significant proportions of the detrital grains were derived from mafic and/or ultramafic sources. The source areas are the mafic and ophiolitic rocks in the Sangun-Renge and Akiyoshi terranes and the felsic volcanic rocks probably from either the Akiyoshi terrane or a source not presently exposed in southwest Japan. However, minor amounts of the detritus were derived from the basement rocks; i.e., carbonates and siliciclastic rocks of the Akiyoshi terrane and the metamorphosed mafic rocks of the Chizu terrane.

Keywords: modal analysis; sandstone; mineral chemistry; provenance; Hayama Formation.

I. Introduction

It is now well established that the composition of sedimentary rocks retains a record of geologic history (e.g., Dickinson and Suczek, 1979). The compositions of sedimentary rocks are commonly used as constrains on potential source areas (e.g., McLennan et al., 1995), to reconstruct tectonic settings (e.g., Dickinson et al., 1983), to understand crustal evolution (e.g., Taylor and McLennan, 1986; Condie, 1993) and to reveal paleoweathering and possible paleoclimatic conditions (e.g., Condie et al., 2000). These investigations are carried out using a combination of sandstone petrography and various geochemical and isotopic techniques.

This paper reports mineralogical data for the sandstones of the Lower Cretaceous Hayama Formation (Suzuki et al., 2001) that is distributed sporadically in Okayama and Hiroshima Prefecture, the Inner Zone of Southwest Japan (Fig. 1a). We discuss the provenance and tectonic setting of these sandstones, and attempt to reconstruct the paleogeography of the study area during the early Cretaceous. In this study we have dealt with two provenance variables, i.e., modal analysis of framework grains and phase chemistry of detrital mineral species; Asiedu et al. (2000a) have already dealt with the bulk-rock geochemical aspect of the provenance.

II. Geological overview

The Hayama Formation (about 400m thick) is composed mostly of limestone breccia, conglomerate, sandstone, and red shale, with minor thin alternating beds of sandstone and mudstone. The formation can be stratigraphically divided into the Upper and Lower members (Asiedu and Suzuki, 1995). The Lower Member (about 300m thick) is dominated by conglomerate and the Upper Member (about 100m thick) by mudstone. The Upper Member includes some

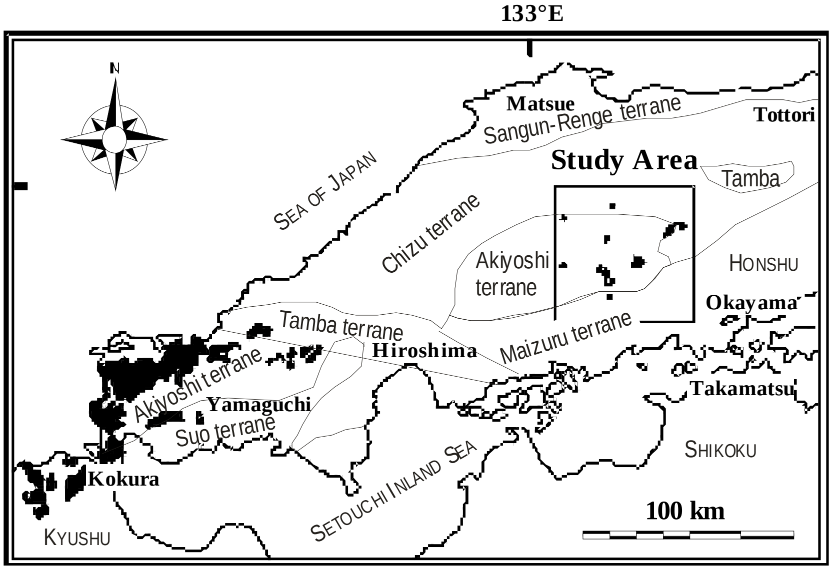

Fig. 1a. Map of inner side of Southwest Japan showing the location of the study area (Pre-Cretaceous terranes after Nishimura, 1990).

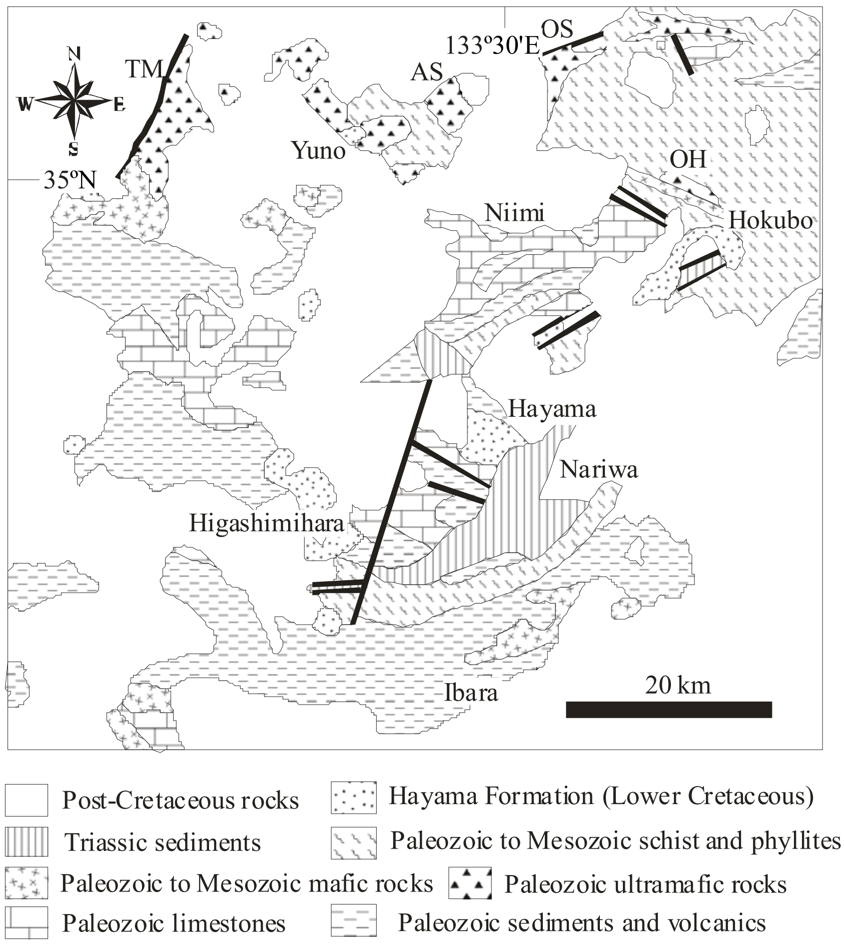

Fig. 2. Ternary diagram showing the compositions of the detrital feldspar grains from the sandstones of the Hayama Formation.

interbeds of felsic tuff. Fission-track dating on samples of the felsic tuff yielded an Albian age (Suzuki et al., 2001). The Formation correlates with part of Wakino Subgroup and Sasayama Group of southwest Japan, and the Kyeongsang Subgroup of southeastern Korea, on the basis of non-marine fauna and non-volcanic lithology. In the Hayama area, the formation is characterized by fining-upward successions with conglomerate at the base and mudstone at the top. Sedimentary facies analysis indicates a fluvial depositional environment and that the detritus was mostly derived from the north (Asiedu and Suzuki, 1995). Asiedu (1998) reconstructed the geometry of the sedimentary basin as a narrow valley.

The basement rocks of the Hayama Formation consist mainly of Paleozoic rocks with minor amounts of Triassic and Jurassic sedimentary rocks (Fig. 1b). They all belong to the Chizu and Akiyoshi terranes. The Paleozoic rocks are composed of limestone, sandstone, mudstone, chert, schist, and felsic and mafic tuffs. Pre-Cretaceous igneous rocks, which include ultramafic, gabbroic, doleritic and granitic rocks, intrude the Paleozoic rocks. The Triassic and Jurassic strata are non-marine to shallow marine in origin and are composed of sandstone and mudstone.

III. Laboratory methods

About 30 sandstone samples spanning the entire stratigraphic section were collected from the Hokubo, Hayama, and Higashimihara areas for a provenance study (Fig. 1). It was not difficult to sample along the entire stratigraphic section because the formation has undergone very little post-depositional tectonic deformation and bedding is near parallel, making statigraphic height proportional to contour levels. Fresh rock exposures are very abundant and readily accessible for sampling.

Seventeen medium-grained sandstone samples were selected for thin- and polished-section study. For each sample, two specimens comprising one thin-section and one polished-section, were prepared for modal analyses of framework grains and mineral chemistry of detrital grains, respectively. Modal analysis on the selected thin-sections was carried out using the Gazzi-Dickinson point-counting technique (Ingersoll et al., 1984). This involves counting grains greater than than 0.0625 mm as individual phases even where they form part of a lithic fragment. The purpose of this is to eliminate apparent variations in the composition of samples resulting only from differences in grain size. Between 400 and 600 points were counted per thin section.

The polished-sections were studied for mineral chemistry by microprobe technique. The phase chemistry of grains of selected minerals (i.e., chromian spinel, epidote, sphene, chlorite and feldspar) was examined with a three-channel JOEL JXA-733 microprobe analyzer at the Department of Earth Sciences, Okayama University. The operating conditions were as follows: acceleration voltage, 15 kV; probe current, 20 nA; counting time, 10 seconds per element; and beam diameter, 10 μm.

IV. Mineralogical constituents

The results of the point-count are shown in Table 1. No significant compositional variations with stratigraphy were observed though the samples nearer to the base of the Formation are slightly richer in chlorite and heavy minerals. The sandstones are texturally and mineralogically immature, and have undergone very little or no metamorphism. The sandstone compositions are characterized by high proportion matrix (between 15 and 30 vol.%; Table 1). According to the sandstone classification of Folk (1974) they are lithic graywackes.

1. Quartz

The proportion of the quartz (including microcrystalline chert) ranges from 5 to 15% of the detritus. Monocrystalline quartz is slightly more abundant than the polycrystalline variety (Table 1). Most of the monocrystalline quartz grains are of volcanic origin as they typically show euhedral shapes, non-undulatory extinction, embayments, and inclusion-free clear transparency. Such volcanic quartz is present in all the analyzed samples. Monocrystalline quartz crystals showing tectonic fabric mostly contains mineral inclusions of white mica. Polycrystalline quartz grains are composed mainly of non-oriented crystallites, commonly three or more crystals per grain, with straight to undulose extinction and straight grain boundaries.

Table 1. Point-count data for the sandstones of the Hayama Formation

Sample No	Qm	Qp	K	P	Lv	Lm	Ls	Chl	HM	C	Matrix
Hokubo area											
UM-H-06	6.3	4.2	3.4	18.4	24.3	1.2	7.6	11.4	1.9	1.9	19.2
UM-H-05	5.5	5.5	0.0	13.8	20.3	6.8	5.9	10.2	1.8	3.4	26.8
LM-H-01	5.9	4.1	1.0	14.8	24.6	4.1	6.5	9.8	3.1	3.2	22.9
LM-H-02	6.1	4.1	1.3	14.5	25.8	3.6	6.2	9.4	3.3	3.0	22.8
LM-H-04	9.8	4.6	1.4	15.0	22.5	2.8	5.2	12.3	1.9	3.4	21.5
LM-H-03	7.4	5.3	2.1	12.0	22.9	4.4	5.2	7.3	2.2	1.9	29.3
Higashimihara area											
UM-I-03	5.8	5.5	0.0	14.2	24.9	1.0	9.0	9.7	3.4	3.3	23.3
LM-I-01	4.7	3.9	0.4	13.1	26.8	1.7	6.8	15.7	3.7	4.3	18.9
LM-I-02	2.4	2.8	0.0	11.7	31.0	7.0	6.5	9.6	3.0	2.8	23.0
Hayama area											
UM-N-08	5.1	3.9	0.2	19.2	20.1	4.8	2.1	9.2	2.9	3.5	28.9
UM-N-07	8.7	2.4	0.9	5.2	39.9	0.2	9.0	1.0	0.5	4.4	27.8
UM-N-06	6.9	3.7	3.0	21.5	21.5	5.3	5.9	4.0	2.3	0.7	25.1
UM-N-05	8.2	5.9	3.1	15.8	27.1	3.9	4.2	6.2	2.5	2.6	20.6
LM-N-01	6.3	3.7	2.9	14.4	30.7	0.2	5.4	8.4	7.8	0.6	19.5
LM-N-02	4.8	3.6	2.4	17.4	17.7	3.8	6.7	14.8	4.7	2.6	21.5
LM-N-03	8.6	4.3	1.1	13.8	23.9	4.3	6.3	14.3	3.4	4.6	15.4
LM-N-04	7.9	5.2	1.2	20.8	25.1	1.9	7.1	5.0	2.1	3.2	20.7

Abbreviations: Qm = monocrystalline quartz; Qp = polycrstalline quartz including chert; P = plagioclase feldspar; F = potassium feldspar; Lm = metamorphic lithic grains; Lv = volcanic lithic grains; Ls = sedimentary lithic grains; Chl = chlorite; C = calcite; HM = heavy mineral; M = matrix content; LM-, Lower Member; UM-, Upper Member

2. Feldspar

Euhedral to subhedral feldspar grains constitute between 6 and 24% of the detritus. Plagioclase is by far the most abundant feldspar variety (Table 1). Both twinned and untwinned plagioclase varieties occur but the latter is more abundant. Plagioclase may be fresh and unaltered but, more commonly, they are replaced by carbonate or altered to clay minerals. Potassium feldspar, which includes sanidine and orthoclase, was distinguished from quartz by presence of cleavage, cloudy alteration and lower refractive indices. Microcline and microperthite were observed in few samples. Microprobe analysis carried out on fresh feldspar crystals with little or no replacement textures shows the dominance of albite and sanidine (Table 2; Fig. 2). The use of feldspar grains in provenance studies, however, is greatly hampered by the process of albitization during sediment diagenesis. To minimize the effect of albitization, only detrital feldspars with no replacement textures were analyzed. The detrital feldspars show bimodal distribution, even in a single thin-section. Dutta and Wheat (1993) have suggested that such compositional bimodality may indicate that the feldspar composition is primary.

3. Rock fragments

Lithic volcanic clasts are the most predominant component in all the analyzed samples (17 to 30%). Two broad categories were identified: felsic volcanic and mafic volcanic clasts. The felsic volcanic clasts are more abundant and are characterized by microcrystalline mosaic of individual quartz crystals with relict feldspar. Vitric varieties also occur and have a groundmass consisting mainly of altered and devitrified glass. Relict shards and flow structures were observed in some samples. Mafic volcanic fragments

Table 2. Representative compositions of feldspar (single grains)

Sample No	LM-N-01		UM-N-08	LM-H-02	
Analysis No	1	13	5	2	7
SiO_2	66.84	69.56	64.34	69.76	68.27
Al_2O_3	20.61	18.68	18.34	18.49	21.37
CaO	2.49	0.54	0.19	0.18	0.72
Na_2O	10.20	11.09	0.81	11.45	9.48
K_2O	0.09	0.07	15.45	0.05	0.61
FeO	0.14	0.06	nd	0.16	nd
Total	100.37	100.00	99.13	100.09	100.45
Formula on the basis of 32 oxygens					
Si	11.698	12.126	11.974	12.154	11.830
Al	4.251	3.838	4.023	3.797	4.364
Ca	0.467	0.101	0.038	0.034	0.134
Na	3.461	3.748	0.292	3.868	3.185
K	0.020	0.016	3.668	0.011	0.135
Fe	0.020	0.009	nd	0.023	nd
Total	19.917	19.838	19.995	19.887	19.648
Molecular Ratio					
Ab	87.66	96.97	7.30	98.85	92.21
An	11.83	2.61	0.95	0.87	3.88
Or	0.51	0.41	91.75	0.28	3.91

nd, not determined

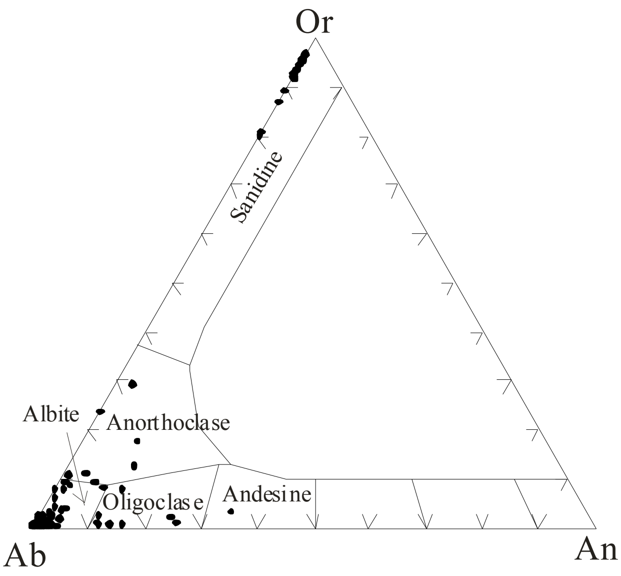

Fig. 2. Ternary diagram showing the compositions of the detrital feldspar grains from the sandstones of the Hayama

mostly show a microlitic texture with laths of plagioclase in an altered alphanitic groundmass. Irregular opaque fragments have been interpreted as volcanic mafic fragments due to occasional appearance of plagioclase and mafic mineral inclusions.

Sedimentary rock fragments include sandstone, mudstone, chert and calcareous fragments. Chert grains include both microcrystalline and radiolarian varieties; microcrystalline chert is, however, included in the polycrystalline quartz category for the modal analysis (Ingersoll et al., 1984). Microcrystalline chert grains were distinguished from microcrystalline felsic volcanic rock fragments by a lack of marked internal relief between individual crystals, lack of feldspar microphenocrysts and sometimes by presence of criss-crossing veinlets. Detrital calcite grains, which constitute up to 3% of the detritus, often contain fragments of fusulinids and other Paleozoic

Table 3. Representative compositions of chlorite aggregate

Sample No	LM-N-02		LM-H-02		
Analysis No	4	7	1	2	8
MgO	17.58	25.26	20.63	32.05	25.60
FeO(tot)	17.90	12.68	14.13	5.64	11.66
SiO_2	28.06	30.74	30.25	31.20	30.41
Al_2O_3	22.07	13.99	18.79	16.13	18.84
Cr_2O_3	0.22	2.03	0.75	0.54	0.09
Ni	0.20	nd	0.15	0.17	0.14
Total	86.03	84.70	84.70	85.73	86.74
(H_2O)	13.97	15.31	15.70	14.27	13.27
Formula on the basis of 28 oxygens					
Mg	5.367	7.704	6.272	9.278	7.512
Fe	3.065	2.169	2.410	0.916	1.919
Si	5.746	6.289	6.169	6.059	5.985
Al	5.326	3.373	4.516	3.692	4.370
Cr	0.036	0.328	0.121	0.083	0.014
Ni	0.033	nd	0.025	0.027	0.022

nd, not determined

foraminiferas similar to those of the Paleozoic limestones distributed in the study area.

Metamorphic rock fragments are generally poorly represented in the sandstones. They are composed of low-grade metamorphic fragments, most probably derived from schists.

4. Phyllosilicates (including chlorites)

White mica is the most dominant phyllosilicate mineral in all the analyzed sandstones and occurs mainly as short plates. It occurs as free grains, as inclusions in quartz and feldspars, and as constituents in rock fragments. Biotite is generally rare.

Chlorite is a common mineral in the sandstones and accounts for up to 15% of the detrital constituents. In thin sections it mainly occurs as single anhedral large flakes with extremely irregular outlines and shows brown or navy blue interference colors. Some of the grains that show navy blue interference colors contain inclusions of opaque minerals and chromian spinel. The occurrence of chromian spinel as inclusions in the navy-blue chlorites together with their chemistry (MgO 16 to 32 %; Cr up to 2030 ppm; Ni up to 2150 ppm; Table 3) suggests a mafic/ultramafic source for these chlorites (Wrafter and Graham, 1989). The navy-blue chlorites can be classified as clinochlore and/or pycnochlorite, and the brown as brunsvigite and/or diabantite (Fig. 3). Although most of the chlorites appear detrital in origin, they were not included in the volcanic lithic grains component of the point counts.

5. Heavy minerals

The sandstones are rich in heavy minerals; their proportion ranges from 0.5 to 8 percent of the detrital content. The heavy mineral assemblage includes, in order of decreasing abundance, epidote, opaque minerals (mostly magnetite and subordinately ilmenite and pyrite), chlorite, chromian spinel, sphene, anatase, zircon and garnet. The zircon grains are mostly either rounded or angular in shape; euhedral types are generally rare. The garnet grains are angular, colorless and truly isotropic. Mineral chemistry of 3 detrital grains shows that they are pyrope-almandine in composition.

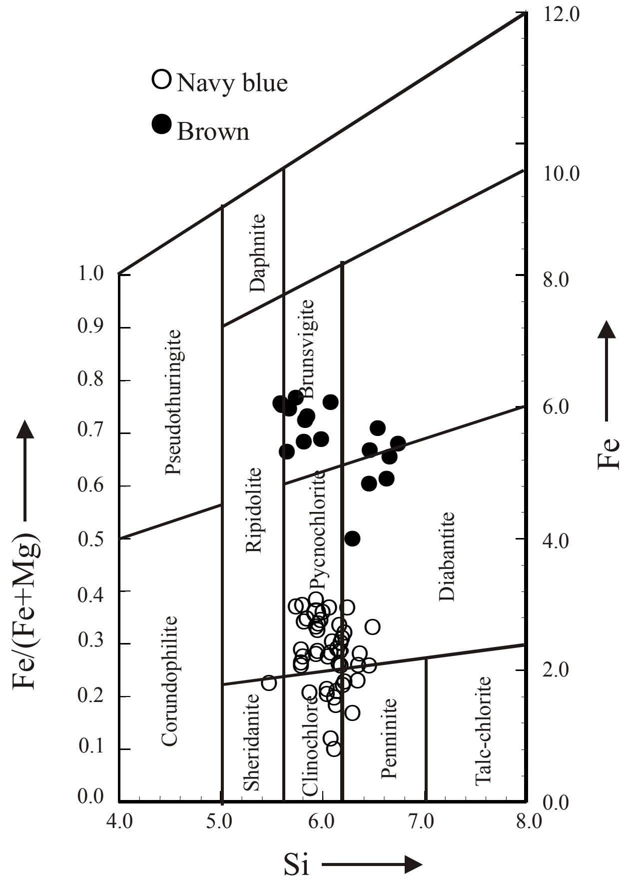

Fig. 3. Chemical compositions of chlorite aggregates from the Hayama sandstones (fields after Hay 1954).

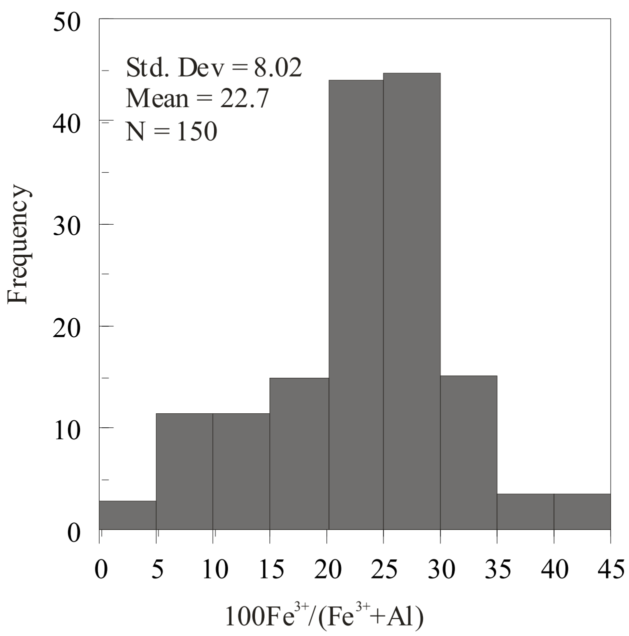

Fig. 4. Frequency of $Fe^{3+}/(Fe^{3+}+Al)$ ratios of detrital epidote from the Hayama sandstones.

a. Epidote

Epidote accounts for over 65% of the heavy mineral suites in some samples. It is pale green or yellowish green in color and is mostly irregular, angular or equant in shape. Few colorless grains were encountered in the petrographic study. The Fe/(Fe+Al) ratios are useful in characterizing epidotes. The epidote grains from the analyzed samples show a wide scattering in their Fe/(Fe+Al) ratios with a mean of about 0.22 (Table 4; Fig. 4). The epidote compositions are comparable to those reported from metagabbros and epidote-amphibolites in the Oeyama ophiolite (Kurokawa, 1985).

b. Chromian spinel

The chromian spinel grains are dark reddish brown to yellowish brown in color and generally show sharp angular shapes with irregular outlines. They occur in almost all the analyzed samples but are generally richer in the samples from the Lower Member of the formation. The chemistry of the detrital chromian spinel suggests derivation from ultramafic members of an ophiolite suite and is discussed in detail by Asiedu et al. (1997). The compositional range of the detrital spinel is similar to those from the ultramafic bodies distributed in the Akiyoshi terrane (Table 5; Fig. 5).

c. Sphene

The detrital sphene grains are mostly pale green in color, euhedral to irregular in shape and mostly free of inclusions. The chemical compositions are very homogeneous and suggest their derivation from igneous rocks (Table 6; Fig. 6). Sphenes from acidic and intermediate igneous rocks contain appreciable amounts of Fe, Al, rare earth elements, and Y whereas those from basic and/or ultrabasic rocks have low or negligible Fe, Al, rare earth elements and Y concentrations. The sphene analyses of the Hayama sandstones show compositions close to the ideal cation proportion of $CaTiSiO_5$, suggesting their derivation from basic and/or ultrabasic rocks (Asiedu et al., 2000b).

Table 4. Representative compositions of detrital epidote

Sample No	UM-H-05	UM-N-08	LM-N-02	LM-N-01	LM-I-01
Analysis No	2	4	1	3	3
SiO_2	38.07	38.07	38.93	38.62	37.83
TiO_2	0.11	0.01	0.24	0.00	0.02
Al_2O_3	25.68	25.63	27.66	28.26	22.01
Cr_2O_3	0.02	0.03	0.02	nd	nd
Fe_2O_3	11.20	11.59	9.57	6.50	13.42
MnO	0.20	0.09	0.11	nd	0.02
MgO	0.02	0.02	1.40	nd	nd
CaO	23.85	23.84	21.60	24.20	23.25
NiO	0.01	0.00	0.01	nd	nd
Total	99.16	99.28	99.54	97.57	96.61
Formula on the basis of 12.5 oxygens					
Si	3.091	3.089	3.100	3.045	3.136
Ti	0.007	0.001	0.014	0.000	0.001
Al	2.457	2.451	2.596	2.626	2.150
Cr	0.001	0.002	0.001	nd	nd
Fe^{3+}	0.684	0.708	0.573	0.429	0.930
Mn	0.014	0.006	0.007	nd	0.006
Mg	0.002	0.002	0.166	nd	nd
Ca	2.074	2.072	1.843	2.044	2.065
Ni	0.001	0.000	0.001	nd	nd

nd, not determined

Table 5. Representative compositions of chromian spinel

Sample No	LM-N-01	UM-N-08	LM-H-01	UM-H-05	LM-H-02
Analysis No	3	5	1	1	2
TiO_2	0.00	0.04	0.04	0.05	0.00
Al_2O_3	24.72	30.27	21.46	24.35	31.72
Cr_2O_3	43.19	38.59	47.73	45.75	36.82
Fe_2O_3	1.07	0.82	0.82	0.49	0.69
FeO	17.36	14.78	17.17	15.34	15.78
MnO	0.28	0.25	0.31	0.26	0.22
MgO	12.60	15.11	12.35	13.76	14.32
Total	99.22	99.86	99.87	100.00	99.55
Formula on the basis of 32 oxygens					
Ti	0.000	0.007	0.007	0.009	0.000
Al	7.190	8.434	6.296	6.984	8.845
Cr	8.427	7.213	9.394	8.803	6.888
Fe^{3+}	0.198	0.147	0.153	0.090	0.123
Fe^{2+}	3.583	2.922	3.573	3.122	3.122
Mn	0.059	0.050	0.065	0.054	0.044
Mg	4.635	5.324	4.582	4.991	5.050
Cr/(Cr+Al)	0.54	0.46	0.60	0.56	0.44
$Mg/(Mg+Fe^{2+})$	0.56	0.65	0.56	0.62	0.62

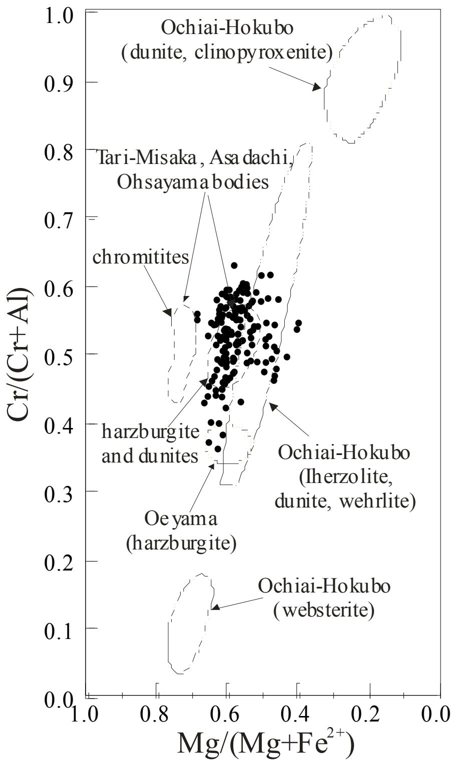

Fig. 5. Cr/(Cr+Al) versus Mg/(Mg+Fe^{2+}) plot of detrital spinel from the Hayama sandstones. Fields of the Tari-Misaka, Ashidachi and Ohsayama ultramafic bodies after Arai (1980) and Nozaka & Shibata (1994), those from

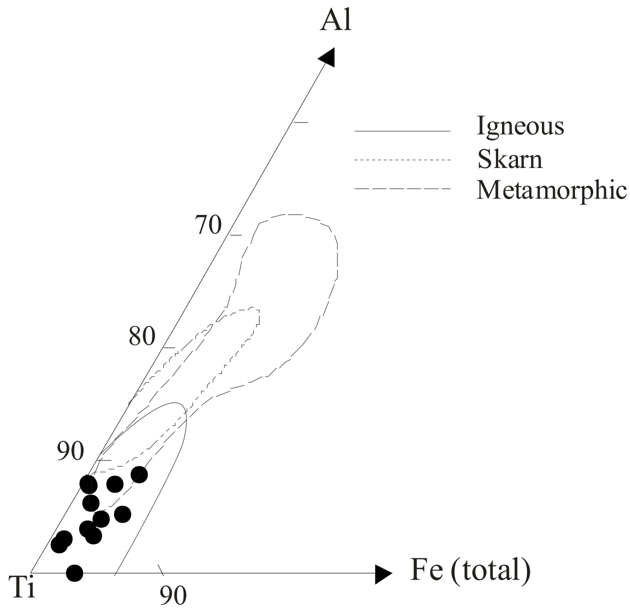

Fig. 6. Al – Ti – Fe (total) ternary plots of detrital sphene from the Hayama sandstones (fields after Asiedu et al. 2000).

Table 6. Representative compositions of detrital sphene

Sample No	LM-H-04		LM-I-01		LM-N-02
Analysis No	1	2	1	2	1
SiO_2	30.89	30.52	30.44	30.50	30.61
TiO_2	35.25	38.98	39.48	39.61	38.31
Al_2O_3	2.27	0.81	0.03	0.69	1.67
Fe_2O_3	0.19	0.01	0.03	0.00	0.02
FeO	1.28	0.39	1.22	0.36	0.57
MnO	0.01	0.13	0.00	0.02	0.00
CaO	27.66	27.56	27.53	27.72	27.52
Total	97.55	98.39	98.73	98.90	98.70
Formula on the basis of 20 oxygens					
Si	4.126	4.041	4.036	4.018	4.034
Ti	3.540	3.881	3.936	3.924	3.796
Al	0.357	0.126	0.005	0.107	0.259
Fe^{3+}	0.020	0.001	0.003	0.000	0.002
Fe^{2+}	0.142	0.043	0.136	0.040	0.063
Mn	0.001	0.015	0.000	0.002	0.000
Ca	3.958	3.909	3.910	3.913	3.885

6. Matrix

The mean matrix content of the analyzed sandstone samples from the Hayama Formation is 23%. The sandstone matrix is generally composed of fine-grained quartz (grain size <0.03 mm), chlorite, mica, opaques, altered lithic and feldspathic fragments, and material too fine to be identified. Although care was taken to avoid alteration due to weathering by collecting only the fresh samples, the high matrix contents suggest that diagenetic alteration of some grains to matrix may have occurred.

V. Discussion

1. Provenance

The petrographic and phase chemistry studies of the Hayama sandstones indicate a compositional mixture of at least four different detrital sources. A major part (estimated up to 50%) of the detritus is interpreted as the component derived from an ophiolitic source. Evidence for this interpretation is supported by the presence of detrital chromian spinel and mafic volcanic fragments and the chemistry of chlorite and sphene. This interpretation is in agreement with geochemical data that show concentrations of Mg, Cr, Ni, Co, Sc (Asiedu et al., 2000a). The lack of detrital pyroxene and amphibole and the abundance of Mg-rich chlorite and albite suggest that the ophiolitic source area may have experienced metamorphism that changed the primary rock constituents to epidote - chlorite - albite assemblages. The chemical compositions of the chromian spinel are comparable to those from ultramafic rocks within the Akiyoshi terrane (Fig. 5). The ultramafic and minor mafic rocks distributed in the Akiyoshi and Sangun-Renge terranes, or an ophiolite complex with a similar character, are therefore, the most probable source for this provenance component.

A significant proportion (estimated up to 40%) of the detritus is interpreted as the component derived from volcanic rocks of felsic composition. Evidence for this interpretation is supported by the abundance of felsic volcanic fragments, occurrence of quartz of volcanic origin and the chemistry of feldspar grains. Felsic volcanic rocks are sporadically distributed in the Akiyoshi terrane and are possible candidate for the supply of these detritus. However, the high proportion of felsic volcanic fragments in the analyzed sandstones, suggests that the source region must be a terrane with predominantly felsic volcanic composition. Therefore, if the Akiyoshi terrane is the source of this provenance component, then we can assume that large quantities of felsic volcanic rocks were distributed in the Akiyoshi terrane during the early Cretaceous. Alternatively, a silicic magmatic arc could have been the source of this provenance component. However, no obvious volcanic terrane of pre-late Cretaceous age is presently exposed in southwest Japan.

A third sedimentary source which contributed only a small amount of the total debris can be assumed for the mudstone fragments, carbonate fragments with associated foraminiferan fossils, red chert with radiolarian remains, and pyrite crystals. The limestone, chert, and mudstone-sandstone units of the Akiyoshi terrane are the probable source for this component.

A heterogeneous source characterizes the final estimated 10% of the detrital grains. This is evidenced by the presence of strained quartz with mineral inclusions, polycrystalline quartz, white mica, K-feldspar, metamorphic fragments, and basic volcanic fragments. The heterogeneous Chizu terrane is a potential supplier of this component.

The common association of the four provenance types in the investigated sandstones, together textural and mineralogical immaturity of the analyzed samples argues for a close proximity of the source areas. Dickinson and co-workers have related detrital sandstone compositions to major provenance types in various discrimination diagrams (Dickinson and Suczek, 1979; Dickinson et al., 1983). In several provenance studies (e.g., Dickinson et al., 1983), samples with greater than 25% matrix are disregarded in order to prevent mistaken provenance assignment due to diagenetic changes to the modal composition. Although 5 out of the 17 Hayama Formation samples fall within this matrix limit, in order to provide data for the entire stratigraphic level, we have included all the 17 analyzed samples in the discrimination plots. In the ternary diagram of Dickinson et al. (1983) the analyzed samples plot in the magmatic arc field (Fig. 7a, b). Taking into consideration the inferred close proximity of the source area to the depositional site, we envisage that a continental magmatic arc presumably supplied the detritus to sedimentary basin where the Hayama Formation formed. The most reasonable geotectonic setting that accommodates all these provenance sources is continental basins formed in the back-arc region. Ingersoll and Suczek (1979) have designed triangular diagrams that permit differentiation of the tectonic settings of depositional basins. On these diagrams the analyzed samples plot in and around the back-arc basin field that is typified by the mixture of detritus from a magmatic arc and rifted continental margin (Fig. 7c, d).

2. Paleogeographic reconstruction

Okada and Sakai (1993) have indicated that the Inner Zone of Southwest Japan is a typical active continental margin characterized by back-arc sedimentary basins controlled by strike-slip faults that are related to the Nagato tectonic zone. Early Cretaceous sedimentary basins in Southwest Japan are closely related to these strike-slip faults and can be classified as strike-slip basins with half-graben structure (Okada and Sakai, 1993; Sakai and Okada, 1997). The Hayama Formation, however, may represent a typical back-arc basin; the basin is not bounded or controlled by fault (Asiedu, 1998). In addition, the sandstone compositions of the Hayama Formation compares well with those from modern

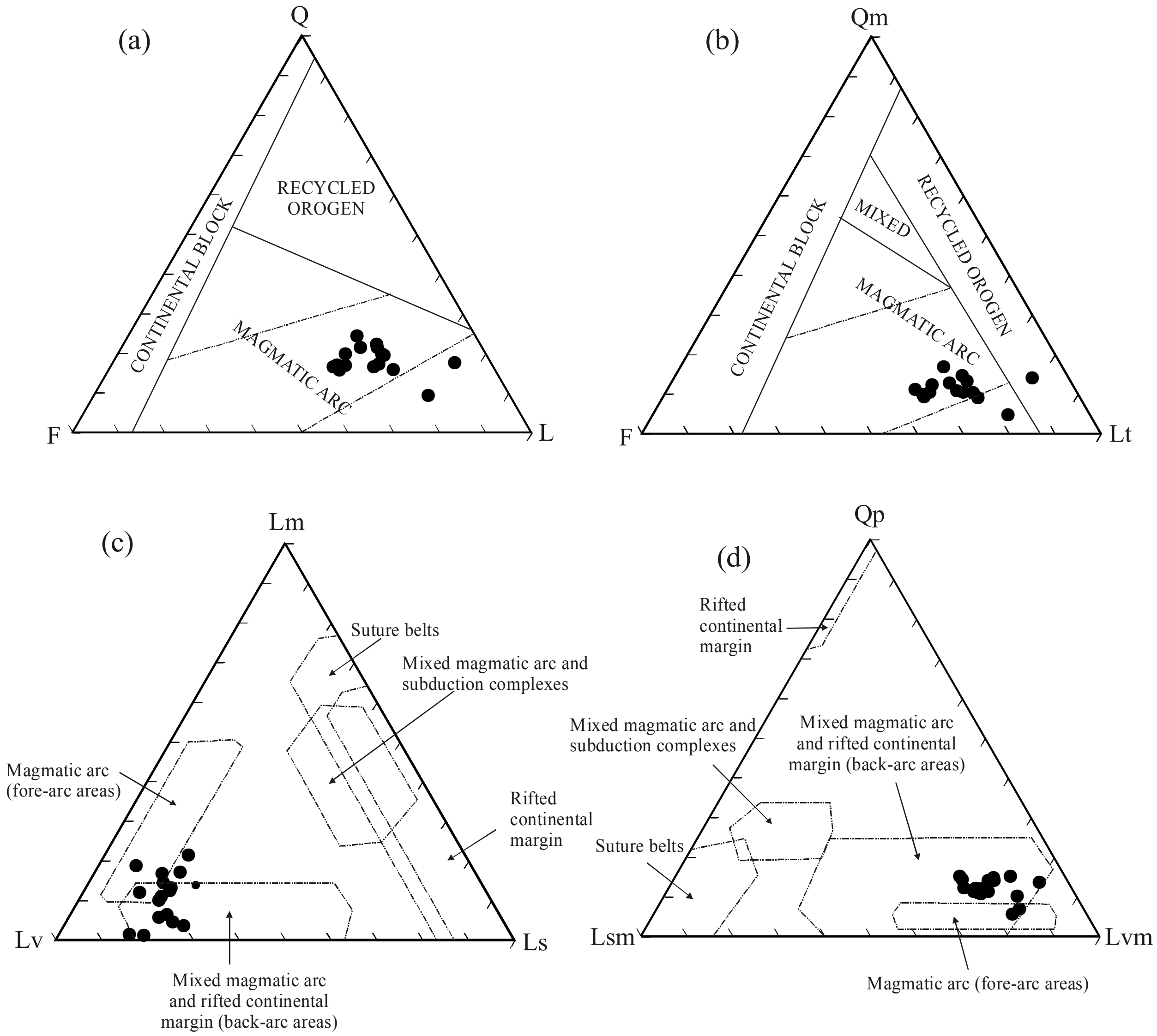

Fig. 7. Ternary diagrams for the analyzed samples: (a) Q–F–L and (b) Qm–F–Lt, after Dickinson et al. (1983); (c) Lm–Lv–Ls and (d) Qp–Lsm–Lvm, after Ingersoll and Suczek (1979). Abbreviations same as Table 1; Lsm, lithic metasedimentary; Lvm, lithic metavolcanic.

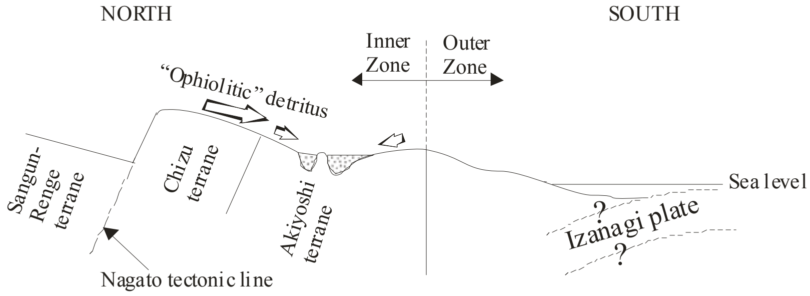

Fig. 8. Schematic illustration of provenance and tectonic environment at the time of deposition of the Hayama Formation (M.T.L = Median Tectinic Line). No scale implied.

back-arc basins and plots within the back-arc basin field of Ingersoll and Suczek (1979).

Okada and Sakai (1993) have suggested that the Lower Cretaceous sedimentary basins began to form at the time of oblique subduction of the Izanagi plate beneath the eastern margin of the Asian continent. Early Cretaceous magmatic rocks are not presently exposed in Southwest Japan but late Cretaceous magmatic rocks are widely exposed. This led Takahashi (1983) and Sakai and Okada (1997) to conclude that the nature of plate boundary during the early Cretaceous was of an oblique-slip type and that plate subduction and arc magmatism occurred in Southwest Japan in the late Cretaceous. It is, therefore, most likely that the volcanic rock fragments of felsic composition observed in the analyzed samples were supplied by felsic paleo-volcanic rocks rather than juvenile magmatic rocks.

We present a tectonic model for the study area as follows: The oblique subduction of the Izanagi plate resulted in a strike-slip movement along the Nagato tectonic zone located in the adjacent plate interior. The strike-slip motion caused a relative subsidence of the block in the interior side and an uplift of the block on the continental side. The subsiding block tilted to the south and sedimentary basins formed on the subsiding block show a half-graben structure (Okada and Sakai, 1993). The Hayama Formation is located to the south of the Nagato tectonic zone and therefore is located in the elevated block. The inferred southerly paleocurrent direction at the time of deposition of the Hayama Formation (Asiedu and Suzuki, 1995) suggests that the elevated block also tilted to the south, resulting in the obduction of ophiolitic rocks in the Sangun-Renge and Akiyoshi terranes for subsequent weathering, erosion and transport to the depositional site (Fig. 8). The heterogeneous basement rocks, and possibly a felsic magmatic arc located to the south of the basin, also supplied the rest of the detritus to the basin.

VI. Conclusions

The provenance of the Hayama Formation has been assessed using an integrated petrographical and phase chemistry approach of derived detrital grains. This approach has revealed that the sandstones of the Lower Cretaceous Hayama Formation is mineralogically immature and hetrolithic in nature and that the major sources are ultramafic rocks and felsic volcanic rocks. The provenance characteristics suggest that the Hayama Formation was deposited on the continental back-arc region of the magmatic arc that was silicic in composition. Major contributors of detritus to the depositional basin were the mafic and ultramafic rocks of the Sangun-Renge and Akiyoshi terranes and a felsic source whose location has not been positively identified.

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