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Modal and chemical compositions of the representative sandstones from the Japanese Islands and their tectonic implications

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Abstract: The Japanese Islands have been situated in an active continental margin or island arc with intense magmatism since late Paleozoic time. Therefore, the sandstones in the islands are good records for tectonic movement and magmatism in a mobile belt on plate convergence. We selected the sandstones from four large turbidite basins as the representatives of the Japanese Islands which reflect the different provenances and tectonic settings.

We used the traditional classification for discriminating the provenance of sandstone, because the most data of the modal compositions of sandstones from the Japanese Islands have been point-counted by the traditional method. Sandstones from the Japanese Islands in different tectonic situations are plotted in the fields separated each other on QFR diagram. On QFR diagram, primitive volcanic arc, evolved and mature magmatic arc, dissected magmatic arc, and renewed magmatic arc provenances are distinguishable in magmatic arc provenance.

Based on the chemical analysis, we propose a new scattered diagram of Al_2O_3/SiO_2 vs. $(FeO+MgO)/(SiO_2+K_2O+Na_2O)$ which enables to discriminate the immature island arc, evolved island arc and mature magmatic arc provenances. The first two correspond to the primitive volcanic arc provenance based on modal composition. This diagram is especially effective for distinguishing the early stages of magmatic arc evolution, but the distinction of the evolved and mature magmatic arc and the dissected magmatic arc is impossible.

These diagrams seem to be useful tools for the comparison among the various basins and tectonic settings of magmatic arc.

Key words: *sandstone, provenance, petrography, chemical composition, magmatic arc, Japanese Islands, Yubetsu Group, Izumi Group, Shimanto Belt*

INTRODUCTION

Dickinson and Suczek [1] proposed firstly the discrimination diagrams for tectonic provenance based on a modal composition counted by the Gazzi-Dickinson method [2]. Then, Dickinson et al. [3] followed the former proposal by the new data collected from various geologic settings in and around North American Continent of Phanerozoic time, and refined their proposal on the basis of statistic treatment. On the other hand, Bhatia [4], Roser and Korsch [5], and Bhatia and Crook [6] proposed discrimination diagrams for tectonic settings based on chemical compositions. Although these proposals are useful keys to clarify the ancient tectonic settings of sedimentary basins, we try to get more detailed information on provenance and tectonic setting especially for a magmatic arc, using modal and chemical compositions of sandstones.

The Japanese Islands with a thick semi-continental crust are situated in a mobile zone where oceanic crust is subsiding into mantle now. In the geologic past, these islands formed an eastern marginal part of Asian Continent where violent igneous activity and tectonic movement took place intermittently from the Late Paleozoic to the Recent. The sandstones deposited in or near the Japanese Islands may provide key infromation to clarify the provenances of sandstones derived from magmatic arc source land.

METHODOLOGY

We selected four large turbidite basins for the representatives or standards of various settings of the Japanese Islands, that is, the Yubetsu, Tamba, Izumi, and Shimanto basins (Figure 1). The turbidite sandstones are generally immature in texture and mineralogy, and expected to reflect their provenance natures directly. Additionally, those basins are supposed to represent different situtations of magmatic arc evolution.

We had also chosen six sandstone specimens from the basins to check some methodological problems. One problem is the difference between the traditional method and the Gazzi-Dickinson method [2]. As pointed by Ingersoll et al.[2] and Zuffa [8], we also had the result that the Gazzi-Dickinson method is more excellent way to get the information on provenance factor, because it decreases the grain-size effect and operator error [9]. The traditional way, however, have also advantageous points that it has more information about rock fragments, and is effective to clarify the relationship between grain size and modal composition which reflects sedimentary environments. Then, we concluded that it was better to use a new data sheet which enables to get point-counting data adaptable for the both methods [9]. The difference of the both ways is mainly in the recognition of rocks fragments as pointed by Zuffa [10]. It is not difficult to count the points on coarse-grained rock fragments according to both procedures at the same time. You can use either the traditional modal composition or new one corresponding to the purpose.

In this work, we used the data of modal composition counted by the traditional method to characterize the sandstones in the Japanese Islands, because a lot of compositional data of sandstones have been accumulated on the basis of traditional point-counting in japan.

Major chemical elements of sandstones were analyzed by ICP-AES method, and FeO was determinded by titration method of Chemex Labs Ltd., Canada. We use a scatter diagram, Al_2O_3/SiO_2 vs (FeO+MgO) / (SiO_2+K_2O+Na_2O)=Basicity Index(B.I.) to describe the chemical characters. This diagram enables to discriminate the provenance types of magmatic arc as will be discussed later.

SANDSTONE PETROGRAY AND THE SUPPOSED TECTONIC SETTINGS

Yubetsu Group in the Tokoro-Nemuro Belt, Hokkaido

The Yubetsu Group is a very thick clastic pile which consists mainly of sandstone, shale, and flysch-type alternations of sandstone and shale. The basin was formed in a trench-forearc region where a oceanic plate (Kulla-Pacific Plate?) was subducted eastward under the Okhotsk paleoland during the late Cretaceous to early Paleogene [11, 12]. Detrital materials were supplied from an immature volcanic island arc situated to the east of the basin [13]. The arc was composed mainly of basic to intermediate volcanic rocks accompanied with a small amount of older sedimentary rocks and granitic rocks [14, 15].

The sandstones of the Yubetsu Group are lithic to feldspathic greywackes, and very poor in both quartz and K-feldspar [14]. They are mostly plotted along the F-R line on QFR diagram (Figure 2). Rock fragments are abundant in intermediate volcanic rocks, but also contain fine-grained sedimentary rocks, and rarely semischist and granitic rocks. Feldspars are

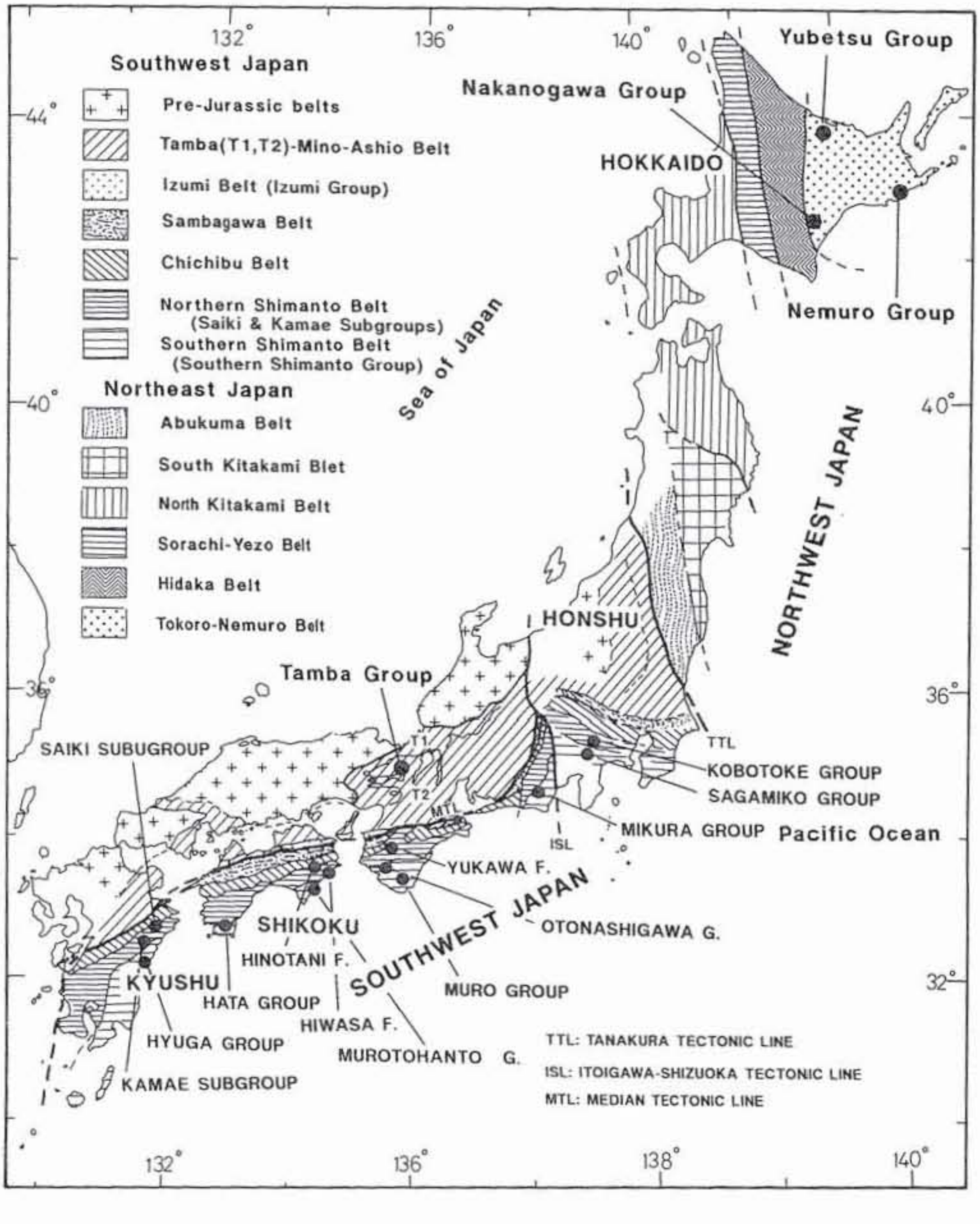

Figure 1. Geologic outline of the pre-Tertiary strata and the location of the studied formations in the main Japanese Islands. Modified from [7].

mostly plagioclase, and K–feldspar such as orthoclase and microcline are rarely found. Accessory heavy minerals such as clinopyroxene and hornblend are commonly included in 1 to 5 %.

Sandstones of the Saroma and Nakanogawa Groups in the Tokoro Belt are similar to those of the Yubetsu Group in petrography as shown in Figure 2 [16, 17]. The both groups distributed in the separated areas can be correlated mostly to the Yubetsu Group on the basis of radiolarian biostratigraphy and lithology [15]. Sandstones of the Nakanogawa Group have slightly abundant quartz, and those of the Saroma Group are rich in plagioclase.

Sandstones of the lower Nemuro Group also have similar characters to those of the Yubetsu Group (Figure 2). They are abundant in feldspars, especially in plagioclase, and very poor in quartz [18]. They were derived mainly from an island arc named Paleo–Kurile arc to the north of the basin. Some authors regarded the Nakanogawa and Yubetsu basins as the western extension of the Nemuro basin along the Paleo–Kuril islands which had been bent in N–S direction by the Tertiary tectonic movement [19, 11], although Nanayama [20] recently considered that quatrz–rich sandstones of the Nakanogwa Group were derived from a more mature island arc located to the west of the basin, probally Paleo–Japan arc.

We believe that these sandstones were derived from the same immature or semi–mature volcanic island arc, probably Paleo–Kurile island arc.

Izumi Group in the Izumi Belt, Shikoku

The Izumi Group distributed along the Median Tectonic Line in Shikoku and western Kinki district consists of sandstone, shale, conglomerate and acidic tuff, and forms a gentle synclinal structure. Turbidite facies composed of interbedded sandstone and shale is predominant. It rests unconformably on the Ryoke Granites, Ryoke metamorphic rocks and middle Cretaceous Sennan "Rhyolites". The thickness is more than 8,000 m in the axial part of the basin,

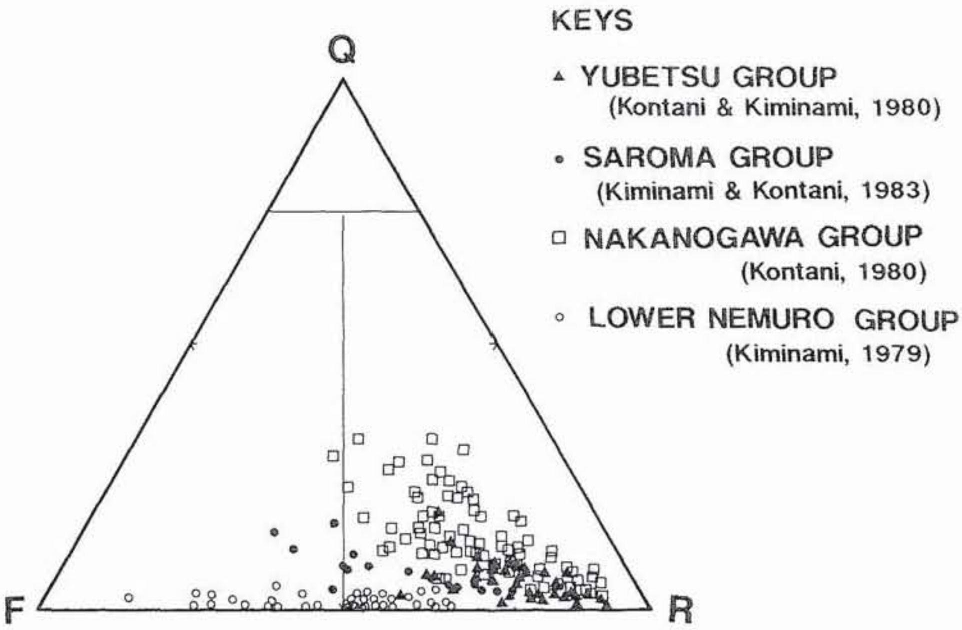

Figure 2. QFR plots of the Late Cretaceous sandstones from the Tokoro–Nemuro Belt in Hokkaido.

and the depocenter moved eastward stage by stage. It yields abundant ammonites and inoceramids, and the age is confirmed to be Campanian to Maastrichtian of Cretaceous.

Sandstones of the Izumi Group are abundant in volcanic rock fragments of acidic to intermediate nature, and classified mostly into lithic wacke (Figure 3)[21, 22]. Matrix is mostly clay minerals such as illite and chlorite, and cement of calcite and slicates are commonly observable. Their total amount ranges from 14 to 36 %. Rock fragments are most abundant constituent, ranging mostly from 38 to 73 %. Then, the sandstones are classified into lithic graywacke with a considerable amount of quatz and feldspars. The rock fragments are mainly acidic volcanic rock fragments such as glassy rhyolite and rhyolitic tuff some of which have welded textures. There are also contained commonly chert, shale, andesitic rocks, and rarely pelitic hornfels and granitic rocks. One sample exceptionally poor in rock fragments in Figure 7 belongs to the marginal facies of the basin, and its composition must reflect the sedimentary environments different from that of the other sandstones. Conglomerates are mostly composed of the clasts of acidic volcanic rocks.

Paleocurrents deduced from current marks on sole plane of turbidite sandstone indicate western axial and northern lateral supplies of clastic sediments [21, 22, 23].

In the late Cretaceous time, there was violent acidic to intermediate volcanic activity in the Inner Zone of Southwest Japan. Volumetric pyroclastics such as the Takada "Ryolites", Nohi "Ryolites", etc. are still widely distributed there. The Japanese Islands were situated in the eastern margin of Asian Continent. On the other hand, a oceanic crust, probably Kulla-Pacific plate, was subducted under Asian Continent. The subduction formed the Cretaceous Shimanto accretional terrane (Northern Shimanto Blet), and seems to be the major cause of the volcanic activity in the Inner Zone. The Izumi Group was located between the volcanism area and the subduction site. Therefore, the Izumi basin is regarded as a forearc basin on continental crust or intra-massif basin by Dickison and Seely [24].

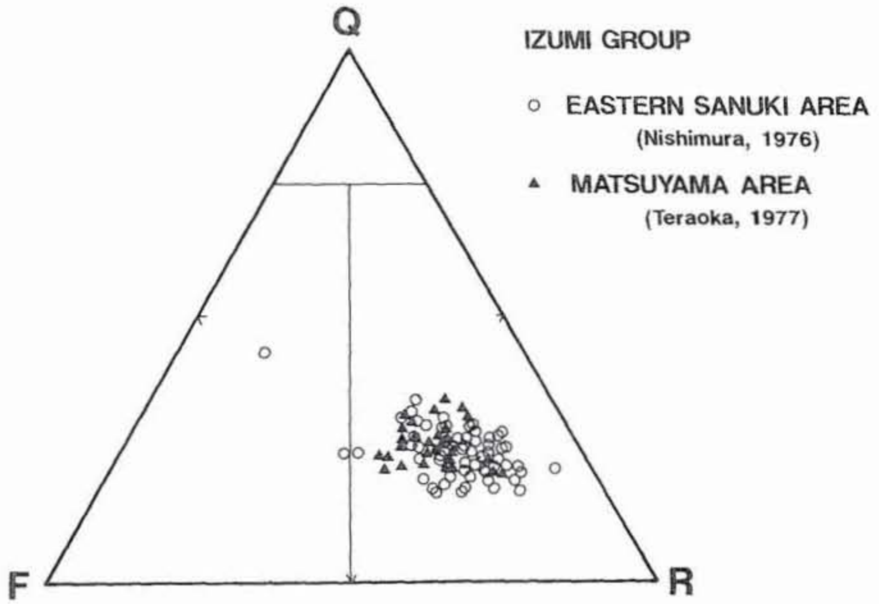

Figure 3. QFR plots of the latest Cretacous sandstones from the Izumi Group in Shikoku, Japan.

Shimanto Supergroup in the Shimanto Blet, Southwest Japan

The Shimanto Supergroup is distributed widely in the outermost zone of Southwest Japan, and regarded as a typical accretion complex in Japan. The Shimanto terrane is divided into the Cretaceous Northern Shimanto Belt and the Paleogene to early Neogene Southern Shimanto Belt. The Northern Shimanto Group in the Northern Belt is composed mainly of sandstone, alternating beds of sandstone and shale, and shale associated with chert, greenstones and acidic tuff. It has so-called eugeosynclinal facies. Radiolarian fossils indicate that chert and associated greenstones are generally much older than surrounding muddy sediments. They form exotic blocks of various size. On the other hand, the Southern Shimanto Group in the Southern Belt consists mainly of sandstone, flysch-type alternating beds of sandstone and mudstone, mudstone, conglomerate and small amount of greenstones without chert. It is supposed to have been deposited in a trench-forearc region.

Kumon [25, 26] once subdivided the Northern Shimanto Belt into three zones, namely northern, middle and southern zones. Recently, Teraoka and Okumura [27] divided the northern belt into the Saiki and Kamae subbelts on the basis of stratigraphy and sandstone composition. The northern zone by Kumon corresponds to the Saiki subbelt, and the middle and southern zones to the Kamae subblet. The strata in the Saiki subbelt range from Barremian to Turonian, and the strata in the Kamae subbelt from Turonian to Maastrchtian in age.

Modal composition of sandstone and conglomerate from the supergroup was extensively investigated [22, 25, 26, 28, 29, 30, 31,32, 33,34, 35, 36, 37, 38, 39, 40, 41]. The representative data are listed in Table 1, and shown in Figures 4 and 5.

Sandstones from the Northern Shimanto Belt are mostly feldspathic to lithic wackes of which matrix exceeds 15 %, and have distinct difference between the Saeki and Kamae subbelts in composition (Figure 4). The framework grains are angular to subangular, and matrix

Table 1. Modal composition of the sandstones from the formations of the Shimanto Supergroup.

Formation	n	ratio among framework grains Qm	Qp	Qt	Pl	Kf	% RF	Ot	% Mtx	Ref. No.
Saiki subbelt										
Yukawa Formation	35	30.8	4.3	35.1	32.0	10.4	22.4	3.8	21.4	[25]
Hinotani F.	72	29.2	3.2	32.5	35.7	11.2	20.6	4.5	21.2	[25]
Saiki Subgroup	146	-	-	26.4	31.2	11.8	30.6	-	18.5	[41]
Kamae subbelt										
Kobotoke Group	28	-	-	26.2	22.2	9.0	42.6	1.2	17.3	[40]
Hiwasa Formation	83	-	-	34.9	19.8	7.9	37.5	3.5	19.1	[25]
Kamae Subgroup	129	-	-	22.3	24.6	7.6	45.6	-	19.8	[41]
Southern Belt										
Sagamiko Group	21	-	-	42.4	17.0	10.4	29.1	1.1	15.7	[40]
Mikura Group	13	33.5	7.4	40.9	22.9	7.2	29.1	3.7	16.8	[38]
Otonashigawa G.	51	42.2	6.0	48.2	24.3	13.4	14.0	3.8	9.0	[25]
Muro Group	214	44.6	9.1	53.7	20.7	13.4	12.2	3.3	10.9	[25]
Murotohanto G.	29	-	-	54.0	18.0	13.1	14.9	4.5	15.0	[30]
Hata Group	42	-	-	42.6	24.5	6.5	26.4	-	-	[28]
Hyuga Group	194	-	-	42.0	22.8	5.7	29.4	-	-	[28]

n: number of specimens, Qm: monocrystalline quartz, Qp: polycrystalline quartz, Qt: total quartz, Pl: plagioclase Kf: K-feldspar, RF: total rock fragments including chert, Ot: others, Mtx: matrix and cement

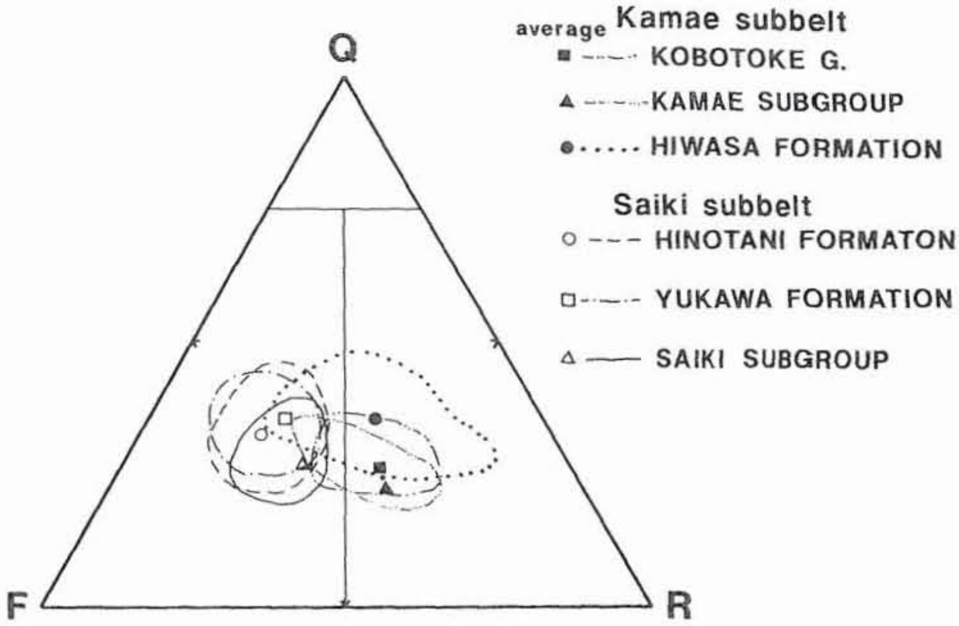

Figure 4. Modal compsosition of the Cretaceous sandstones from the Northern Shimanto Belt, Southwest Japan.

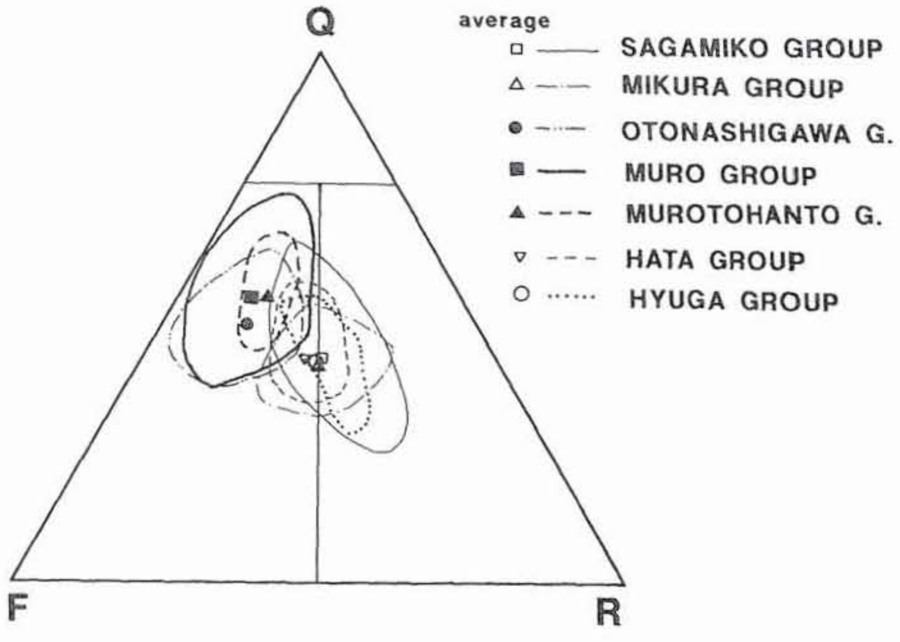

Figure 5. Modal composition of the Paleogene sandstones from the SouthernShimanto Belt, Southwest Japan.

is mostly clay and silica minerals. Sandstones of the Saiki subbelt are rich in feldspars, and plagioclase is abundant as twice or triple as K–feldspar. Rock fragments are mostly intermediate to acidic volcanic rocks associated with shale, chert, quartz schist, etc. On the other hand, sandstones of the Kamae subbelt are abundant in rock fragments, and poor in feldspars. Rock fragments are mostly acidic volcanic rocks, accompanied with shale and granitic rocks. There exists a progressive change of modal composition among the sandstones from the Northern Shimanto Belt.

Kumon[25, 26] pointed out that the stratigraphical change of modal composition reflects the evolution of igneous activity which took place in the Inner Zone of Southwest Japan under the continental arc–trench system. This process named "roofing" means the initiation of intermediate volcanic activity on continental crust and successive violent acidic volcanism represented by the Nohi "Rhyolites" which cover extensively the older rocks as a roof.

The Paleogene sandstones from the Southern Shimanto Belt in eastern Shikoku and the Kii Peninsula are mostly quartz–rich arkosic arenite with a small amount of rock fragments. The Paleogene sandstones of the whole Shimanto terrane have similar properties to each other, but a slight areal difference can be recognized (Figure 5). Sandstones from the Kanto, Chubu, western Shikoku and Kyushu districts are slightly abundant in rock fragments mainly of acidic volcanics. The difference regarded as petroprovince is considered to be due to areal variation of the dissection degree of the magmatic source land once covered by acidic volcanic rocks [42].

Tamba Group in the Inner Zone, Southwest Japan

The Tamba Group in Kinki and Chugoku districts is composed of sandstone, shale, flysch–type alternations of sandstone and shale, siliceous shale, limestone, chert and greenstones. There occur a lot of radiolarian and fusulinid microfossils. Limestone and the associating

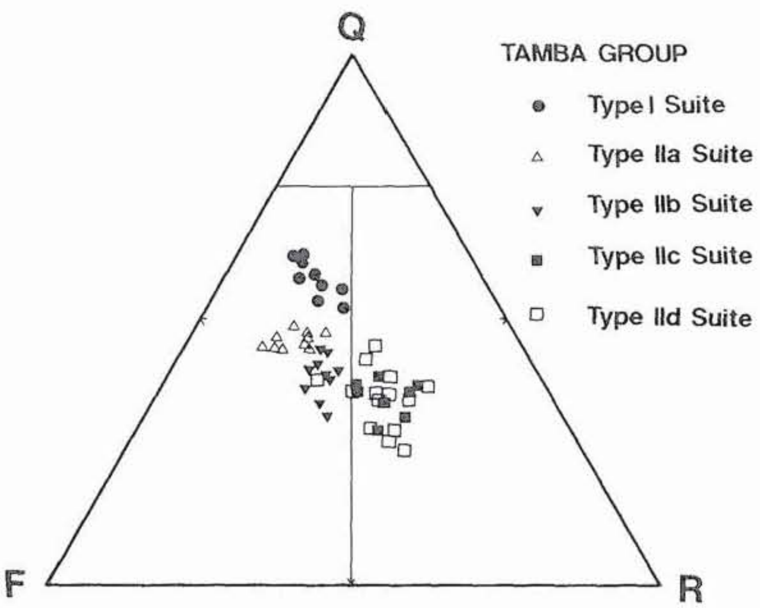

Figure 6. QFR plots of the Jurassic sandstones from the Tamba Group in Kinki district, Japan. After [44, 45].

greenstones are mostly late Paleozoic, and chert are late Paleozoic to early Jurassic in age. They occur as older blocks in muddy clastic sediments of Jurassic to earliest Cretaceous age, and are considered to be exotic in origin. Therefore, the sedimentation age of the group is the middle Jurassic to earliest Cretaceous. The Tamba Group consists of two distinct suites designated as Type I and Type II [43]. Type I suite is composed mainly of Triassic–Jurassic chert, middle Jurassic siliceous shale, and middle to late Jurassic shale and sandstone. Type II suite consists mostly of Permian chert and greenstones, Triassic chert and early–middle Jurassic mudstone and sandstone. Type II suite has been recently subdivided into Type IIa to IId subsuites [44, 45]. The age of the subsuite become old form Type IIa to IId, judging from radiolarian fossils. The Tamba Group and the equivalent Mino Group in the neighbouring Chubu district are an accretion complex of late Jurrasic to earliest Cretaceous time.

Sandstones of the Tamba Group are mostly arkosic wacke (Figure 6). They are abundant in quartz and feldspars, and poor in rock fragments [44, 45]. They are mainly fine–grained to medium–grained, and are subangular to subrounded, rarely well–rounded in texture. Muscovite is relatively abundant in accessory minerals. There are differences in composition between those of Type I and II suites, and further, among Type IIa to Type IId suite sandstones.

Sandstones of Type I are rich in quartz and poor in rock fragments compared with those of Type II suite. They have following characters. Matrix is mostly clay minerals with calcite cement, and its amount ranges form 10 to 33 % (20 % on an average). Quartz is most abundant component, and the ratio of monocrystalline quartz to polycrystalline quartz which is an aggregate of a few crystals of quartz is 0.5 on an average. Plagiocase is a slightly more abundant than K–feldspar, or nearly same. Rock fragments are acidic to intermediate volcanic rocks, quartz–schist, slate, chert, etc.

Sandstones of Type II suite are slightly poor in quartz and rich in rock fragments. Furthermore, the amount of rock fragments increases from Type IIa to Type IId subsuites [44, 45]. Sandstones of Type IIa subsuite contain a little smaller amount of quatrz, but nearly same amount of rock fragments, compared with those of Type I suite. Sandstones of Type IIb subsuite are distinctly poorer in quartz and slightly richer in rock fragments than those of Type I suite. Sandstones of Type IIc includes more rock fragments than those of Type IIb subsuite. Acidic volcanics are dominant in the rock fragments. Sandstones of Type IId subsuite are almost same as those of Type IIc subsuite in composition.

The sandstones of the Tamba Belt were considered to have been derived from a dissected magmatic arc [44, 46]. It should be mentioned that the decreasing trend of rock fragments from Type IId to Type I suite might correspond to the dissecting process of the magmatic arc source land.

PETROGRAPHIC CRITERIA FOR MAGMATIC ARC PROVENANCE

The following four tectonic provenances can be recongized among the magmatic arc source land based on the petrographic criteria as shown in Figure 7. The tectonic situations and provenance natures are also illustrated in Figure 8.

Primitive volcanic arc provenance

The sandstones which are abundant in rock fragments or plagioclase and very poor in quartz must represent primitive volcanic arc where basic to intermediate volcanism takes place violently. The crust of the islands is thin and immature like as that of the present Izu–Marina Islands arc. In the later and more evolved stage of this provenance, there may be some acidic volcanism and granitic intrusions which are indicated by the presence of quartz, microcline feldspars and acidic volcanic fragments. These sandstones are plotted along or near the F–R line on QFR diagram (Figure 7).

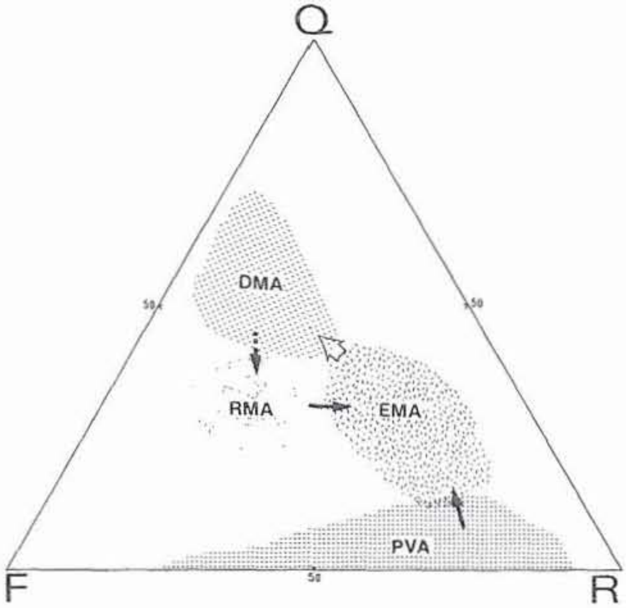

Figure 7. Tentative proposal for discriminating provenance type of magmatic arc, based on the traditional point-counting method. Solid arrows show evolving and maturing process, and open arrow indicates unroofing and dissecting process.
PVA: primitive volcanic arc, EMA: evolved and mature magmatic arc, DMA: dissected magmatic arc, RMA: renewed magmatic arc, Q: quartz, F: feldspars, R: rock fragments

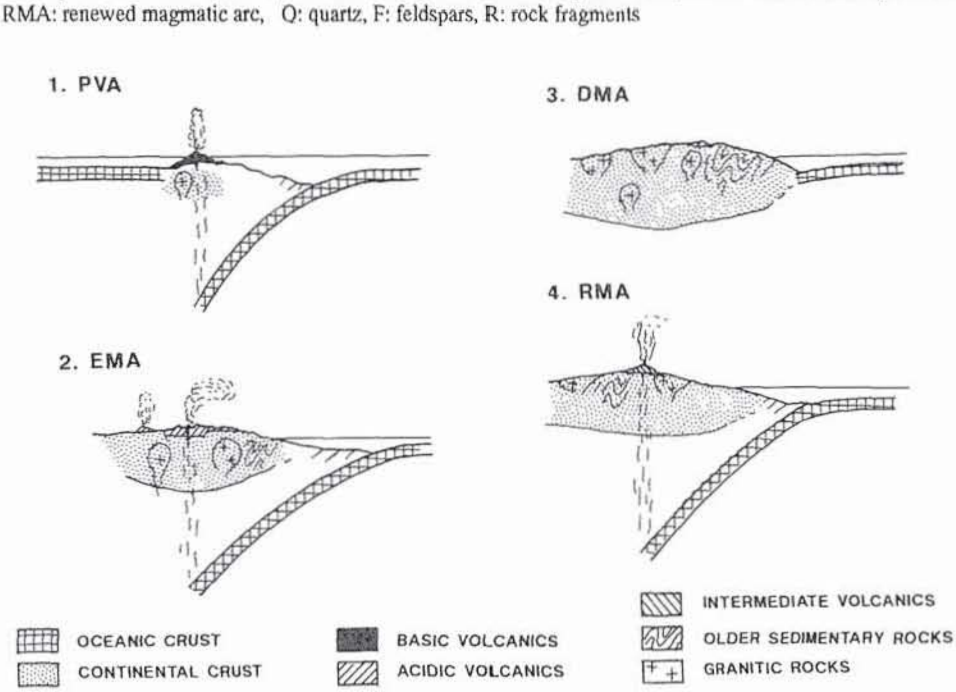

Figure 8. Schematic cross sections of magmatic arc provenances and their tectonic situations. Alphabetic symboles are same as those in Figure 7.

The representative or typical sediments of this provenance are the Yubetsu Group, Nakano-gawa Group and Nemuro Group mentioned before. Similar sediments were also reported from the basins in a modern primitive volcanic arc-trench system, that is, the forearc and backarc basins in the Izu-Bonin arc (ODP Leg 126; [47]), Atsuka Basin in the Alutian arc [48] and Middle American trench off Guatemala [49]. Sandstones from the Western Facies of New Zealand [50] and the middle Permian strata in the Maizuru Belt of Southwest Japan [51] have similar properties of modal composition, and their provenance were supposed to be volcanic islands.

Evolved and mature magmatic arc

Sandstones plotted in the middle to lower right position on QFR diagram are indicative of an evolved and mature magmatic arc provenance. The sandstones are dominant in rock fragments, but contain also fairly abundant quartz and feldsparss. Rock fragments are mostly acidic volcanic rocks. This provenance may be characterized by thick continental crust and acidic to intermediate volcanic activity associated with acidic plutonism. It forms a mature island arc or continental arc.

Sandstones of the Izumi Group and from the Kamae subbelt of the Northern Shimant Belt are typical examples derived from this provenance. The Izumi Group was deposited in a intra-massif basin or forearc basin on continental crust next to violent volcanism site. It partly overlies the acidic pyroclastic rocks of middle Cretaceous time, Sennan "Rhyolites". It was elucidated that the coarse clastic sediments of the late Cretaceous Shimanto Supergroup corresponding to the Kamae Subgroup were derived also from the Inner Zone of Southwest Japan where violent volcanic activity took place extensively [25].

Sand compositions from the modern analogue of this provenance type are rarely reported. Sands from the late Pleistocene fluvial sediments north of Tokyo Bay has very similar composition [52]. There are distributed Mesozoic strata, older crystalline rocks and Quaternary volcanoes, some of which volcanoes are still active, to the north of Tokyo Bay. The sediments were derived surely from the surrounding areas.

Tertiary sandstones of the Bristol basin along the Alaska Peninsula and the Chehalis-Grays Harbor basins have a similar modal compositions [53]. These basins are interpreted as forearc or backarc basins, and volcanic activity took place near the basins.

Therefore, we can regard these lithic arkose sandstones to represent evolved and mature magmatic arc provenance. The provenance has continental crust where active volcanism of intermediate to acidic nature take place. The older sedimentary rocks and granitic intrusives form the basements of the volcanic rocks.

Dissected magmatic arc

Arkosic sandstones plotted in the area of low rock fragment amount, and moderate quartz and feldsparss content must represent dissected magmatic arc provenance (Figure 7). The stratigraphical or time-sequential changes from lithic sandstones to arkosic sandstones is recognized in a few basins [54, 44, 39]. There is extensive cropping out of granitic rocks which formed deeper facies of previously-existed volcanic rocks, and older sedimentary rocks. The characters of source land may resemble partially those of continental block provenance.

Renewed magmatic arc

What happen when new volcanism occurs on dissected magmatic arc? Kumon [25] considered that the sandstones from the Saiki subbelt of Northern Shimanto Belt were derived from the Inner Zone of Southwest Japan where the activity of intermediate volcanic rocks named the Kanmon Group initiated on thick continental crust constituting the eastern margin of

Asian Continent. The basement rocks are older sedimentary rocks, granitic rocks and metamorphic rocks.

The sandstones of the Saiki subbelt are feldspathic wackes abundant in plagioclase and slightly poor in quartz. The rock fragments are mostly intermediate to acidic volcanic rocks accompanying sedimentary rocks and granitic rocks. These characters are common throughout the Shimanto Belt from Kanto Mountains to Kyushu [22, 25]. Additionally, the Cenomanian sandstones of the Onogawa Group in the Inner Zone of Kyushu have the same composition as those of the Saiki subbelt [22].

It is difficult to find a modern analogue of this type sandstones and provenance, because of the scarcity of modern sand composition based on this viewpoint. Pliocene sands in the Middle American Trench off South Mexico may represent an example of this type of provenance [49]. Another reason is the difficulty to distinguish the renewed magmatic arc from the dissected magmatic arc. The both resemble each other in rock constitution. The key of discrimination is the stratigraphic change of the sandstone composition. The properties of rock fragments may be supporting means, that is, relative abundance of plagioclase and volcanic fragment of intermediate nature. We suppose that some of sands (sandstones) regarded as dissected magmatic arc by Dickinson and Suczek [1] and Dickinson et al. [3] might have been derived from a renewed magmatic arc (for example, Pliocene to Miocene Queen Charlotte basin in western Canada; [53]).

CHEMICAL PROPERTIES AND TECTONIC SETTING

After trial and error, we concluded that the diagram of (Al_2O_3+SiO_2) vs. (FeO+MgO)/(SiO_2 +K_2O+Na_2O) can discriminate best the sandstones derived from magmatic arc [55]. Al_2O_3 amount in sandstone depends mainly on feldsparss and clay amount. SiO_2 amount is proportional to quartz amount. Then, Al_2O_3/SiO_2 roughly correspond to the ratio of feldspars to quartz. In general, FeO and MgO are contained much more in mafic volcanics. In contrast, Na_2O, K_2O and SiO_2 are abundant in felsic volcanics. Therefore, (FeO+MgO)/(SiO_2+Na_2O +K_2O) means rough measure of basicity of the source volcanic rocks. Then, we called the ratio, (FeO+MgO)/(SiO_2+Na_2O +K_2O), Basicity Index (B.I.) [55].

Figure 9 shows chemical characteristics of the sandstones from the Yubetsu Group, Nakanogawa Group, Izumi Group, Tamba Group, Saiki Subgroup and Kamae Subgroup on the diagram. The sandstones from the Yubetsu Group are highest in Al_2O_3/SiO_2 ratio and B.I. Those from the Nakanogawa Group are plotted in slightly lower positions in respect of B.I. Sandstones from the Izumi Group, Tamba Group and Kamae subgroup of the Shimanto Belt are distributed in the same field of the lowest B.I. and Al_2O_3/SiO_2 ratio. Sandstones of the Saiki Subgroup of the Shimanto Belt are located between the second and the third group. These plots show a definite trend of distribution as a whole. Miyashiro [56] clarified that the magmatism of arc changes progressively from basic magmatism to acidic one with the thickening of the crust of arc. The trend of decreasing of B. I., and Al_2O_3/SiO_2 ratio reflects the general evolution of magmatic arc. We can recognize several clusters which correspond to the provenance types defined based on modal composition, that is, immature island arc, evolved island arc, and mature magmatic arc provenances for the sandstones. The first two correspond to the immature volcanic arc provenance based on the modal composition. The last one contains large categories based on modal composition. Sandstones of the evolved and mature magmatic arc provenance and the dissected magmatic arc are plotted all together, and can not be distinguished from each other, because the both provenances are almost the same in magma composition. Sandstones of the renewed magmatic arc are located in the right margin of the mature magmatic arc province of the diagram. This diagram is very sensitive for discriminating the early stage of magmatic arc evolution. The name of provenance type has been partly revised here from that of Kiminami et al. [55] to avoid confusion with the

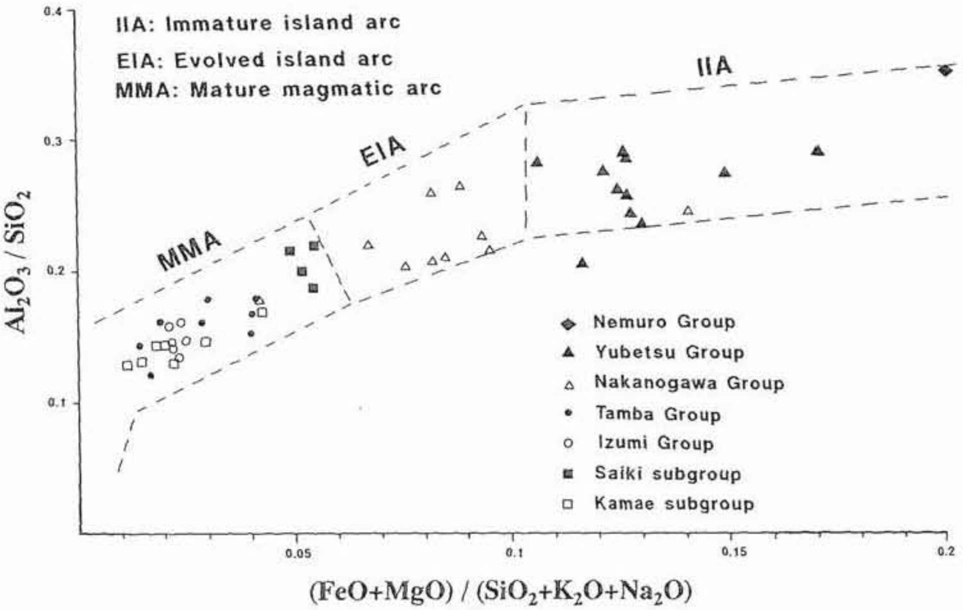

Figure 9. Tentative proposal of a discrimination diagram for provenance of sandstones, based on chemical composition.

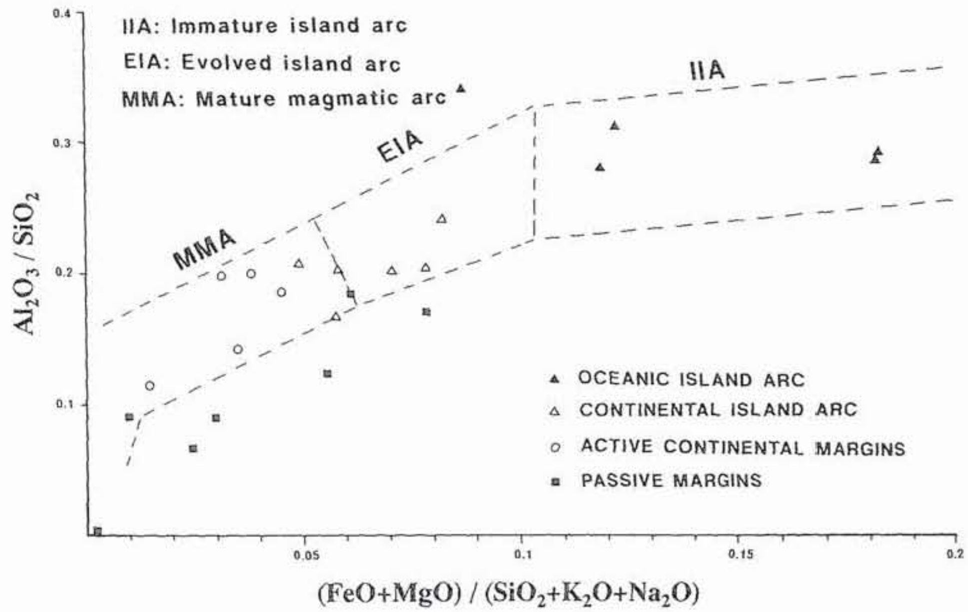

Figure 10. A test of the (Al_2O_3+SiO_2)–B.I. diagram to discriminate provenance, using the data of Bhatia [4].

provenance name based on modal composition.

Sandstone compositions reported by Bathia [4] were also plotted on this diagram (Figure 10), and tested the reliability of the diagram. Sandstones classified as oceanic island arc provenance correspond to the immature island arc provenance, and those of continental arc provenance are plotted in evolved island arc area. Sandstones of active continental margin are scattered in mauture magmatic arc, and those of passive continental margin are mostly out of the any fields. Then, we believe that the diagram proposed above is effective for analysing magmatic arc provenance.

DISCUSSION

As mentioned above, it is concluded that the sandstones derived from the magmatic arc provenance have peculiar properties of modal and chemical compositions depending on their provenance characters. The new point of this proposal is the recognition of tectonic provenances which correspond to the progressive stage of arc evolution. Magmatic arc is initiated as a volcanic island arc of basic to intermediate magma like the Izu-Bonin Islands arc, and grows up to a large island arc of intermediate to acidic volcanism like the Japanese Islands arc which have continental or semi-continental crust [56]. This process is called "maturing" in this paper. The mature magmatic arc starts to be eroded immediately after the volcanism, and the erosion results in the wide outcropping of the deeper facies of igneous rocks and the older sedimentary rocks after the decease of volcanism. This dissecting process was called "unroofing" by Mansfield [54]. The deeply dissected magmatic arc provenance may have similar provenance properties to those of continental block provenance. The revival of the volcanism in the dissected magmatic arc or continental margin may take place by the change of plate motion. The volcanic rocks begin to cover the granitic rocks and older sedimentary rocks again, and overlis them extensively at later stage. This covering process was called "roofing" by Kumon [25, 26]. The diagrams proposed here enable to discriminate the evolutional stage of magmatic arc provenance based on the modal and chemical composition of sandstones.

The diagram based on modal composition, however, still has some weak points. One is that the boundary between the provenance types on QFR diagram is somewhat arbitrary. The QFR mode by traditional point-counting method is affected largely by grain size. The data used for the diagram include all range of sand grain size, because most compositional data lack grain-size data. Another point is the scarcity of composition data of the modern sands derived from the provenances corresponding to the present proposal.

Mack [56] warned that the routine use of the plate-tectonic provenance diagrams lead to the recognition of error populations. We agree with him in principle, but we think that the careful treatments enable us to eliminate the unsuitable data from the consideration. One way is to use the data from large basins which reflect the large area of source land in the detrital compositions. This may avoid the influence of relict source rocks distributed in a local area.

Another way is to weight the data of immature sediments such as fluvial sandstone and turbidite sandstone, decreasing the influence of various depositional environments. As generally believed, sedimentary environment affects the composition and texture of sandstone. For example, Ito and Masuda [58] reported the systematic change of modal composition from fluvial to shallow marine in the same drainage basin. It shows a progressive change of mineralogic maturity. It is important to study on immature sandstones for recognizing the provenance, considering the textural maturity of sandstones which may be a guide of mineralogic maturity.

We examined only the sandstones supposed to be derived from magmatic arc provenance in this paper. There may be some difficulty to distinguish it from the other tectonic provenances. Most probable confusion may exists between the dissected magmatic arc provenance and a part of continental block provenance. Properties of rock fragments, that is, the ratio of volcanic rocks, sedimentary rocks, schistose rocks and plutonic rocks, may be useful to avoid misunderstanding of the provenance. The stratigraphical or time–sequential change which corresponds to the evolution of magmatic arc, should also provide an important key of correct provenance interpretation.

CONCLUSION

The provenance of sandstones derived from magmatic arc can be discriminated as immature volcanic arc, evolved and mature magmatic arc, dissected magmatic arc and renewed magmatic arc provenances on QFR diagram based on the traditional point–counting method. This proposal for provenance determination is based on the evolution of magmatic arc. It provide the more detailed information on source land and tectonic setting.

The discrimination diagram based on the major chemical compositions also enable us to distinguish the plate tectonic setting and the evolution stage of magmatic arc. This diagram is effective for discriminating the early stages of magmatic arc evolution.

Then, these diagrams provide powerful tools to interpret the tectonic setting and magmatic provenance in the geologic past.

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