2. Methods

To infer the provenance, three methods were adapted in this study, namely modal compositions of sandstone and conglomerate, and chemical analyses of detrital chromian spinel, garnet and clinopyroxene.

2-1. Modal composition of sandstone

The measurement of modal compositions of sandstone had been used only to describe or classify the sandstone (e.g. Okada, 1971). But Dickinson and Suczek (1979) and Dickinson et al. (1983) proposed the ternary diagram to infer the tectonic setting from the modal compositions of sandstone. Furthermore, Marsaglia and Ingersoll (1992) subdivided the provenance category of magmatic arc origin defined by Dickinson et al. (1983) into intraoceanic arc and continental arc. In this study, tectonic settings of provenance were based on the schemes of Dickinson et al. (1983). In order to compare with the diagrams in the other papers, the diagram proposed by Okada (1971) is also given.

Sandstone samples were collected from all the formations in the study area and thin-section were prepared. It is known that the modal compositions depend on the grain size (e.g. Shiki, 1966). The author tried to collect medium-grained size sandstones. In the collected samples, several suitable samples were chosen and stained for K-feldspar following to Kumon et al. (1992). The thin-sections were observed under the petrographic microscope to describe the nature of clastic grains, and were then point-counted to measure the modal compositions counting 500 points in each thin-section. For the reference of the grain size of the samples, the longest axes of 100 sand-sized grains were also measured. In this study, both Gazzi-Dickinson method (Ingersoll et al. 1984) and traditional method (e.g. Okada, 1971) were adapted to draw ternary diagrams of Dickinson et al. (1983) and Okada (1971), respectively.

The chert fragment is counted as sedimentary rock fragment in the Okada's scheme. In the Gazzi-Dickinson method, however, the pure chert is included as polycrystalline quartz, though the chert including some impurity is counted as sedimentary rock fragment. The "total lithics" of the Gazzi-Dickinson method means a sum total of volcaniclastics, polycrystalline quartz, sedimentary lithics and other rock fragments.

According to Okada's scheme (1971), Q-F-R compositional diagram can be divided into three fields, namely quartzose, feldspathic and lithic arenite or wacke. The sandstone of over 15% matrix is wacke, and below 15% matrix is arenite. There are two diagrams, namely Q-F-L and Qm-F-Lt in the schemes proposed by Dickinson et al. (1983). Both Q-F-L and Qm-F-Lt diagrams are divided into three fields, namely continental block, magmatic arc and recycled orogen. These fields are subdivided into three fields respectively. The vertexes of the Q-F-L diagram are ①quartz grains (Q) including both monocrystalline and polycrystalline ones, ② feldspar grains (F) and ③ lithic fragment (L) excluding polycrystalline quartz or pure chert. The vertexes of the Qm-F-Lt diagram are ① quartz grains (Qm) excluding polycrystalline one, ② feldspar grains (F) and ③ total lithic fragment including polycrystalline quartz (Lt).

2-2. Clast composition of conglomerate

In this study, measurement of clast composition of conglomerate was carried out at one locality from the Mineoka Group. First, whole volume of the sample was measured, and then, clasts were extracted using hammer and chisel. The extracted clasts were numbered one by one, and their a, b and c axes and roundness were measured using calipers. The longest and intermediate axes (designed as the operational a- and b-axes, respectively) define the maximum projection area (plane) of a pebble; the intermediate and short axes (operational b- and c-axes) define the minimum projection area of a pebble (Krumbein, 1939). As for measurements of roundness, the roundness chart of Krumbein (1941) was used in this study. All the clasts were polished and divided into some categories by observation with loupe. Representative clasts of each category were prepared for thin-sections, and then, the clasts were identified under the microscope.

2-3. Procedure of chemical analysis of detrital heavy minerals

Analyses of detrital chromian spinels, garnets and clinopyroxenes were carried out using an EPMA in this study. The thin-sections of the samples yielding many heavy minerals such as serpentine sandstone were prepared in a usual way (these thin-sections are called "usual thin-section" in this study), and were observed under the microscope for finding detrital heavy minerals. In the case of the samples yielding a less number of the heavy minerals, the heavy liquid separations were adapted in this study. SPT (sodium polytungstate) was selected for heavy liquid. The way of the heavy liquid separation is as follows (mainly based on Sato and Suzuki, 1991; Danhara et al., 1992):

First, the samples were crushed into about 5 mm chips using a jaw-crusher. These chips were crushed into the particles under 250 μm using an iron mortar and a sieve. These particles under 250 μm were collected more than 80 g, and then panned to exclude the extremely fine-grained particles. Carbonate materials and iron oxides were eliminated with dilute HCl (20%) not to damage the SPT, and then washed with water. After drying, strongly magnetic substance such as magnetite is also carefully removed with a bar magnet to give no damage to SPT. At each stage, the samples were weighed after drying.

Fig. 4 illustrates the arrangement of equipment used for heavy liquid separation. Heavy liquid was filled in the separating funnel, and the dry weighed sample was then added to the liquid, which was stirred to ensure that the grains were thoroughly wetted. The heavy minerals accumulated in the bottom of the funnel

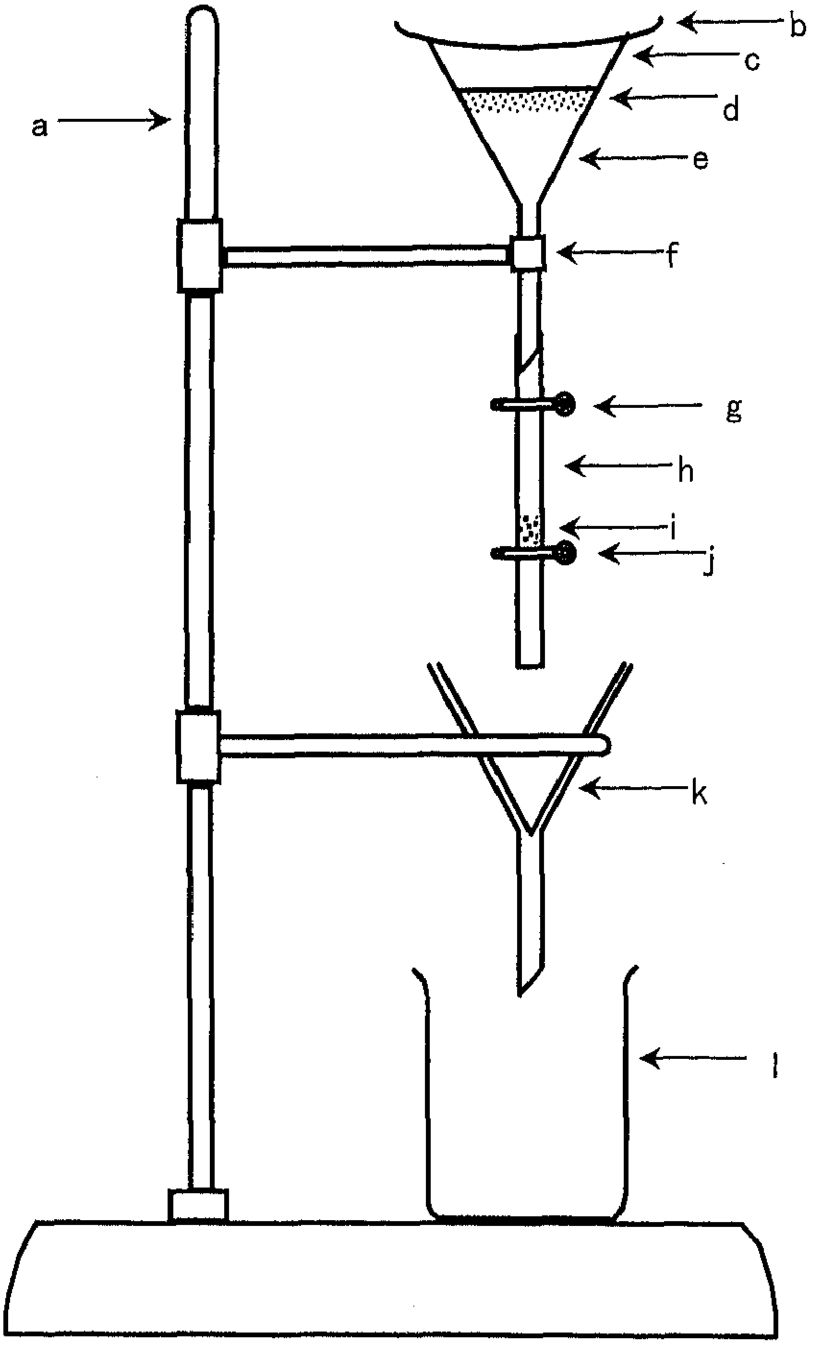

Fig. 4. Arrangement of equipment for heavy liquid separation.
a) Retort stand, b) watch glass, c) separating funnel, d) position of light fraction, e) heavy liquid, f) funnel support, g) upper pinch clip, h) rubber tube, i) position of heavy residue, j) lower pinch clip, k) funnel with a filter paper and l) collecting beaker.

above the lower pinch clip. When no more grains sink (after about 10 hours separating time), the upper pinch clip was closed and the lower pinch clip was opened slowly, thus allowing the heavy fraction to pour onto the filter paper in the lower funnel. A new funnel with filter paper was placed under the separating funnel. The light fraction was then drained into the new funnel. Subsequently the wall of the separating funnel is rinsed with a jet of distilled water in order to remove any adhering grains. Both fractions were washed thoroughly with distilled water. After drying, the heavy fraction is weighed.

The separated heavy minerals were mounted onto the slide glass cut in half with Petropoxy (Palous Petro Products Co.), and hardened with a hot plate at 130 ℃. The mounted glass was polished to expose the grains. Then the polished slide glass was put on the other slide glass with Petropoxy. After hardening, half cut glass was shaved, and the opposite sides of grains were exposed and polished with a grinder.

These thin-sections were observed under the microscope for finding out detrital chromian spinels, garnets and clinopyroxenes. As for chromian spinels, the number of spinels per 1 gram of original samples is calculated based on the number of spinels in mounted thin-sections and lost weight at each step of heavy liquid separation such as panning. These heavy minerals were analyzed with an electron microprobe analyzer (EPMA, JXA8621 super microprobe of JEOL. Co.), by 20 kv acceleration potential and $1.0*10^{-8}$ A probe current settings in the Chemical Analysis Center, the University of Tsukuba. Eleven elements (SiO_2, Al_2O_3, Cr_2O_3, TiO_2, FeO, MgO, MnO, CaO, K_2O, Na_2O, NiO) were analyzed in most cases to calculate specific ratios. In the case of the chromian spinels from the Setogawa and Himalaya-Bengal areas, ZnO was also analyzed.

2-4. Chromian spinel

Chromian spinel is a ubiquitous accessory mineral in mafic and ultramafic rocks. Therefore, the occurrence of detrital chromian spinel can show the timing of emplacement of mafic or ultramafic rocks, which comprise an ophiolitic complex in the Mineoka Mountains and the Himalayas. Furthermore, the chromian spinel is chemically more durable than other ultramafic minerals such as olivine. Compositional analysis of chromian spinel is applied in petrologic studies of spinel-bearing mafic and ultramafic rocks (e.g. Dick and Bullen, 1984; Arai, 1994b), because the composition of chromian spinel is a sensitive indicator of physico-chemical conditions in parental melt. Chemical compositions of chromian spinels have potential to provide an understanding of tectonic setting in the source area. If detrital chromian spinels are found in specific terrigeneous clastic rocks, these can be a useful key mineral concerning not only exposed ages of mafic-ultramafic rock body but also tectonic environments (Arai, 1992b; Hisada and Arai, 1993).

It is known that Fe^{3+} and Fe^{2+} were calculated assuming spinel stoichiometry and using following the equations;

$$2\,(Mg + Fe^{2+}) = Cr + Al + Fe^{3+}$$

$$Fe^{2+} + Fe^{3+} = Fe\ (total)$$

$$Fe\ (total) = Fe + Mn + Zn - 2Ti$$

The variability of the spinel chemical compositions is chiefly based on the Cr-Al and Mg-Fe^{2+} reciprocal variation. The notation Cr# is used for atomic ratios of Cr/ (Cr + Al), and Mg# is used for atomic ratios of Mg/ (Mg + Fe^{2+}), following common practice in petrologic literature (e.g. Dick and Bullen, 1984). The most significant diagnostic features of spinel analyses are: ① the correlation between Cr# and Mg#, ② the range of TiO_2wt% and Cr#-range, and ③ the atomic ratio among Al, Fe^{3+} and Cr.

2-5. Garnet

Garnet is a ubiquitous mineral in granitic rocks and metamorphic rocks. It has been known that the chemical compositions of garnet, especially in the metamorphic rocks, vary according to its genetical conditions (e.g. Miyashiro, 1953; Banno et al. 1984), and the detrital garnet has been used to infer the provenance of clastic rocks (e.g. Adachi and Kojima, 1983; Takeuchi, 1986). Recently, Teraoka et al. (1998) proposed ternary diagrams to infer the nature of the source rocks from the chemical composition of detrital garnet.

Garnet is a solid solution composed mainly of six end members, namely almandine, pyrope, spessartine, grossular, andradite and uvarovite. The former three members are called as pyralspite, while the latter three members are called as ugrandite. Generally, the garnets are described using the ratio of each end members. The values of Fe^{2+} and Fe^{3+} are needed to decide the molecules of each end-member, and they were calculated based on Droop (1987). Garnet structural formulae have been calculated on the basis of 12 oxygens. The values of Fe^{2+} and Fe^{3+} are calculated after the following procedures;

1) If cation total (S_1) < ideal number of cations per formula unit (T), leave all iron as Fe^{2+}. If $S_1 > T$, Fe^{3+} will appear.
2) Calculate the number of Fe^{3+} ions per X oxygens (12 oxygens in this case) from the following equation;

   $$Fe^{3+} = 2X\,(1 - T / S_1)$$

3) Normalize the formula to T cations. In other words, multiply each number by T / S_1.
4) If $Fe^{3+} > T - S_2$ (total of normalized cations except for cation of iron), set all iron as Fe^{3+}, otherwise a negative Fe^{2+} will appear.
5) Calculate the number of Fe^{2+} ions from the following equation;

   $$Fe^{2+} = T - Fe^{3+} - S_2$$

Two triangle diagrams of almandine—spessartine+ugrandite—pyrope and Mn—Fe—Mg were used to describe the detrital garnet and infer the provenance in this study. The end member molecules of garnet were calculated after Rickwood (1968).

2-6. Clinopyroxene

Clinopyroxene is one of the major rock-forming minerals. It is understood that the chemical compositions of clinopyroxene in volcanic rocks vary according to those of their host lavas (e.g. Kushiro, 1960). For instance, the clinopyroxenes from alkali basalts are Al- and Ti-rich but Si-poor with respect to clinopyroxenes from tholeiites (e.g. Le Bas, 1962). The chemical differences between liquids of main magmatic series are reflected in the compositions of clinopyroxenes, particularly for the elements readily incorporated in their matrix (Leterrier et al., 1982). It is known that other factors such as crystallization order of minerals and cooling rate of the magma also result in varieties of the compositions of the clinopyroxene. There are some diagrams to infer the source rocks from the chemical compositions of clinopyroxenes (e.g. Le Bas, 1962; Leterrier et al., 1982). Le Bas (1962) and Leterrier et al. (1982) treated only clinopyroxenes in basaltic rocks and they did not treat those in the metamorphic rocks or other magmatic rocks such as gabbro. However, their diagrams have been already used to infer the nature of source rocks of detrital clinopyroxenes in volcanic detritus (e.g. Styles et al., 1989; Saito and Fujioka, 1992). In this study, the diagrams of Leterrier et al. (1982) were adapted to infer the source rocks of the detrital clinopyroxenes, because sandstone in the Boso Peninsula and Koma Mountains sometimes contains a large amount of intermediate to mafic volcanic fragments with detrital clinopyroxenes.

In this study, clinopyroxenes are discriminated according to the Ca-Mg-Fe diagram of the Morimoto (1988) at first. In this diagram, the value of Fe is a total of Fe^{2+}, Fe^{3+} and Mn^{2+}. The value of Fe^{2+} and Fe^{3+} is necessary to follow their diagram, and those values were calculated based on Le Bas (1962) and Neumann (1976). Pyroxene structural formulae have been calculated on the basis of 6 oxegens. Fe^{2+} and Fe^{3+} are calculated using following equations;

$$Al^{IV} = 2 - Si \qquad \text{(If Si is >2, } Al^{IV} \text{ is 0)}$$

$$Al^{VI} = \text{total Al} - Al^{IV}$$

$$Fe^{3+} = Na - [Al^{IV} - (Al^{VI} + 2Ti)]$$

$$Fe^{2+} = Fe_{total} - Fe^{3+}$$

Secondary, the source rocks of detrital clinopyroxenes were inferred using the diagrams proposed by Leterrier et al. (1982). According to Leterrier et al. (1982), there are three steps to discriminate clinopyroxenes. In the first step, clinopyroxenes are divided into two categories, namely, clinopyroxenes from alkali basalts and from non-alkali basalts, that is, orogenic basalts and non-orogenic tholeiities, using the first diagram (Ca + Na vs. Ti diagram). For clinopyroxenes from non-alkali basalts, the second diagram (Ca vs. Ti + Cr diagram) discriminates the clinopyroxenes obtained from non-orogenic tholeiites (the most important type being MORB) and from orogenic basalts. In the final step, the third diagram (Ti vs. total Al diagram) separates clinopyroxenes obtained from orogenic basalts into two types: calc-alkali and tholeiitic basalt types.