A STUDY OF THE TENRYUKYO GRANITE, WITH SPECIAL REFERENCE TO PLAGIOCLASE

by

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(with 1 table and 11 text-figures)

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I. Introduction

The Ryoke metamorphic belt, one of major tectonic units of the Japanese islands, runs continuously from the central parts of the Honshu island for west to the island of Kyushu, forming a geologic backbone of the western half of the Japanese islands by a paired arrangement with the Sambagawa metamorphic belt, another major tectonic unit having an equal significance. It is characterized by the presence of abundant granitic rocks, gneisses and migmatites confronted to the associated Sambagawa metamorphic belt formed exclusively of crystalline schists in green schist facies.

The belt was first designated by T. HARADA as early as 1890, based on the typical development around the mid-course of the river Tenryu, the Ryoke district, central Japan. Since then, several studies have been made for various districts of the belt. With them, a comprehensive study made by H. KOIDE (1958) has the most decisive leadership for the geological as well as petrological studies of the belt. At present, though the geological framework of the Ryoke metamorphic belt has been revealed, there remain many detailed problems unsolved.

The writer has been engaged in the petrological studies on the Tenryukyo granite that developed in wide extent for the district immediate north of the Ryoke district, which is considered to be the one of representatives of the product of central core of the Ryoke metamorphic belt. Although the Tenryukyo granite has been designated as the intrusive granite having definite feature, it is revealed by the detailed study that a part of it, at least, has the nature of migmatite in origin, and further possesses a wide extent of rock facies variation.

The present study has been carried by the measurement of the optical natures of the rock forming plagioclases of every rock facies developed in the district, and their petrological significance is considered by the statistical treatment based on these measured data of large quantity.

As already published with other collaboratory authors, co-existence of plagioclases of different composition and of different ordering degree in the extent of a thin section is the prominent feature of some plutonic and migmatitic rocks (HUNAHASHI, KIM, OHTA, and TSUCHIYA, 1968). In this paper, detailed field observations and measuring results on the Tenryukyo granite and allied gneissic and migmatitic rocks are given, and they are considered as a whole in concern to the origin and transitional course of these granitic rocks.

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II. Geology and Petrography

The district investigated is situated in the southern part of the Ina valley which is formed around the mid-course of the river Tenryu. Geotectonically, the district covers the area corresponding the structural core of the Ryoke metamorphic belt of central Japan (Ryoke Research Group, 1955; Geological Survey of Japan, 1961).

Greater part of the district is occupied by the so-called Tenryukyo granite. However, it is not represented by a single lithofacies as it has been understood, but there is wide extent of variation ranging from the rock facies having gneissic or migmatitic aspect to that of several type of coarse grained granitic features.

The spatial arrangement of thus discriminated lithofacies and their tectonic relations are represented in Figure 2. The central part of the district is formed by coarse grained granitic representatives, and they are bounded in lithofacies by migmatitic and gneissic varieties. Diabasic or gabbroic rocks of earlier ages are intercalated as seams within the migmatite and gneiss.

The Tenryukyo granite itself has been described as is characterized by the coarse grained gneissose structure with porphyritic megacrystals of potash feldspar. Although the lithofacies of said character is abundantly developed in this district, it often transits gradually without any discontinuity to other diverse lithofacies such as migmatite, gneiss and other type of granite. Coarse leucocratic hornblende biotite granite, which has been defined as an absolute intrusive mass called Ikuta granite, can be viewed by the detailed field survey as the complexes of gneiss and migmatite concordantly arranged with gneissose

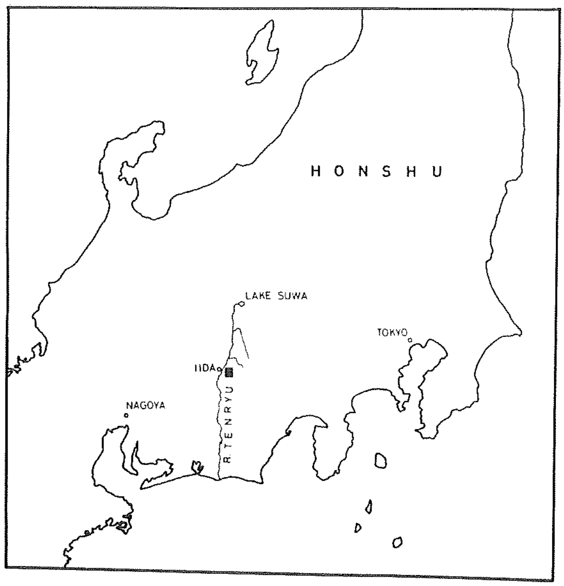

Fig. 1. Index map of the Takagi-mura district.

granite. Accordingly, it may be said that the central part of the Ryoke metamorphic belt is occupied by gneisses and migmatites having commingled relations to the several types of granite.

All the rock species present in this district are classified into the following three rock suites and respective sub-lithofacies.

1. Migmatite rock suite
   - agmatite-nebulite
   - granitic migmatite
2. Gneissose granite suite
   - coarse grained gneissose granite (gneissose granite I)
   - coarse grained potash feldspar porphyritic gneissose granite (gneissose granite II)
3. Coarse hornblende biotite granite suite
   - coarse grained hornblende biotite granite

As to the tectonic relation of each rock species, following remarks may be worth of note.

1. The foliations of each rock species are arranged, in general, into major trends of N30° ~ 45°E.
2. Although the gneissose granite suite is disposed in concordant relation to those of migmatitic rock suite in general, discordance between porphyritic type (gneissose granite II) and non-porphyritic type (gneissose granite I) is

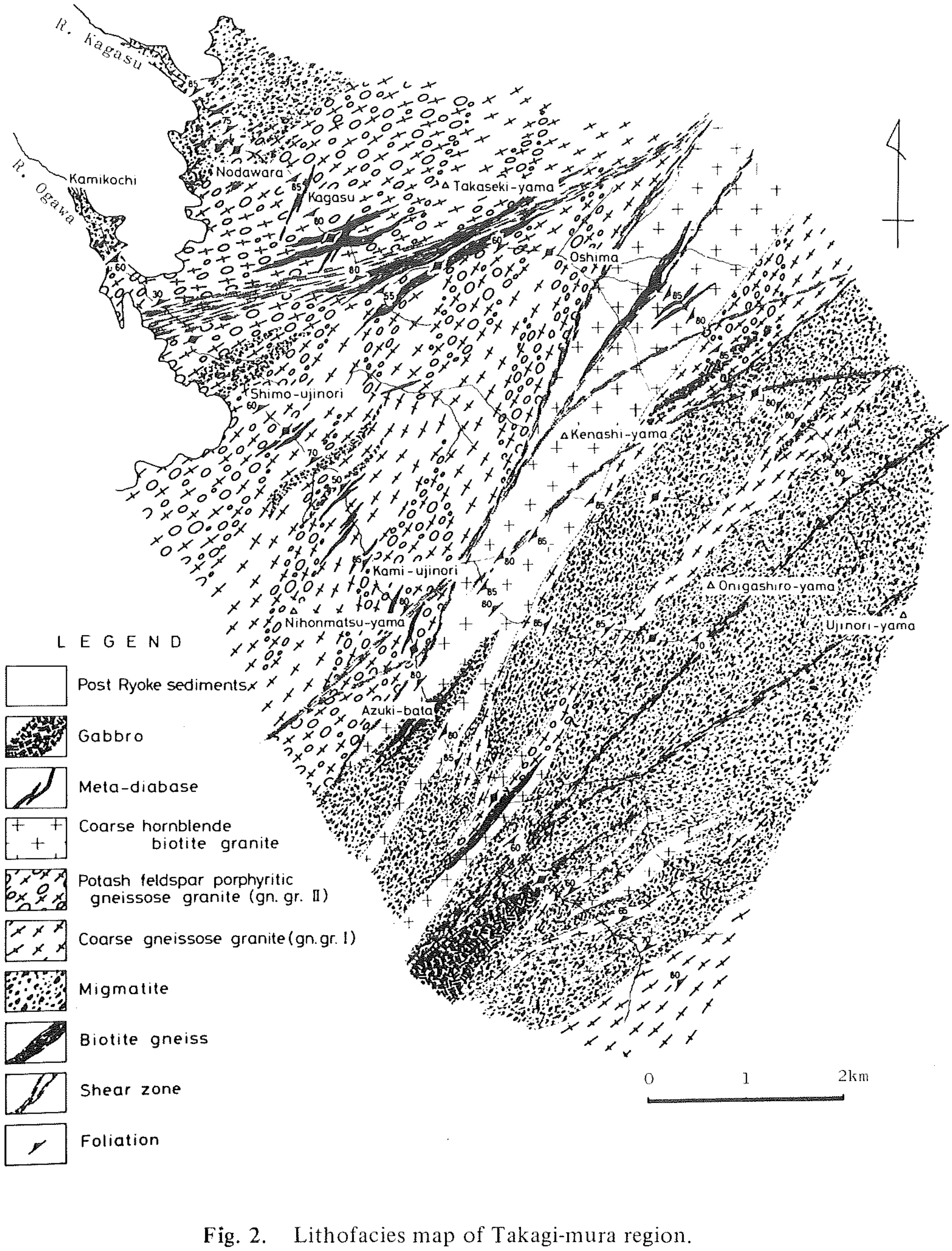

Fig. 2. Lithofacies map of Takagi-mura region.

apparent. The foliation of porphyritic type approaches rather to N–S trend slightly crossing that of non-porphyritic type which takes the trend of

NE–SW or NEE–SWW. Dispersed distribution of porphyritic type having different foliation within the non-porphyritic type also tells some different tectonic elements may have controlled the formation of both types of rocks.

3. Coarse grained hornblende biotite granite suite has rather intrusive nature compared to those of the other suites.
4. All the rock species of the district have always some remnant features of the host rock in such forms as palaeosome, neosome and banded layers escaped from the replacement processes. In this aspect, each rock species is closely allied to one another. They may be the products of progressive granitization started from gneiss and developed to the formation of migmatite, gneissose granite and coarse grained granite, that prevail in the central part of the Ryoke metamorphic belt of the region.

Following is a brief note on the lithological characters of those rock species. The nature of constituent minerals in each lithofacies is presented in Table 1.

1) Migmatitic rock suite:

This rock suite includes various lithofacies with wide range of variation from schist and gneiss to highly migmatized granitic migmatite. Among them, granitic migmatite is the most predominant, and is widely developed around the upper stream of the river Ogawa and Kagasu, in the southeastern half of the region (Fig. 2). Rocks of less migmatized types such as gneiss or agmatite-nebulitic migmatites are only found in a restricted area, the vicinity of Azuki-bata hamlet, the midstream of the river Ogawa.

Agmatite-nebulite group of rocks has abundant gneissic remnants. These palaeosomes take commonly an ellipsoidal shape with 7–10 cm diameter in long axis, and evidently show gneissic character both in megascopic and microscopic features. The interspace between them is filled with those of nebulitic character. In general, agmatitic and nebulitic varieties are disposed side by side with clear surfaces in field occurrence. Often, however, the palaeosomes are digested and obscured. Consequently, the rocks as a whole turn into nebulitic variety, whose texture approaches to granitic migmatite. In this respect, agmatite and nebulite of the district can be grouped into one rock unit.

The modal values of main constituent minerals in agmatite and nebulite are as follows;

Agmatite: quartz 45.8%, potash feldspar 14.5%, plagioclase 17.5%, biotite 20.4%.

Nebulite: quartz 34.2%, potash feldspar 14.3%, plagioclase 38.8%, biotite 12.7%.

Table 1. Petrographic properties of constituent minerals of each lithfacies

name of lithofacies	quartz	potash feldspar	plagioclase	biotite	hornblende	others
agmatite	fine granular fresh 0.3 × 0.2 mm in size	microclinic in minor amount 2Vx=70°−80°	fine granular 0.5 × 0.5 mm in size(α), and medium rather porphyritic 0.5−1.5 × 0.5−1.0 mm in size (β)	reddish brown fine 0.2 × 0.05 mm in size	none	muscovite garnet opaques
nubulite	fine to medium anhedral 0.7 × 0.5 mm in size weak wavy extinction	microclinic partially orthoclase 2Vx=65°−80°	fine weak zoning, besides α type and β type little amount of γ type (Porphyritic of 1.5 × 1.0 mm in minimum size)	reddish brown 0.5 × 0.2 mm in size: alter to chlorite	none	garnet zircon tourmaline opaques
granitic migmatite	anhedral 1.0 × 1.0 mm in size blastic	orthoclase 2Vx=55°−82° microcline 2Vx=65°−84°	fine to medium subhedral (α and β type) and porphyritic anhedral (γ) grains weak zoning	reddish brown some times altered to chlorite	none	garnet apatite zircon opaques
gneissose granite I	anhedral blastic 1.5 × 1.0 mm in size wavy extinc tion	orthoclase 2Vx=50°−64° microcline 2Vx=64°−84°	fine to coarse grains (α,β,γ type). Zoning is moderate. Albite- and Carlsbad-low twin in coarse grains	greenish brown clotted and filled up among others	none	apatite zircon sphene opaques
geissose granite II	porphyritic intense wavy extinction 3.0 × 2.5 mm in size	orthoclase porphyritic 2Vx=44°−72° microcline 2Vx=60°−84°	fine to coarse grains (α,β,γ type) Zoning is clear. Partially altered to albite by potash feldspar	greenish brown clotted 1.0 × 0.3 mm in size	none	garnet sphene zircon apatite sericite
coarse hornblende biotite granite	very coarse abundant 3.5 × 2.5 mm in size wavy extinction	orthoclase coarse 2Vx=46°−68° microcline partial 2Vx=62°−80°	fine to coarse grains (α,β,γ type) Zoning is moderate. Some amount of Pericline-low twins besides Albite- and Carlsbad twins	greenish brown small amount clotted 1.5 × 0.8 mm in size	anhedral 0.7 × 0.5 mm in size greenish	apatite sphene zircon

The granitic migmatite has rather fine grained porphyritic texture with porphyroblastic plagioclases of 5–8 mm in size. The rock is adamellitic formed with quartz-plagioclase-potash feldspar-biotite assemblage. By the increase of amount of plagioclase porphyroblasts the rock attains to coarse grained texture and some gneissosity and approaches to that of gneissose granite suite. The modal value of main constituent minerals is as follows; quartz 28.7%, plagioclase 45.5%, potash feldspar 13.0%, biotite 12.6%.

2) Gneissose granite suite:

This rock suite is characterized by coarse grained gneissose structure and abundance of potash feldspar. It is divided into two rock types; gneissose granite I and II. The former is a coarse grained granite with clear gneissosity and has no porphyritic potash feldspar, and the latter is characterized by hipidiomorphic megacrystals of potash feldspar of 20–30 mm, which sometimes attain to 50–70 mm in size. The gneissosity of the latter is rather weak than the former.

The texture of the gneissose granite I is medium grained granitic texture with clear, parallel arrangement of biotite. Sometimes plagioclase takes prophyritic nature with 8–10 mm in size. The gneissose granite II shows porphyritic texture with huge hipidiomorphic potash feldspar. However, grain size and optical characters of the other constituent minerals are allied to those of the gneissose granite I.

The modal values of main constituent minerals are as follows;

Gneissose granite I: quartz 30.5%, plagioclase 44.6%, potash feldspar 18.9%, biotite 5.9%.

Gneissose granite II: quartz 31.7%, plagioclase 30.8%, potash feldspar 32.9%, biotite 4.5%.

3) Coarse hornblende biotite granite suite:

The rock is almost homogeneous coarse grained granite with weak foliation, and is characterized by leucocratic appearance. Besides the huge sheet-like body found in the middle area of the region, some small sheet- or vein-shaped bodies of the granite are found with harmonic structure to surrounding rocks in the upper stream of the river Ogawa and Kagasu, in the area of migmatite and gneissose granite.

The granite has coarse grained equigranular granitic texture. The modal value of the main constituent minerals is as follows;

quartz 27.8%, plagioclase 49.6%, potash feldspar 11.1%, biotite 1.7%, hornblende 1.7%.

III. Studies on plagioclases of respective lithofacies

There is surprizingly wide difference of chemical composition and ordering degree between co-existing plagioclases in the extent of a rock thin section. The descriptions and their considerations on this fact have already been published by the present writer with collaboratory authors (HUNAHASHI, KIM, OHTA and TSUCHIYA, 1968). It was concluded that each lithofacies has its proper mode of concentration or proper style of distribution curve made by statistical treatment of compositional variation in one thin section. When some lithofacies revealed side by side in close connection, a mode of concentration is inherited to the succeeding lithofacies, and a culminated feature of one lithofacies is always primordially revealed in the preceding lithofacies. It may be said that the rock forming condition is well reflected in the nature of plagioclase.

The present writer has attempted to clarify the actual courses of the formation of such diverse lithofacies grouped into Tenryukyo granite by a detailed investigation on respective rock forming plagioclases.

A. Composition

The measurement has been made by optics of each grain using universal stage. The KAADEN'S estimation diagram has been used in combination with 2V diagram presented by J.R. Smith (1958).

In general, plagioclases in each lithofacies can be divided into three types. They are, α type, β type and γ type from their crystal habits and grain size. The α type shows fine grained (0.5 mm x 0.5 mm), granular, and the β type is medium grained (0.5–1.5 mm x 0.5–1.0 mm) hypidiomorphic columnar habit, and the γ type has allomorphic, rather porphyritic nature of 1.5 mm x 1.0 mm in minimum size. These plagioclases show ordinary weak zonations. Accordingly, the measurement was made separately of respective types at core and mantle. The An frequency curves of each lithofacies, which have been made statistically with ± 2.5% unit considering the accuracy of KAADEN'S estimation diagram, and the measurements are illustrated respectively in Figure 3. The summarized histogram for them is shown in Figure 4.

Each An frequency curve shows higher concentration comparing to such granitic rocks as the Kisokoma granodiorite and the Hidaka granite (TSUCHIYA, 1967; KIM, 1964a). The An-contents range approximately from An_{15} to An_{45} in the core and from An_{10} to An_{45} in the mantle except for the albite rim in the gneissose granite II. Conspicuous variation of An-contents among each lithofacies is not detected in the cores as well as in the mantles. Minor changes, however, effected by variations of lithofacies can be recognized through detailed observation.

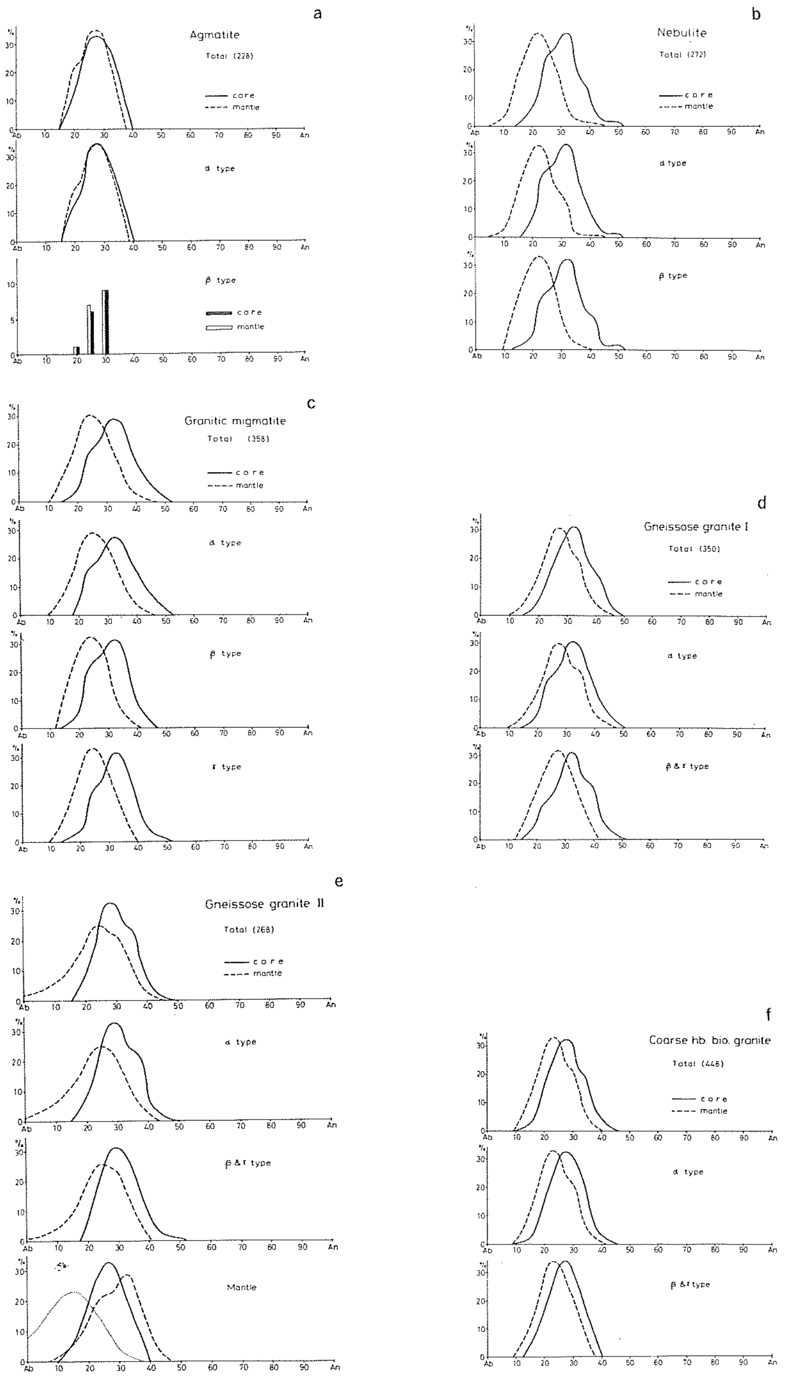

Fig. 3. An frequency curves based on unit range ± 2.5%An of each lithofacies. "α type" means plagioclases of 0.5 mm x 0.5 mm in maximum size. "β type" means those of 0.5–1.5 mm x 0.5–1.0 mm in size. "γ type" means those of 1.5 mm x 1.0 mm in minimum size.

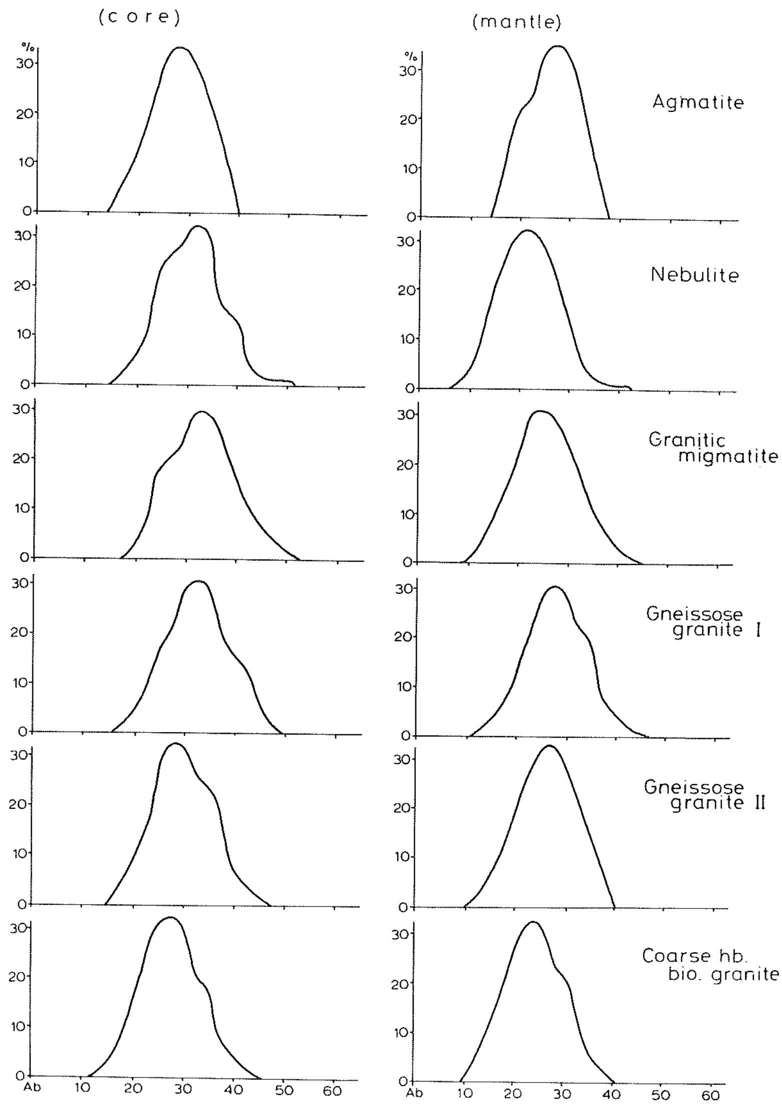

Fig. 4. Summarized histogram of An frequency curves in each lithofacies.

In the core, the frequency curves vary from normal type distribution in the agmatite to abnormal one in the granitic migmatite and the gneissose granites having one or two subsidiary modes within them. The curve turns to rather normal type again in the coarse hornblende biotite granite. Accompanied with this transition the An-contents of main modes vary from An_{27} of the agmatite to An_{33} of the nebulite, the granitic migmatite and gneissose granite I, and to An_{27} of the gneissose granite II and the coarse hornblende biotite granite in succession. In short analogous transistions are recognizable in the compositions of main mode as well as in the shape of the frequency curves.

In the mantle, each frequency curve shows rather normal type distribution compared with that of the core, and the An-contents of main modes take similar value of approximately An_{23} in each lithofacies except for the agmatite and the gneissose granite I, of which main modes situate in An_{27}. Although conspicuous variation of An-contents is not recognized among them both in the cores and the mantles, the variation presented should be regarded as gradual change in minor mode. Especially, it is important that the main modes among every lithofacies show an analogous An-content. The evidence indicates that there is no gap or abrupt change in composition regardless the notable difference of lithologic appearances in each rock suite. And it is concluded that each lithofacies shows a series of granitization from migmatites.

It is noteworthy, however, to examine analytically in more detail the frequency curve of the gneissose granite II of which lithologic appearance is characterized by large potash feldspar megacrystals. The analyzed histogram of An frequency of the mantle is illustrated in Figure 3–e. The histogram shows the plagioclases included by or contacted with potash feldspar megacrystals have more basic main mode of An_{33} compared to that of original plagioclases of no connection with them. On that particular plagioclase of the former, the mantles are fringed around with narrow rims of which An value of main mode of frequency curve is about An_{16} (i.e. albite rim). The albite rim is believed obviously as a reaction rim with potash feldspar, and basification of An-content of the mantles of those plagioclases are also considered as an effect of such reaction.

Although in principle An frequency curve ought to have a normal distribution with narrow compositional range if the chemical composition and pressure is constant and the rock attains to chemical equilibrium, the presented curves exhibit abnormal ones being accompanied with subsidiary modes or being distributed in wide compositional range. The frequency curves will be re-examined analytically in chapter IV.

B. Order-disorder problem in plagioclase

The shifting of optical orientation in potash feldspars under heat treatment at high temperature was recognized initially by BARTH (1934) who proposed the idea of order-disorder transition. The idea has been also applied to plagioclases, and optical as well as X-ray methods have been employed to settle the problem. KÖHLER (1941) found that the ordering degree is controlled by temperature of crystallization of plagioclases and that the deviation of a pair of angles between compound surface of twin, and optical axes (i.e. KÖHLER angle) in twinned grain are correlative to temperature. "Order-disorder" is regarded now as the problem of configuration of elements in crystal, and some types of them are presumed as the factor: Si-Al order-disorder, Na-Ca order-disorder and others. Commonly plagioclases in plutonic and metamorphic rocks are believed as order type which is the low temperature type due to Si-Al order and Na-Ca order. There are, however, some descriptions of plagioclases with intermediate optics in natural rocks, and further examples of plagioclases with disordered characters even in plutonic rocks were described (KANO, 1955; SLEMMONS et al., 1962, URUNO, 1963; MURAKAMI, 1963; KIM, TSUCHIYA and SAKO, 1967; HUNAHASHI, KIM, OHTA and TSUCHIYA, 1968). The writer has taken up the problem as a mean to reveal the formation condition of the Tenryukyo granite.

When the optical orientation of plagioclase is projected into the KAADEN'S diagram and compared to the high and low estimation curves of plagioclases, the projections can be tentatively classified into three groups; ordered type transitional type and disordered type respectively. Those three groups can be recognized with a certain ratio (O:T:D ratio) even in one thin section. The method was previously mentioned in detail (TSUCHIYA, 1965). The O:T:D ratio is correlative to approximately the ordering degree.

On the other hand, the ordering degree can be represented in another way. The method of "ordering index" was originally proposed by SLEMMONS (1962). He defined the high and low estimation curves of plagioclases as ordering index = 0 and ordering index = 100 respectively, and estimated the ordering index in each grain. This method, according to him, has good accuracy compared to X-ray and 2V methods (mean deviation of indices from X-ray and 2V methods is 10 for compositional range from Ab to An_{70}).

The two methods, O:T:D ratio and ordering index have been used in combination within this paper. The estimation diagram of ordering index, however, has been rewritten because the SLEMMONS'S diagram differs from that drawn on the basis of the KAADEN'S diagram.

1. O:T:D ratio

The O:T:D ratios of each lithofacies is illustrated in Figure 5, and the synoptic diagram of them is shown in Figure 6. In every lithofacies, except for the agmatite, the core always shows more ordered character compared to the mantle. The fact was also recognized in the Kisokoma granodiorite as well as in the Ainuma-nai Tertiary holocrystalline rock and in the Hidaka gabbros (KIM, 1964; TSUCHIYA, 1965; KIM, TSUCHIYA and SAKO, 1967). Therefore it is considered as a common nature among igneous rocks. Although the O:T:D ratio in the agmatite has intense disordered character and deviates from those of the other lithofacies, the ratios of the other lithofacies make a continuous

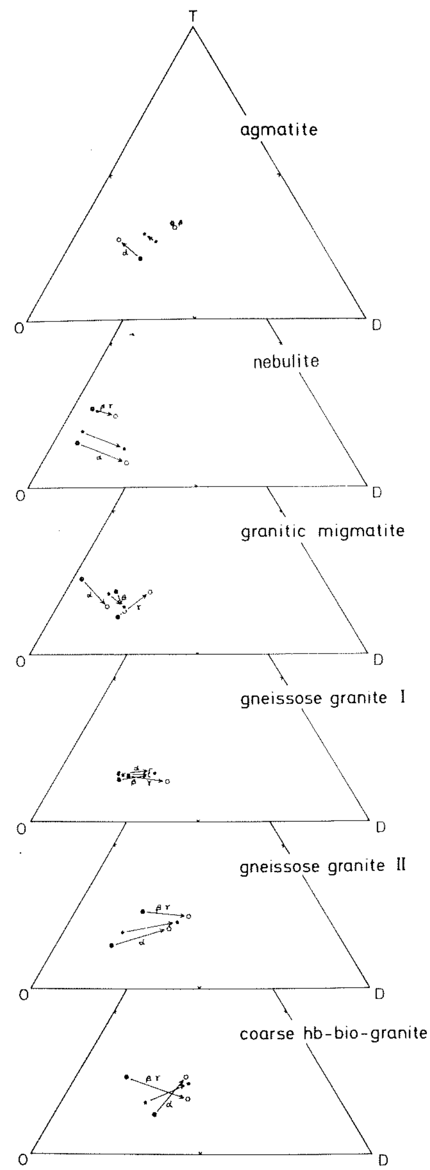

Fig. 5. Diagram showing the O:T:D ratio of plagioclases from each lithofacies. Trends shown in dart mark means the variation of ratios from core to mantle. The mark * is the total ratio in each lithofacies.

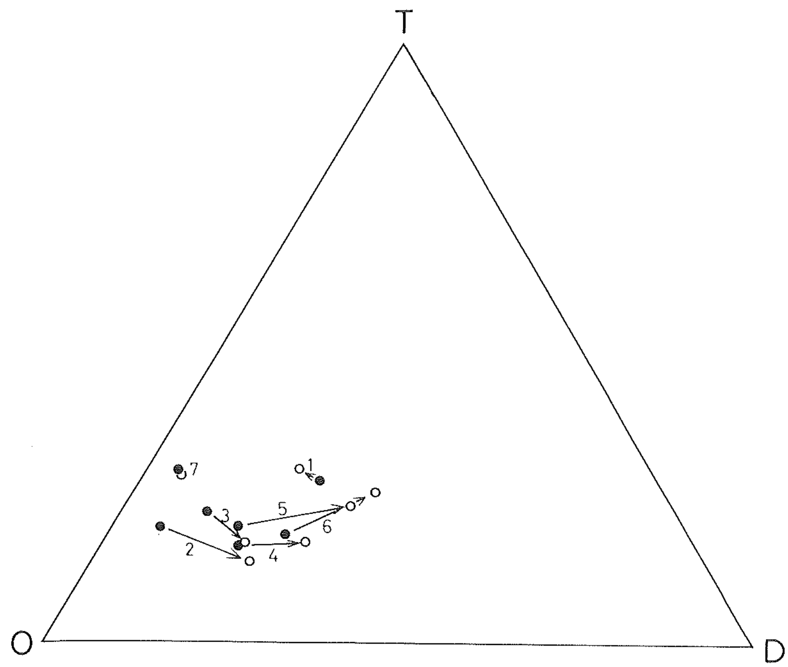

Fig. 6. Summarized diagram showing the O:T:D ratios of plagioclases from the whole lithofacies, adding sillimanite biotite gneiss from the Otagiri region. Trends shown in dart marks mean the variation of ratios from core to mantle.
1. Agmatite, 2. Nebulite, 3. Granitic migmatite, 4. Gneissose granite I, 5. Gneissose granite II, 6. Coarse hornblende biotite granite, 7. Sillimanite biotite gneiss (Otagiri region).

series of disordering from the nebulite to the granitic migmatite, the gneissose granite I, the gneissose granite II and further to the coarse hornblende biotite granite successively. Especially the transition of ratios from the granitic migmatite to the gneissose granite I and from the gneissose granite II to the coarse hornblende biotite granite proves successive transition of three major suites in field occurrences combined with the result of examination of An contents in previous section. To examine the figures more in detail, however, there is no continuous transition between the agmatite and the nebulite, whose thin sections represent palaeosome and neosome prepared from the same exposure. But a continuous transition is recognizable between the sillimanite banded gneiss and the nebulite (Fig. 6). The former specimen was brought from the Otagiri area (TSUCHIYA, 1966). Therefore, abnormally disordered state of the agmatite is regarded as an unstable step of the process of migmatization. The gneissose granite II is the rock with the most intensely disordered plagioclases whose O:T:D ratio of the mantle is plotted almost in the field of the Tertiary holocrystalline rock (KIM, TSUCHIYA and SAKO, 1967). This intense disordering is due to potash feldspar blastase which characterizes the gneissose granite II. Further discussion will be found in the next chapter.

2. Ordering Index

Ordering index in each lithofacies is illustrated in interrelation with An-content in Figure 7. The field of ordering indices between 90–100 shows

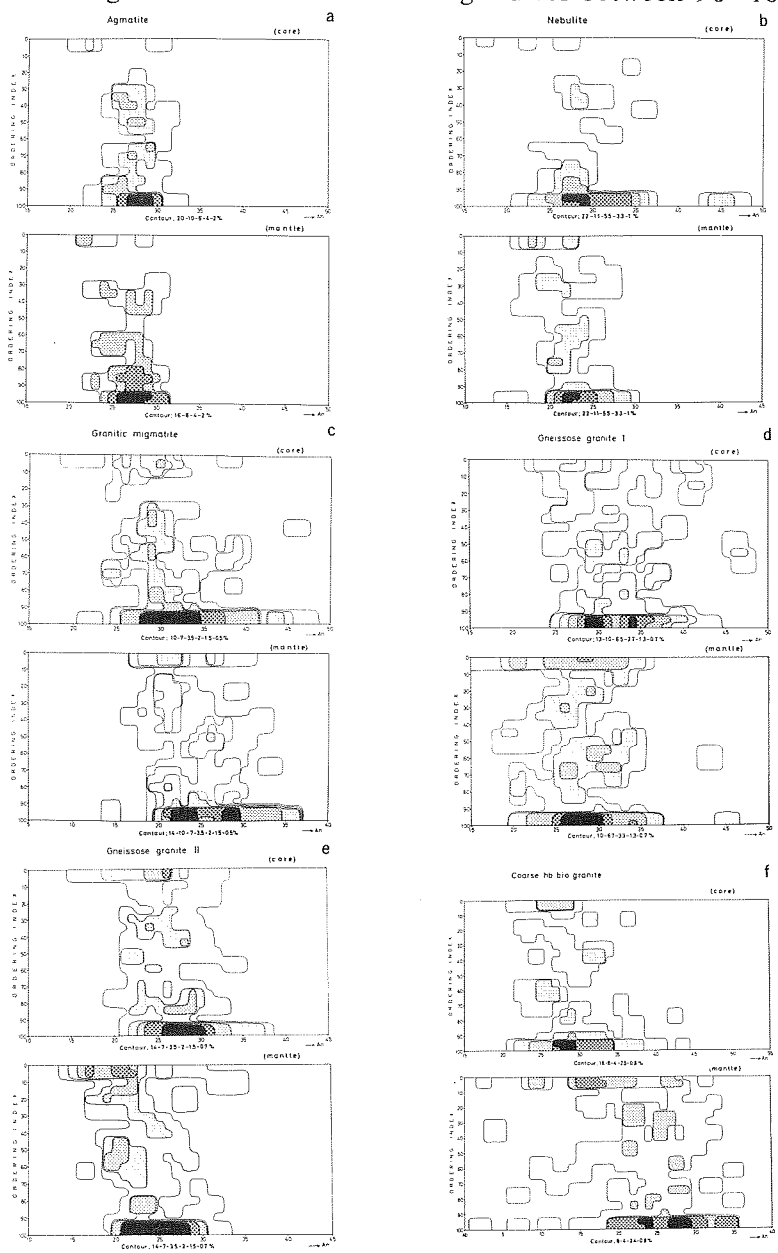

Fig. 7. Contoured diagrams showing the relation between ordering index and An content of plagioclases in each lithofacies.

the most high concentration in every histogram. And the next is concentration in the field between 0–10 except for the agmatite and nebulite. Some other notable concentrations are seen in ordering indices of about 30, 50 and 70, in which those of 30 and 70 are more predominant. The existence of concentration of ordering indices in the intermediate fields is newly obtained information. Although the relation of order-disorder has been presumed as gradual transition, it is a problem for further discussions whether such concentrations ought to be regarded as transitional steps of order-disorder transition in this granite or as a common character in plagioclases.

To examine the ordering index in relation to An-contents, the ordering indices of 90–100 coincide with the main modes of frequency curve of An-content in every histogram. Those of 0–10 in the cores coincide similarly with the main modes, but those in the mantle consists of more albitic compositions correspond to the side slopes of the frequency curves. The fact is more obvious in the gneissose granite suite and the coarse hornblende biotite granite suite. Such relation in the mantles is more remarkable in the Kisokoma granodiorite examined previously (TSUCHIYA, 1965). As to the facts in the Kisokoma granodiorite, the writer concluded that the chemical composition of plagioclases crystallized in later stage increased in albite molecule, and disordered plagioclases crystallized mainly due to rapid change of the temperature resulted from the migration of the massif. In the Tenryukyo granite, such tendency is seen only in the mantles of the rocks performed in later stage. It may be assumed that the processes of granitization of the granite were advanced without so rapid change of temperature as in the Kisokoma granodiorite.

IV. Some petrological and crystallographical problems of plagioclases

The distribution of An-content of plagioclases is already mentioned in chapter III. The plagioclases, however, show wide range in the frequency curves, and subsidiary modes are seen in some of them. The evidences will be examined more in detail in this chapter.

When estimating the An-content of plagioclases on the basis of the KAADEN'S diagram, it is noted that the An estimation curve is more reliable in the range from An_0 to An_{50} ; the error of measurement in this range is about ± 1.5 An%. The An frequency histogram of the figures were therefore reconstructed on the basis of this revised accuracy (Fig. 8).

Main modes of the new histograms do not differ in composition from those made by ± 2.5 An% unit. However, subsidiary modes appeared on the side of main mode even in those of normal distribution in previous examination (Fig. 8–a, cf. Fig. 3–a). On the other hand, subsidiary modes become more evident in those of abnormal distribution (Fig. 8–b, –c and –d, cf. Fig. 3–b, –c and –d). It is possible to divide a chain of distributions of An-content in each new histogram into more minor subgroup shows normal distribution. Those minor subgroups are believed as constituent unit of An frequency curves. The mean value of An content of those minor subgroups is 17, 20, 22–24, 27–28, 33, 37 and so forth in An%. The most of those values of An content are also to be seen in many other granitic rocks (Fig. 10).

The concept of "degree of concentration" of the An frequency was proposed previously by HUNAHASHI, KIM, OHTA and TSUCHIYA (1968). The degree of concentration can be calculated for each An frequency curve, and the sum of them has been plotted in histogram (Fig. 9). This histogram indicates that the most frequently represented An contents are An_{23}, An_{27}, An_{33}. These An-contents having high frequency are quite common in previously examined rocks both in plutonic and metamorphic rocks, in spite of the presumed large differences in the rock forming condition (Fig. 10). It seems probable, therefore, that the crystallographic factors determine the frequency of occurrence of particular An-content rather than the formation condition. The analyzed minor subgroup in the frequency histogram of ± 1.5 An% unit may be due to the existence of those crystallographic factors.

The plagioclase series has recently been studied in great detail from the crystallographic viewpoints, and the whole series based on the differences of structures in the low temperature plagioclases (DEVORE, 1956; GAY, 1962; BROWN, 1962; RIBBE, 1962; CRAWFORD, 1966; DOMAN, CINNAMON and BAILEY, 1965; BAMBAUER, CORLETT, EBERHARD and VISWANATHAN, 1967). Some of An-contents showing high frequency in the histogram An_{23} , An_{33} and An_{50} can be correlated with the all crystallographic gaps presented until now in the plagioclase series. This suggests again the crystallographic structure plays a major role in determining the composition of plagioclases in natural circumstances. However, actual relationship cannot yet been classified and more detailed studies along these lines are necessary. The distribution of An-contents in wide range is a common nature among previously studied plutonic and metamorphic rocks, even in a pluton type granite with homogeneous appearance having been expected to possess constant chemical composition. One exceptional case is that in Himalayan garnet gneiss examined by KIM (HUNAHASHI, KIM, OHTA and TSUCHIYA, 1968). Those heterogeneity in plagioclase compositions must have been originated to a great extent from crystallographic structure. It is quite necessary to examine other constituent minerals as to their chemical composition and other properties in this way for a new style petrology and crystallography.

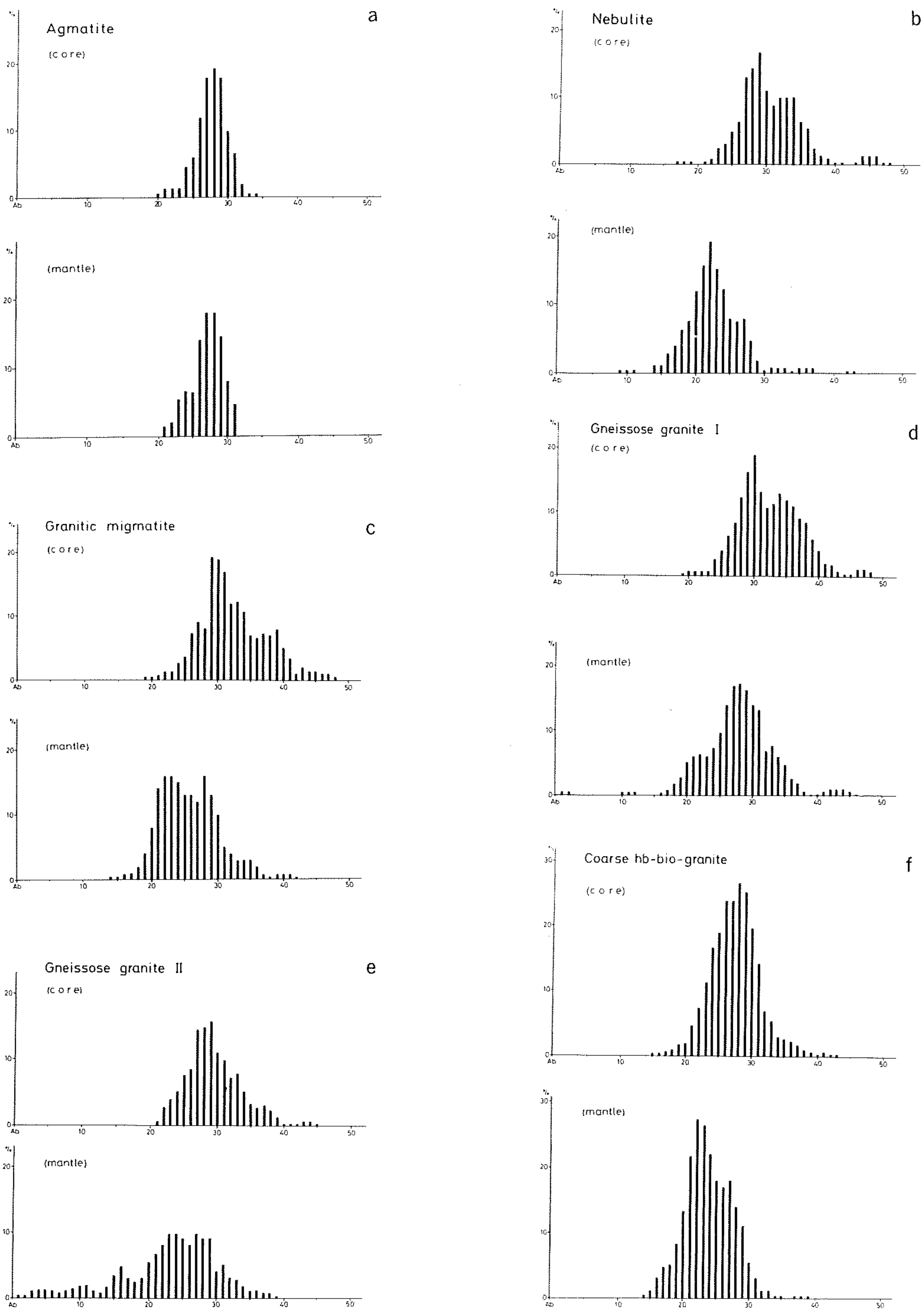

Fig. 8. An frequency histograms of plagioclases from each lithofacies with unit range ± 1.5%An instead of ± 2.5%An as used in the previous diagrams (cf. Figure 3).

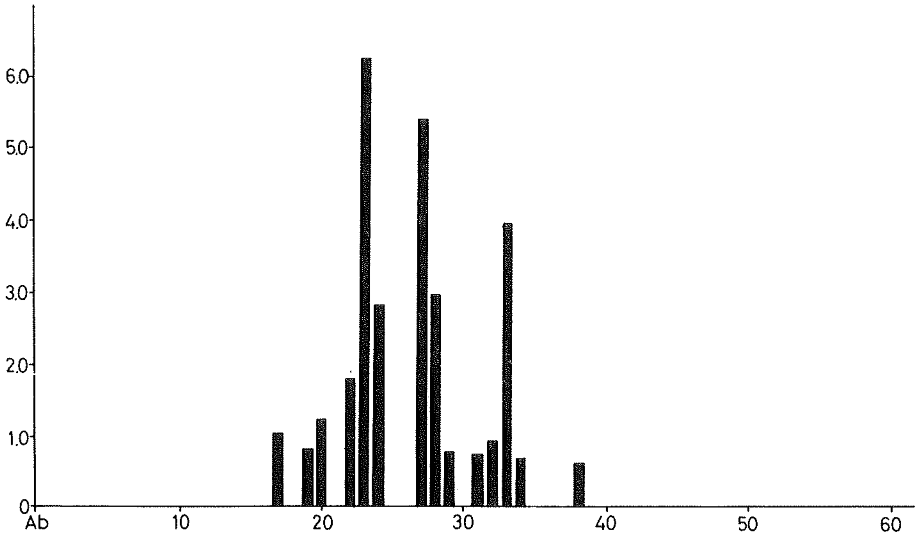

Fig. 9. Diagram representing the high frequency occurence of plagioclasses in the whole lithofacies of the Tenryukyo granite. The height of the histogram at a given composition is the sum of the "degree of concentration" of all curves with a mode at this point.

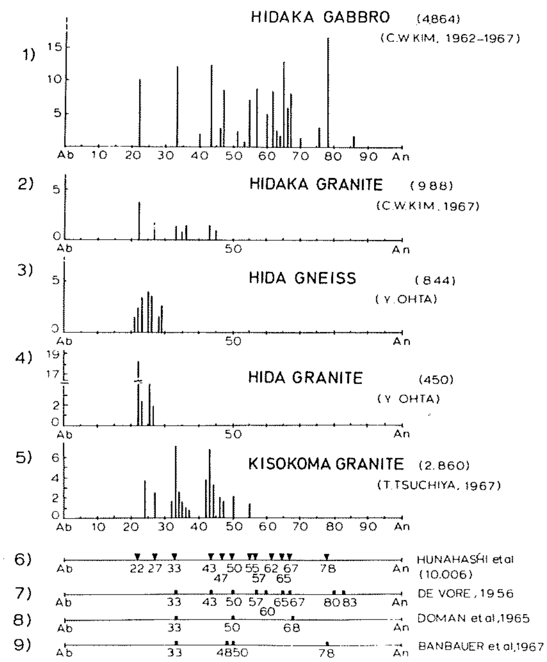

Fig. 10. Diagram representing the high frequency occurrence of plagioclases of certain composition in several kinds of plutonic and metamorphic rocks and their correlation with crystallographic results (after Hunahashi, Kim, Ohta and Tsuchiya, 1968).

Although the phenomenon of order-disorder transition in feldspar has been known for four decades (BARTH, 1934), the studies from crystallographic view points are now under the way. Therefore, the whole aspects and the factors which will control the ordering degree have many things to be solved. It is said, however, the main factor to determine ordering degree is temperature(BUERGER, 1948). The interpretation has derived from the evidences that synthetic plagioclases had disordered character in early days of experiments and ordered one turn to disordered state by heat treatment. Then, it has been believed that under high temperature disordered plagioclases are formed and *vice versa*. But the temperature, as a main factor, needs to be considered more strictly, because, for example, ordered plagioclases were synthesized in the recent experiments.

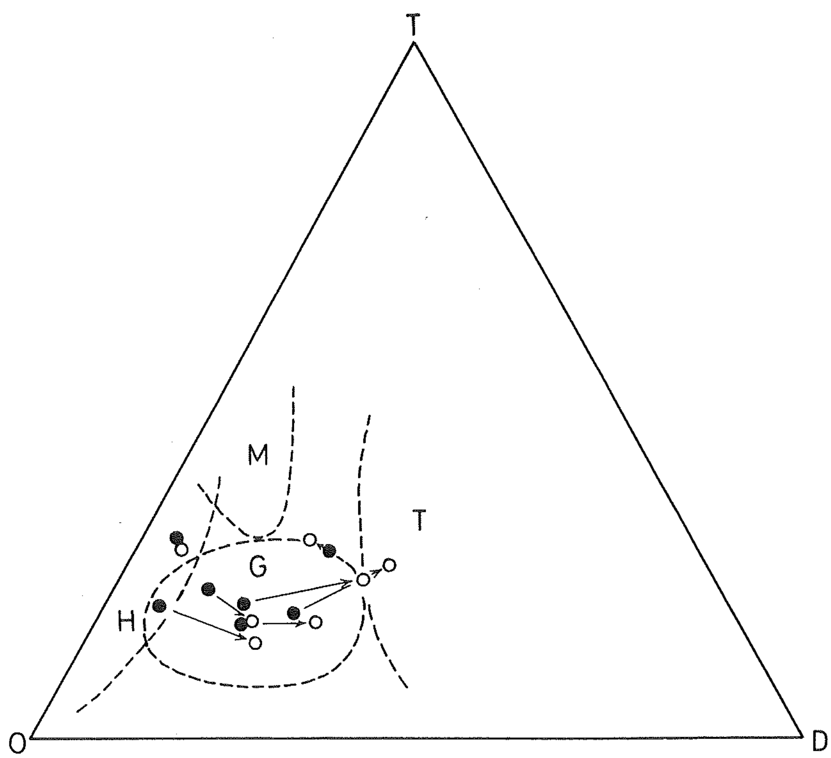

Fig. 11. O:T:D ratio diagram summarized briefly from different kinds of igneous and metamorphic rocks from Hokkaido and the Ryoke metamorphic belt.
M . . . . gneiss migmatite series
G . . . . granite series
T . . . . Tertiary holocrystalline rock series
H . . . . Himalayan schist and gneiss series
The superposed dotts are the O:T:D ratios of the Tenryukyo granite. The data of this diagram are obtained by Kim and Tsuchiya.

The writer believes that the rate of temperature to bring a crystallized plagioclase at normal temperature will control its ordering degree. If a rock formed under rapid decrease of temperature, constituent plagioclases may show disordered character and *vice versa*. The facts that the plagioclases formed in later stage show more disordered state and the mantle takes more disordered ratio than that of the core in every lithofacies except for the agmatite, can be explained reasonably by the above-mentioned interpretation. The littleness of variation of ratios from the core to the mantle of the Tenryukyo granite except for the gneissose granite II, compared to the other granitic rocks, may indicate the temperature did not decrease so rapidly.

The summarized diagram for the variation of O:T:D: ratio estimated by KIM and the writer is illustrated in Figure 11 superposing the ratios in the results of this paper. The plotted positions of them can be grouped in accordance with the origin and rock species; namely gneiss-migmatete series, granite series and the Tertiary holocrystalline rock series. Some noteworthy specimens, polymetamorphosed Himalayan schist and gneiss examined by KIM (unpublished) are plotted along the O—T side field in the diagram. It is a problem for further consideration. Though grouping and interpretation of the projections on the diagram are unsettled, some successive relationships may be recognizable in it.

The projections of the Tenryukyo granite are chained as a successive series in the field of the granite series, and the most disordered projection attains the field of the Tertiary holocrystalline rock series.

Whether the most ordered projection continues to the gneiss-migmatite series or the polymetamorphosed rock series is a problem for further discussion.

V. Summary and conclusion

The Tenryukyo granite was formed in the early phase of the Ryoke plutonism as a synkinematic granite. The variation of lithofacies from migmatite to coarse hornblende biotite granite shows itself the course of granitization. Most part of the massif has been suffered intense effects of potash feldspar blastase after the formation of original granite. Texture of the original granite was altered and metasomatic recrystallization of feldspars was carried on. There reconstruction and recrystallization have resulted in the formation of characteristic feature of potash feldspar porphyritic granite with intense gneissose structure of the Tenryukyo granite. Although detailed investigation on this problem will be mentioned in another paper, the reconstruction ought to be considered from its intensity and its scale as a new granitization. The potash feldspar blastase is considered as the product of potassium metasomatism yielded through its process.

On the other hand, plagioclases in the Tenryukyo granite exhibit a wide range of compositional distribution in each lithofacies. Even within one thin section the co-existing plagioclases have An-content ranging from An_{10} to An_{45}. This distribution is not arbitrary, but has a definite mode of An frequency within its distribution range. The variation of An-contents of modes among lithofacies is not so remarkable, but minor differences, the variation of subsidiary modes, can be traced in the sequence of lithofacies formation. That is, some subsidiary modes may be seen in the An frequency curves of the granitic migmatites and the gneissose granites. They signify a sensitive indication of the beginning of a new trend, the formation of new lithofacies.

An-contents of modes and subsidiary modes are summarized in the histogram of "degree of concentration". The histogram indicates the following compositions of plagioclases have been crystallized more readily than others in the granite; An_{23}, An_{27} and An_{33}. These concentrated compositions coincide with those of previously estimated plutonic and metamorphic rocks; 22, 27, 33, 43, 50, 55, 62, and 78 in An% (HUNAHASHI, KIM, OHTA and TSUCHIYA, 1968). Some of these An values may be correlated to the discontinuous points of crystallographic properties of plagioclase series.

Detailed analysis of each frequency curve indicates that the curve is consisted of a number of minor subgroups of plagioclase, each of which shows itself normal distribution curve. The mode of this new curve coincides with mode or subsidiary modes of the original frequency curve which is in fact a composite curve. Then, these subgroups ought to be regarded as being controlled by crystallographic properties of plagioclases. Therefore, the nature of plagioclases under natural circumstances, the variation of An-content and co-existence of different composition in one lithologic unit, may also be concluded as due to their crystallographic properties.

The O:T:D ratio involves in itself some unsettled problems, because the crystallographic aspects of order-disorder state have been investigated on a full-scale since only before the last decade. However, it is evident among lithofacies of the Tenryukyo granite that the ordering degree of plagioclases varies in decreasing disordered ratio in order to the sequence of lithofacies formation. The evidence is quite identical with those of the Kisokoma granodiorite and the Ainuma-nai Tertiary holocrystalline rock. If, as the most crystallographers believe, a disordered plagioclase was crystallized at high temperature, the evidences should indicate that the temperature in these granites had increased in later stage of crystallization. But this conclusion contradicts to geological evidences. The writer believes that the ordering degree is controlled mainly by cooling rate of temperature.

Therefore, the concerned fact in the Tenryukyo granite tells that the cooling rate of temperature must have been more great in the formations of rocks in later phase than in early phase. And the small variation of its ratios compared to those of the Kisokoma gradoniorite and the Ainuma-nai Tertiary holocrystalline rock may indicate that the cooling rate of temperature not so rapid as in the others.

Notably disordered ratios of plagioclases in the gneissose granite II, especially in their mantles, have been caused by potash feldspar blastase. Existence of some convergent projections in about ordering indices of 30, 50 and 70 is newly presented. It is a problem for further discussion whether the order-disorder transition in plagioclase series is gradual as has been so believed, or some readily converged points exist in intermediate indices.

The writer believes that a rock is formed as a mixed product of materials reacting under variable physico-chemical conditions, in opposition to the current view that a rock is the product of a certain chemical equilibrium established under constant physico-chemical conditions. Revealed heterogeneity of plagioclases may support the writer's opinion.

Statistical methods have been used to determine the factors primarily responsible for the heterogeneity of plagioclases. That the differences in relative stability of the various plagioclase compositions — resulted from crystallographic discontinuities or abrupt change in the properties of plagioclase series — seems to be the most important factor.

Precise knowledge for other rock-forming minerals is needed for defining the factors responsible for rock-forming process.

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