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On the Gabbro of the Cape of Muroto, Shikoku Island, Japan. Part 2

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Abstract

Judging from the properties of the intraformationally intruded diabase and of the various rock-facies formed by the differentiation, the intruded magma, or the liquid separated from the phenocrysts in the earliest stage of the crystallization after its intrusion probably had the chemical composition corresponding approximately to a point on the Mg-rich part of the En–Fs line on the $MgO–FeO–SiO_2$ diagram.

From the magma is formed olivine-bearing diabase with granophyric patch in the marginal part and olivine-two pyroxene-gabbro with biotite-hornblende-dioritic part in the inner normal part. These differentiates are identified in each rock section. No differentiate, except pegmatite-facies, exists separated and in large mass.

Judging from the variation curve acquired by plotting the composition of various rocks, the rocks formed in the inner part seem to be weakly Fe-richer and strongly felsic component-richer than those formed in the outer part. This weak Fe-enrichment of the inner rocks is mainly subject to the fractional crystallizatian of the minerals in the earlier stage (e. g. olivine, the monoclinic pyroxene of the earlier stage, etc. and iron oxide in the earlier stage) which occupy the greater part of the colored constituents in each rock, as the minerals in the later stage (e. g. rhombic pyroxene, hornblende, biotite, etc., and iron oxide in the later stage) are found only in small quantities in all the rocks. Judging from the microscopical investigation, the residual solution by the process of oxidation gradually becomes Fe''-poor, although the solution concentrated weakly in Fe in the earlier stage by the fractional crystallization, and relatively felsic component-rich, during the course from the crystallization of the olivine to that of biotite. During that course, there are successive precipitation of magnetite due to the oxidation of the liquid (the formation of the calc-alkaline suite).

Considering the mineralogical paragenesis, the temperature of the crystallization of the augite and hypersthene is lower than that of the basic intrusives of *Kratogen.* As the crystallization of olivine, also, is considered to be succeeded by that of augite, at least, in the inner part-members of the normal facies, according to the microscopical investigation, the temperature of the crystallization of the magma, on the whole, seems to have been lowered. The lowering of the crystallization temperature should be mainly due to the effect of the volatile substances in the magma. Besides this effect, there are some proofs of the volatile substances acting on the magma: the oxidation of Fe and the development of the pegmatite facies much more remarkable

than that of the gabbros in *Kratogen.*

In the earlier stage of the formation of the pegmatite formed under a lower temperature than that of the normal gabbro, olivine, augite and rhombic pyroxene crystallize successively (the formation of the coarse-grained melanocrate), but by the gradual prevailing of oxidation (the voluminous precipitation of the magnetite) and by the saturation in SiO_2 in the magma, the olivine ceases to crystallize and the En- and Wo-richer augite crystallizes and then amphibole appears, excluding the crystallization of rhombic pyroxene.

By the differentiation of the Muroto magma, having the properties mentioned above, the calc-alkaline suite were formed. Judging from the properties of the mineral crystallization, the influences of the contamination of sialic materials upon the magmatic differentiation probably were weak.

A. The magmatic differentiation

(1) On the intruded magma

Among the intraformationally injected diabases, those of comparatively narrow width (0.2m. ca.), which have aphanitic and microdoleritic texture, consist of the microlites of plagioclase in the form of skeletal crystal (Pl. II), two pyroxenes, brownish green hornblende and little biotite, but colored mineral is often represented by hornblende only. Very rarely there are phenocrysts of plagioclase and olivine, and a few of the plagioclase phenocrysts show reverse zoning in their core-part, and they resemble in their characters the reversely zoned plagioclase* which rarely appears in the fine-grained gabbro. On the other hand, the marginal part of this diabase of comparatively broad width (0.5m. ca.) closely resembles the above written narrow diabase, but in its inner part olivine gradually increases its amount, and the skeletals disappear. This inner part resembles the marginal chilled diabase of the main mass with coarse-grained doleritic texture in its mineralogical character and texure. The inner portion of the interformationally intruded diabase is regarded as the product by rather slow cooling, the composition of which is nearer to that of the marginal portion of the main mass. Judging from its mineral paragenesis, the intraformationally intruded diabase underwent a certain degree of differentiation, though not complete: therefore, it can hardly be said to be a quenched phase that completely represents the intruded magma, though various characters of this rock are in common all over this region.**

Considering, however, from the geological conditions and the texture, the chemical composition and other properties of the intraformationally intruded and chilled diabase with the narrow width are the most important clues to clarify the properties of intruded magma, even though the diabase might have solidified under the influence of Soret action and the oxidation through the escape of the volatile constituents into the country rock. This diabase is transitionally related

* The reversely zoned crystal is very small in quantity among the feldspar ones.

** But it should be considered to resemble closely the intruded magma in its chemical composition, juding from the following descriptions.

TABLE 1 Original magma, chilled phase, chilled basalt of various basic rocks, and the intraformationally intruded diabase of Muroto gabbro.

	1	2	3	4	5	6
SiO_2	48.2	48.8	48.7	51.9	53.3	52.2
TiO_2	1.4	0.6	0.6	1.1	0.6	1.3
Al_2O_3	19.1	16.2	16.5	15.1	16.4	15.4
Fe_2O_3	1.2	3.6	3.4	1.0	0.5	1.6
FeO	8.7	9.4	8.4	9.7	8.3	8.7
MnO	0.1	0.3	0.3	0.3	0.2	0.1
MgO	7.9	8.1	8.2	8.2	6.7	7.3
CaO	10.7	10.1	12.3	9.7	11.5	10.0
N_2O	2.4	2.2	1.2	1.8	1.6	2.4
K_2O	0.2	0.1	0.2	0.7	0.9	0.8
P_2O_5	0.1	0.2	0.1	0.1	—	0.2

1........Average Skaergaard chilled phase.
2........Muroto diabase.
3........Original magma of Pigeonitic rock series.
4........Average Karroo chilled basalt.
5........Average Tasmanian chilled basalt.
6........Average Palisade chilled basalt.

to the marginal diabase of the main body, with the exception of the example of the mode of occurrence mentioned in Part 1.

The chemical composition of this diabase is shown in Table 1, together with that of the basic intrusives in other regions.

a) This diabase of Muroto gabbro is richer in SiO_2 than the original magma of Skaergaard gabbro[1)], but is poorer than the average chilled basalt of Karroo-[2)], Tasmania-[3)], and Palisade-[4)] gabbro, or diabase, and rather closely resembles the original magma[5)] of the volcanic rock "the pigeonitic rock series," but is richer in alkalies and Fe. The points representing the chemical compositions of all those magmas, including that of the Muroto diabase, are arranged in a line on the Q-Fo-Fa diagram and in the limited area on the A-F-M diagram, and so the significant deviation of the chemical properties from those magmas and the Muroto diabase can not be observed clearly.

b) The diabase has plenty of Fe, and it is as notable in oxidation as the original magma of the pigeonitic rock series.

c) Al_2O_3 is not abundant.

d) When the colored essential components, excluding accessories, calculated by Tomita's[6] method is plotted to the Q-Fo-Fa diagram, the Muroto diabase comes on the Mg-richer part of the En-Fs line and if the Muroto magma closely resembles the diabase in respect to the chemical composition, olivine should naturally crystallize in fractional crystallization[7] from the magma. This assumption corresponds to the field-fact written above and the microscopical investigation.

e) Not only this diabase, but all the rock species are different from gabbros in *Kratogen* in the fact that there are neither pigeonite, nor oriented plate-, or graphic texture-bearing rhombic pyroxene. This fact shows that the intruded magma crystallized at a lower temperature than the other bodies, as will be mentioned below.

The difference between the intraformationally intruded diabase and the marginal diabase in the main body is that the latter is richer in olivine, though they closely resemble each other in their bulk composition, and the intraformationally intruded diabase seems to have been formed on the top of the intrusion in the nearly quenched state, when the Muroto magma was intruded, and the magmatic part, after undergoing a considerable differentiation in the process of very rapid cooling, formed the marginal diabase. Then the differentiation was gradually carried into the inner part of the body.

(2) Characteristics of the crystallization of ferromagnesian constituents

The olivine is contained in all species except the coarse-grained augite-gabbro (pegmatitic), and is sometimes included in the monoclinic pyroxene and plagioclase in idiomorphic crystal in the fine-grained normal facies of the outer portion of the body, but the shape of olivine in the medium-grained normal facies of the inner portion is affected by that of plagioclase being more euhedral (Pl. II). The granularity of the olivine is generally similar to that of the other co-existing mineral and it develops in the coarse-grained facies like other minerals. The plagioclase is subhedral or euhedral. The monoclinic pyroxene crystallizes ophitically between the plagioclase crystals, and in the medium-, or coarse-grained facies, it does not completely enclose the olivine, and these two come into contact in anhedral form with each other. At least, in the later stage of the inner rock-facies, the olivine shows nearly simultaneous crystallization with the monoclinic pyroxene. The rhombic pyroxene crystallizes sporadically in a portion of the margin of the olivine, especially resorping the latter at the part where the latter touches the plagioclase, and in this part, the zonal formation of the amphiboles (cummingtonitic amphibole → brown hornblende → green hornblende) around the rhombic pyroxene and the crystallization of the biotite are especially conspicuous, and moreover, the change of olivine into talc and serpentine through autometamorphism is frequently seen. Around olivine, completely included in the augite in the fine-grained facies, the rim of rhombic pyroxene is not perceived. The rhombic pyroxene touches the monoclinic pyroxene on a simple boundary. The hornblende often appears on the margin of the pyroxene, and where it touches olivine and rhombic pyroxene, cummingtonite is found as the inner most rim of the zoned amphibole, but where it touches monoclinic pyroxene, there is no cummingtonitic rim. It is one of the characteristics of all the rock species that there is only a little crystallization of the rhombic pyroxene, amphiboles and biotite. The residual liquid in the formation stage of these minerals may have been reduced to a scanty amount. The order of the beginning of the crystallization is olivine, plagioclase, monoclinic pyroxene, rhombic pyroxene, hornblende and biotite, and the relation between olivine and monoclinic pyroxene is of the parallel crystallization. All these minerals are perceivable through the thin section of one handspecimen. Taking into consideration the formation of the Ab-rich zonal structure of the plagioclase and these colored minerals which appear in a section, the differentiation from olivine-gabbro to biotite-hornblende-diorite is regarded to have been carried out in the normal rock-facies. In the normal facies, the quartz never crystallizes, but in the marginal diabase, the granophyre in microscopic vein or patch is sometimes seen in the thin section, and it is limited in this granophyre in the diabase that quartz appears, and this means that the differentiation of the normal facies is in a lower degree than that of the marginal diabase corresponding to the olivine-diabase and granophyre association. This difference of the differentiation-grade was caused by the cooling-velocity of the liquid and the degree of the reaction between the mineral and the liquid, etc..

As the chilled diabase contains a little olivine and plagioclase phenocrysts, the intruded magma had already begun to crystallize at the time when it was injected. The crystallization after the intrusion proceeded from the margin to the interior in the main body, on the whole, under comparatively rapid cooling, so that it is considered that the pyroxene of the inner part, for example, had crystallized at a period when the crystallization of the amphibole went on at the outer part. During the crystallization of olivine and at the beginning of that of monoclinic pyroxene, the magmatic diffusion, the writer thinks, was in a comparatively perfect state, though there was the rearrangement of the diffusion at an intermediate period between the formation of the fine-grained facies and of the medium- —coarse-grained facies (See Part I). However, the rhombic pyroxene, the amphibole and other minerals crystallized, in quite an imperfect condition of the diffusion, from a small amount of liquid, with which were filled the narrow interstices of the minerals crystallized already.

According to the study of Kuno[8], the temperature of the crystallization of the augite and hypersthene of this kind is considered to be about 900°–1000°C, and 200°–300°C lower than that in the dry melt. The crystallization of olivine, as written above, was nearly simultaneous with that of monoclinic pyroxene, at least, in the later stage of the inner rock facies. So it is noticed that the crystallization of these minerals has been done successively without any gap. Therefore, the crystallization of the minerals of the Muroto body, including

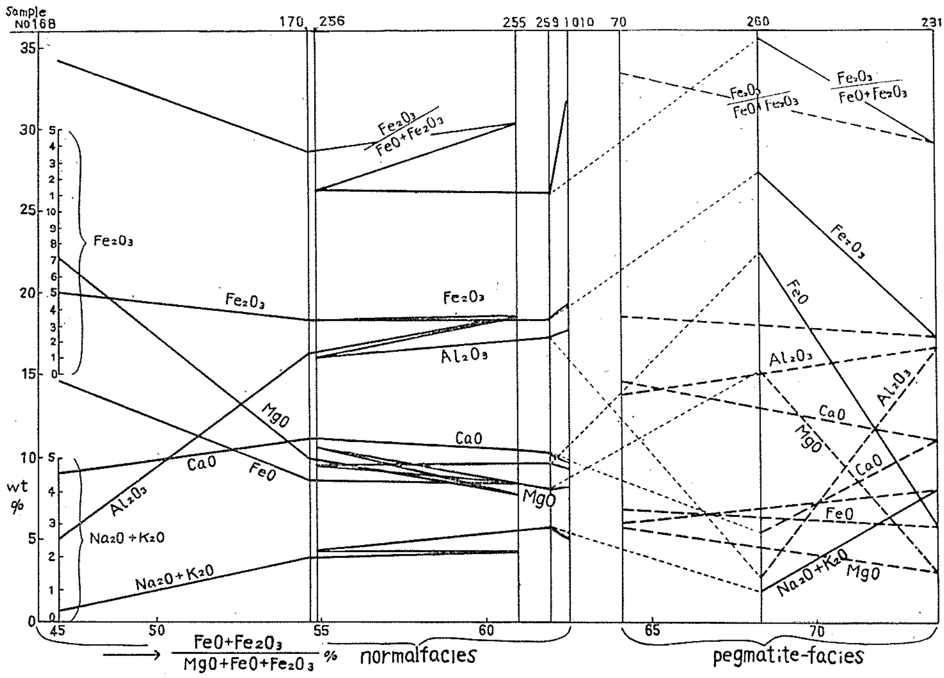

Fig. 1 The variation diagram

olivine, is presumed to have been carried out at a lower temperature than that of the magma in Skaergaard and other regions. Thus the intruded Muroto magma is presumed to be comparatively richer in volatile substances, of which H_2O is especially predominant, compared with the basics of *Kratogen.*

(3) The mutual chemical relation of the facies in the gabbro

The marginal diabase is conspicuous in iron oxidation as in the case of the intraformationally intruded diabase. In the portion, about 1.5m, between the margin of the main body and the first concentration zone of the colored minerals, $FeO+Fe_2O_3/MgO+FeO+Fe_2O_3$, SiO_2 and alkalies decrease, and MgO increases. In the normal rock facies of the inner part, the value of $FeO+Fe_2O_3/MgO+FeO+Fe_2O_3$ generally increases and the value of $Fe_2O_3/FeO+Fe_2O_3$ is variable, though it is generally greater than that of the intraformationally intruded diabase.*

* At the time when the magmatic crystallization reached from the stage of the rapidly cooled fine-grained facies to that of a slowly cooled medium- –coarse-grained facies, magnetite-rich melanocrate patches (the third zone of the concentration of ferromagnesian minerals) are formed, and in this stage some changes of $Fe_2O_3/FeO+Fe_2O_3$ and $FeO+Fe_2O_3/MgO+FeO+Fe_2O_3$, due to the fact that the diffusion in the magma has been brought out in a more perfect degree than before, are seen. The discontinuity of the differentiation course caused by the diffusion can be noticed in the tables and the diagrams (See Part 1).

The small patches rich in iron ore are sporadically detected in the main mass area. This is one of the remarkable evidences of the oxidation of Fe" occurred during the crystallization of the magma even after the intrusion.

TABLE 2. Chemical composition of various rock-facies

A) Sample no.	214	1007	248	168	170	255	256	259	1010	260	231	70
SiO_2	47.58	46.39	46.10	42.05	46.49	46.58	45.26	46.11	45.52	37.22	52.43	50.90
TiO_2	0.82	1.29	1.16	0.51	0.67	0.85	0.57	0.71	0.82	1.09	0.96	0.83
Al_2O_3	15.75	15.26	15.01	4.97	15.94	18.06	15.65	16.92	17.26	2.71	18.11	13.80
Fe_2O_3	3.55	4.30	3.39	4.95	3.37	3.60	3.28	3.31	4.22	12.19	2.34	3.45
FeO	9.18	9.53	9.76	14.50	8.36	8.29	9.21	9.42	9.07	22.10	5.69	6.74
MnO	0.29	0.24	0.21	0.31	0.20	0.36	0.34	0.50	0.35	0.47	0.21	0.20
MgO	7.92	8.36	9.78	21.92	9.74	7.62	10.30	7.82	7.95	15.93	2.97	5.72
CaO	9.88	9.05	9.20	9.05	10.89	10.32	10.72	9.94	9.35	5.33	10.83	14.52
Na_2O	2.17	2.26	2.28	0.61	1.90	2.16	2.11	2.65	2.40	0.75	3.91	2.61
K_2O	0.08	Trace	0.10	0.05	0.04	0.03	0.07	0.19	0.02	0.20	0.06	0.34
P_2O_5	0.20	0.20	0.23	0.12	0.26	0.25	0.20	0.09	0.24	0.17	0.28	0.18
$H_2O(+)$	2.46	2.42	2.32	0.92	2.18	1.91	2.11	2.07	2.21	1.63	2.21	1.30
$H_2O(-)$	0.53	0.53	0.42	0.26	0.39	0.15	0.15	0.39	0.29	0.34	0.19	0.26
Total	100.41	99.83	99.96	100.22	100.43	100.18	99.97	100.12	99.70	100.13	100.19	100.85
$\frac{Fe_2O_3}{FeO+Fe_2O_3}$	27.87	31.09	25.79	34.15	28.71	30.28	26.27	26.00	31.75	35.55	29.11	33.89
$\frac{FeO+Fe_2O_3}{MgO+FeO+Fe_2O_3}$	61.63	62.33	57.35	47.02	54.64	60.94	54.82	61.94	62.56	68.28	73.63	64.08
B) Norm												
Quartz	—	—	—	—	—	—	—	—	—	—	3.74	1.37
K-felsp.	0.51	—	0.62	0.27	0.22	0.16	0.39	1.11	0.11	1.17	0.33	2.00
Na-felsp.	18.87	19.71	19.87	5.24	16.41	18.61	18.25	22.81	20.87	6.45	33.82	22.23
Ca-felsp.	33.85	32.51	31.29	10.79	35.63	40.27	33.85	34.57	37.33	3.54	32.43	25.14
Diop. Wo	6.28	5.19	5.89	14.07	7.44	4.28	8.02	6.41	3.56	9.30	8.61	19.28
Diop. En	3.60	3.09	3 64	9.28	4.69	2.53	4.91	3.55	2.13	5.13	4.26	11.44
Diop. Fs	2.40	1.84	1.89	3.80	2.29	1.54	2.67	2 61	1.35	3.83	4.19	6.86
Hyp. En	15.39	16.03	11.04	3.81	11.60	12.34	3.77	3.30	10.06	10.76	3.31	2.90
Hyp. Fs	10.24	9.47	5.72	1.55	5.65	7.49	2.04	2.43	6.33	8.02	3.29	1.72
Oliv. Fo	0.87	1.66	7.26	29.45	5.93	3.14	12.30	9.17	5.73	17.18	—	—
Oliv. Fa	0.63	1.06	4.93	13.24	3.21	2.08	7.36	7.44	3.97	14.14	—	—
Magnetite	5.28	6.43	5.07	7.24	4.98	5.33	4.86	4.91	6.30	18.01	3.47	5.04
Ilmenite	1.60	2.54	2.26	0.97	1.29	1.16	1.11	1.46	1.60	2.08	1.87	1.60
Apatite	0.51	0.51	0.54	0.31	0.64	0.60	0.47	0.20	0 60	0.41	0.67	0.44

Table 2 The chemical compositions of the various rocks of the Muroto Gabbro

sample no. 214 the intraformationally intruded diabase

〃 no. 1007 (the lower margin) } the marginal diabase

〃 no. 248 (the upper margin)

〃 no. 170 } the fine-grained normal facies (two pyroxene-olivine-gabbro)

〃 no. 255 (no. 170....the 1st concentration zone of the colored constituents)

〃 no. 256 }

〃 no. 259 } the medium-grained normal facies (two pyroxene-olivine-gabbro)

〃 no. 1010 }

〃 no. 260 the coarse-grained melanocrate (pegmatitic: in the innermost pegmatite)

〃 no. 231 the coarse-grained augite-gabbro (pegmatitic: associating with no. 259 and no. 260)

〃 no. 70 the coarse-grained augite-gabbro (in the uppermost pegmatite)

〃 no. 170→ } (Sampled regularly from the lower margin to the centre)

〃 no. 1010

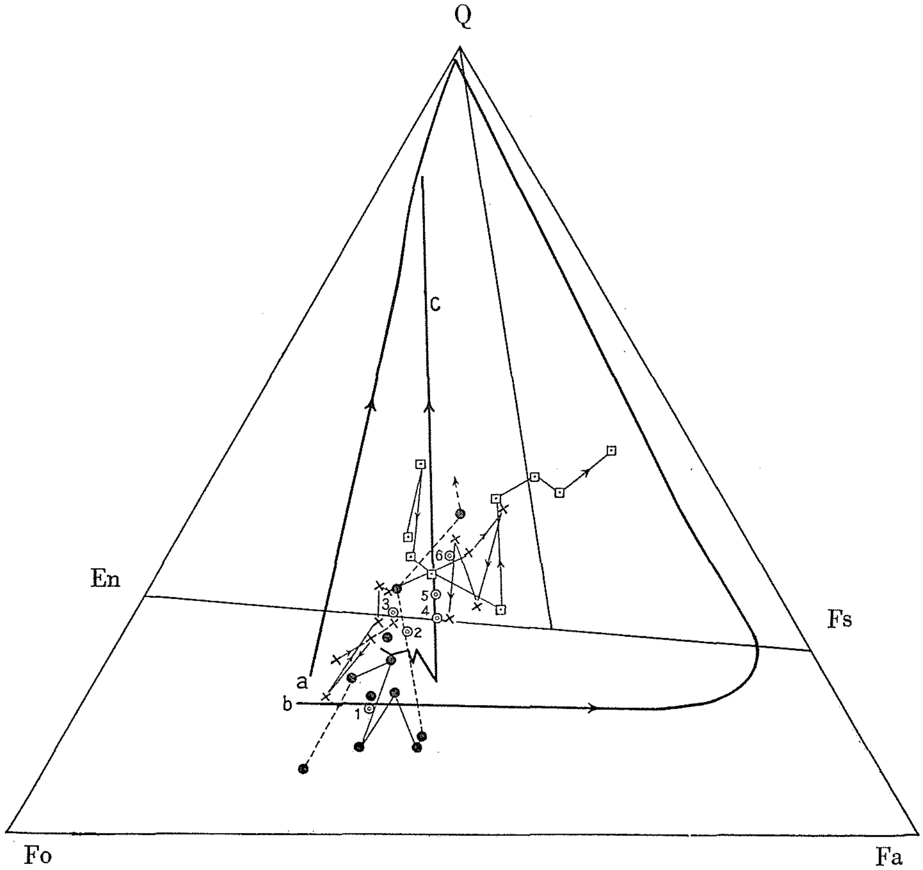

Fig. 2 Q·Fo·Fa diagram Line a: the calc-alkaline suite Line b: the trend of Skareaard magma Line c: the trend of Greenstone magma Black circle: the Muroto facies Square: Tasmanian dolerite (Wellington sill) Cross: Palisade sill (George Washington Bridge section) Double circle: 1. average Skaergaard chilled phase 2. Muroto diabase 3. original magma of pegeonitic rock series 3. average Palisade chilled basalt 5. average Karroo chilled basalt 6. average Tasmanian chilled basalt

As can be judged by the norm, the A-F-M and other diagrams, during the formation of the normal facies, the Fe"-enrichment is observed, though much weaker than those of other gabbros in *Kratogen*. The following may be the reason. The chemical composition of an analysed hand-specimen is the total chemical composition of various facies contained in it, consisting of the rocks facies from gabbro to more acid rock. The weak Fe-enrichment shown in the A-F-M diagram, etc., does not mean the Fe-enrichment of the residual liquid of the successive stage in the course of the differentiation. The greater part of the handspecimen consists of the minerals in the earlier stage (olivine, augite, basic core of plagioclase, etc. in general). So the weak Fe-enrichment in the diagram means the Fe-enrichment in the ferromagnesian minerals together with the crystallization of the iron ore in the earlier stage: the chemical composition of olivine and augite crystallized in the earlier stage, gradually became somewhat Fe-rich, but due to the increasing precipitation of the iron ore (titanomagnetite), the residual solution, afterward, became gradually poor in Fe and relatively rich in alkalies in the latest stage: the residual solution changes its composition into the direction of the average line of the calc-alkaline suite. So the diorite phase in a handspecimen was formed from the residual solution. In a word, one type of the calc-alkaline suite, at least, was formed by the differentiation of the Muroto magma. Therefore, the variation curve acquired from the chemical compositions of the various facies of the Muroto gabbro does not have

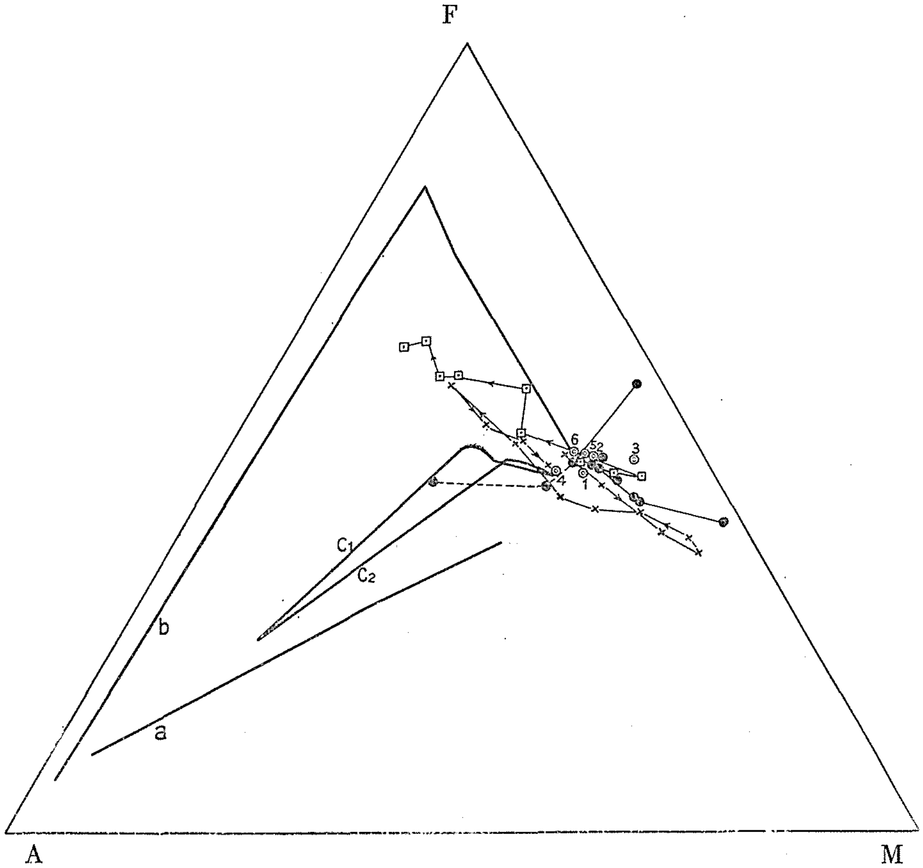

Fig. 3 A·F·M diagram (F: FeO only) Legend: the same as in Fig. 2

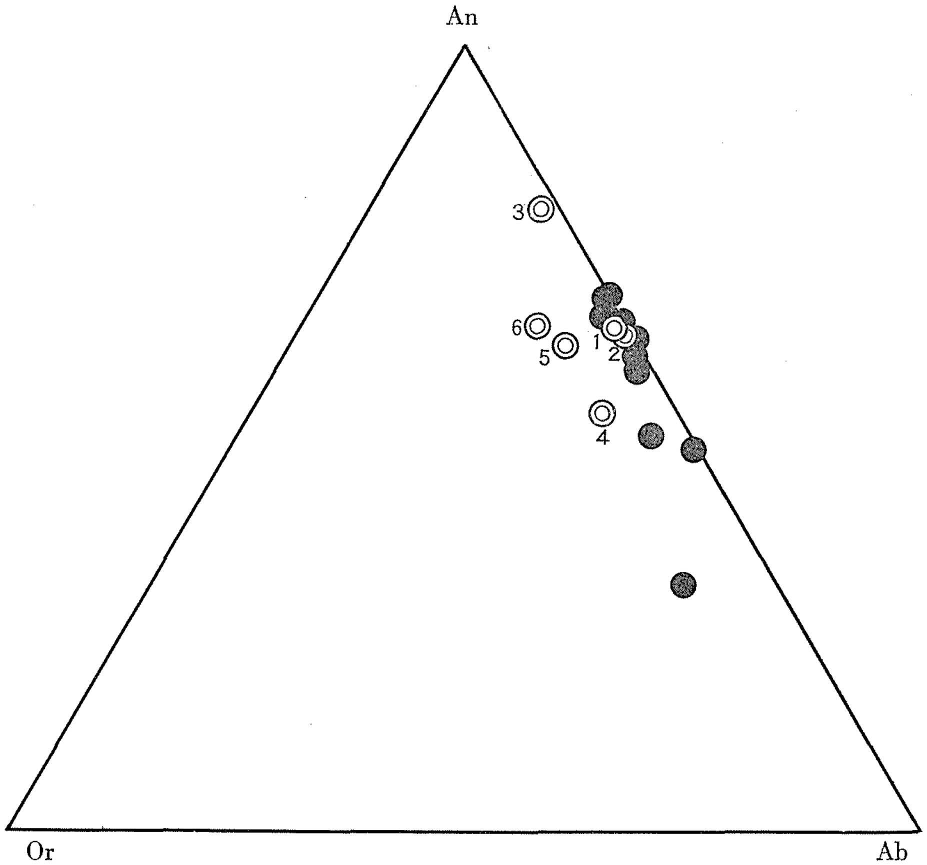

Fig. 4 Or·Ab·An diagram black circle: Muroto rocks. double circle: the same as in Fig. 2 and Fig. 3.

the same meaning as the curves acquired from of other intrusives.* In short, during the period of the crystallization of olivine, including the earlier stage of that of the monoclinic pyroxene, the liquid changes its composition into the direction of weak Fe-enrichment (although felsic components-enrichment was rather strong), and then apparently into the direction of the felsic mineral component-enrichment.**

The effect of the oxidation of iron (the formation of iron ore) is conspicuous upon the magma, and this effect brought out these changes of the magmatic

* It is shown in Fig. 5 that the Fe-enrichment is inconspicuous in the later stage of crystallization, though the ferromagnesian minerals were concentrated in the earliest stage.

** In the earlier stage, the Fe''-fractionation overcame the oxidation of Fe'', i. e. there was a weak Fe-enrichment in the magma, and gradually, in the later stage, the Fe''-oxidation defeated the Fe''-fractionation, i. e. alkali-fractionation became conspicuous in the residual magma.

composition mentioned above.*

That the intruded magma should be comparatively SiO_2-poor is considered to be the reason why a considerably large amount of olivine is contained in the normal facies. Moreover, some amount of olivine phenocryst might have been contained in the intruded magma already at the time of the intrusion, together with the crystallization after the intrusion. If the intruded magma had some amount of olivine phenocryst, the intra-formationally intruded diabase, having a very small amount of phenocryst, probably corresponds to the liquid part of the intruded magma which had been separated in the earliest stage of crystallization from the phenocrysts by the crustal movement, e. g. squeezing out.

(4) Oxidation of Iron ore

Judging from the composition of intraformationally intruded diabase and the trend of the rock facies in the A-F-M diagram, the intruded magma is considered to have large $Fe_2O_3 / FeO + Fe_2O_3$, unlike other magmas of the basic intrusives in *Kratogen*; the pegmatitic facies (lower temperature) have large

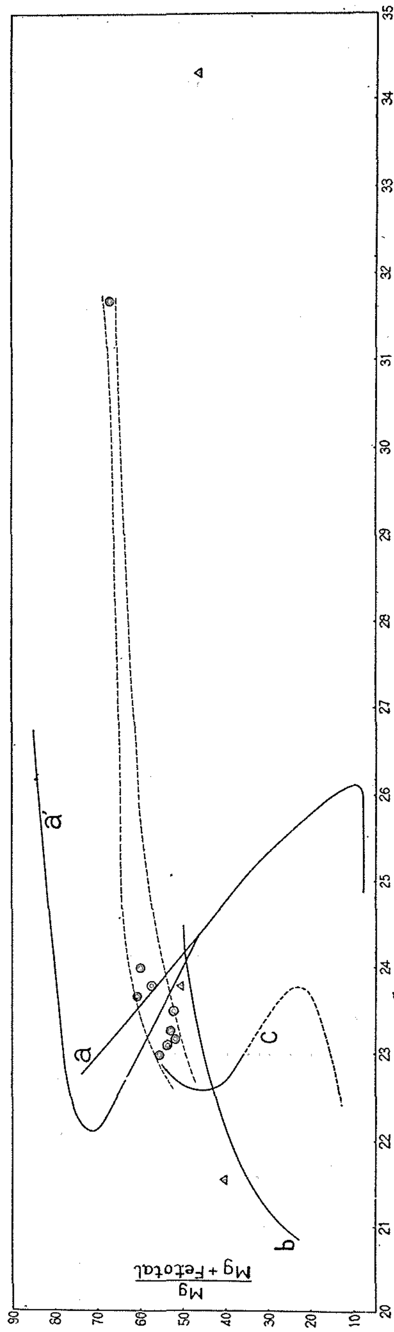

Fig. 5 The Relation between Linkage Factor and $\frac{Mg}{Mg+Fe\ total}$ (28)

a......Skaergaard intrusion a'......Stillwater intrusion b......Calc-alkaline series c......Greenstone flow double circle......the diabase and the normal facies of the Muroto rock triangle......the pegmatitic facies of the Muroto rock

* Together with the oxidation, the contamination must be considered, and it will be treated in the next article.

$Fe_2O_3/FeO+Fe_2O_3$ than the normal facies (higher temperature), and the normal facies also have generally its higher value than the intraformationally intruded diabase consolidated in the earliest stage; these facts show not only that the intruded magma was in the state of oxidation of Fe'' preceding the intrusion, but also that the oxidation went on actively during the crystallization after the intrusion. In the field, the development of the streaks and lenses of titano-magnetite are seen, especially, in the coarser-grained facies, and under the microscope, the crystallization of the iron ore* is observed in various stages: the octahedrons in the olivine, and the vermicular crystals around it, the irregular-shaped in and around the pyroxenes and the amphiboles, and the pseudomorphic replacements after the ferromagnesian minerals.

This oxidation is caused by the H_2O in the magma.[9) 10)] The magma increases its $Fe_2O_3/FeO+Fe_2O_3$ according to the increasing O-oxidizing effect[9)]** during the fall of temperature, and the crystallized mineral was oxidized at the time of the escape of H_2O[10)]: the former oxidation is comparatively significant in the Muroto mass which was consolidated at a comparatively low temperature, but the latter also is considered to have happened, e. g. by the escape of volatiles to the country rocks, in the earlier period of crystallization after the intrusion, when the consolidated crust of the magma was thinner; the country rocks are metamorphosed strongly and broadly by the solution of the hydrothermal character derived from the magma, as mentioned in next article.

The genesis of the coarse-grained facies (the pegmatitic facies): —

The pegmatitic facies in the Muroto mass is voluminous, compared with the basic masses in *Kratogen*. It seems to the writer that this fact is caused by the comparatively high concentration of volatile substances. The coarse-grained melanocrate*** of the first stage of the pegmatitic formation is remarkable in the

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* According to the magnetic experiments by Kawai, the iron ores with magnetism in Muroto rock are the titanomagnetite.

** "Experimental work by Kennedy (1948) has shown that the ferric-ferrous ratio of basaltic magma depends on the temperature of the melt and the partial pressure of O_2 vapour in equilibrium with the melt. The partial pressure of O_2 depends on the total pressure of the volatiles and the degree of dissociation of H_2O, the principal volatile constituent in equilibrium with the magma. The dissociation of H_2O into H_2 and O is proportional to the temperature. Kennedy's (1948) data, ..., indicate that the decrease of dissociation of H_2O for a given temperature drop, with constant total volatile pressure, is more than offset by the increased oxidizing effect of O_2 on iron at the lower temperature, so that the effect of a drop in temperature, the pressure remaining constant, is an increase in the ferric-ferrous ratio of the melt." (Cornwall, 1951, p. 159).

The relations between the volatile pressure and the confining pressure may be even complicated, but the ferric-ferrous ratio of the Muroto magma even after intrusion is considered to increased slowly as the temperature fell.

*** The melanocrate develops in small schlieren or patch in the normal gabbro, and in the pegmatite in contact with the normal gabbro. The melanocratic lens in the normal gabbro of the later stage described in Part 1, is one of this pegmatitic melanocrate, which should, the writer considers, be classified in the pegmatite-formation judging from the recent survey.

oxidation of Fe, owing mainly to the lowering of the temperature of the liquid (See Table 2). By the formation of this melanocrate, the residual liquid becomes poor in FeO and relatively rich in MgO and CaO, as pyroxene components, and SiO_2*. So in the coarse-grained augite-gabbro (the second stage), olivine ceased to crystallize, and Wo- and En-rich augite appears without the occurrence of rhombic pyroxene. Judging from the tentative diagram[11] of the pyroxene En-Fs-Wo, the solution changed its chemical composition from the cotectic line between the two pyroxene areas to the En- and Wo-rich augite area, owing to the strong oxidation of Fe at the time of the formation of the coarse-grained augite-gabbro.

Its mode of occurence makes it evident that the formation of the pegmatite facies was done at a later stage than that of normal rock-facies composing the country rocks of the former. At Tsukimigahama, several seams of the pegmatite crop out parallel to one another in the comparatively upper portion of the main mass. These seams do not seem to have been formed simultaneously: the facies of the upper level have lower value of FeO in their augites, and smaller $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$ in their bulk compositions than the facies of the lower level (approaching the centre part of the main mass). During the consolidation of the normal gabbro, the volatile components, which boiled out from the consolidated portion of the lower part in the mass, concentrated at the upper margin of the liquid part not solidified yet which had contact with the already solidified normal gabbro of the upper part of the sill, and due to the concentration of the volatiles that portion was a little later in consolidation than the country rocks. This process was repeated and these pegmatites were formed. Therefore the rock in the centre part of the sill is thought to be of a later period than the rock of upper horizon. One of their characteristics is that the pegmatites are Ab-rich in plagioclase-composition and large in $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$ and $Fe_2O_3/FeO+Fe_2O_3$, compared with the mother rock. Fe and alkalies, perhaps, have been carried, by the volatiles, to concentrate there. The pegmatite facies of Muroto resemble those of the basic intrusives in *Kratogen*[12], but the former is much greater in volume and is generally Fe''-poorer than the latter.

It is interesting that the aegirin-augitic rim rarely develops, having dark green color and a little higher index than the core augite, at the portion where augite contacts with magnetite, in the coarse-grained melanocrate. Moreover, the patch consisting of the oligoclase and the hastingsitic rim* -bearing hornblende, is rarely observed in the coarse-grained augite-gabbro. These mean the development of the strong alkali fractionation in limited portion of the residual solution.

(5) The contamination of the magma

In all the intraformationally intruded diabase and various facies, there is the

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* In the melanocrate, the crystallization of olivine and monoclinic pyroxene is nearly simultaneous and afterward the rhombic pyroxene appears.

** This rim of the hornblende is infrequently noticeable in the normal gabbro.

paragenesis of the comparatively lower temperature, and from this fact, it would be considered that the contamination worked on this magma.

a) Among the plagioclase crystals contained in the intraformationally intruded diabase, the marginal diabase and the fine-grained gabbro, the crystals* having reversely zoned structure in the core** are perceived (Part I, Fig. 2), though very few in number.

b) Very rarely the plagioclase with xenolithic core mottled with extra-fine-grained minerals, is perceived.

These facts observed by the writer seem to have connection with the contamination, but in the field, there are no xenolith and no other evidence of the contamination visible to the naked eye. The igneous body and the country sediments are in contact with each other in a comparatively simple manner. In the country rock, sericite, albite, epidote and rarely biotite crystallize by the hydrothermal metamorphism, and at the time of the intrusion, minerals of the higher grade thermal metamorphism, besides these minerals, may have appeared, but those are not perceivable now : the contact metamorphism of the higher grade might have been camouflaged by the retrogressive metamorphism.

As made clear in the above description, these evidences of the contamination are not commonly perceived in a mineral species, but are noticed rarely and weakly in a few of the early formed crystals in a mineral species. This fact indicates that the contamination is not the absolute element which controlled the differentiation of the magma. It is presumed that the contamination may have happened in a portion of the magma generated in the deeper zone, e. g. near the margin of the magma in contact with the country rock, and though this contaminated portion diffused all over the liquid, it did not greatly change the magmatic composition, because the quantity of the contaminating sialic materials was small***.

As was seen, the contamination of the sialic materials occurred without doubt, but the contamination took place rather weakly before the intrusion.****

Out of the magma differentiated and contaminated, a part of the magma seems to have been separated by orogenic movements, e. g. by squeezing out, and intruded into Muroto area : therefore, judging from the mineral paragenesis, the crystallization temperature of the separated and intruded magma is considered to

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* The description of the reversely zoned crystals crystallized by the change of the diffusion of the magma after the intrusion in Part I should be revised, because such crystals are very rare and are observed only in the earlier rock-facies.

** By the contamination, the reaction is displaced to the right in the following equation.

$$CaO\cdot(Mg, Fe)O\cdot 2SiO_2 + Al_2O_3 + SiO_2 = CaO\cdot Al_2O_3\cdot 2SiO_2 + (Fe, Mg)O\cdot SiO_2$$

*** The plagioclase with the reversely zoned structure formed by the contamination, may have migrated all over the liquid. Also in this portion, some rhombic pyroxene have been formed, but the liquid composition after the contamination may not have been able to stabilize it, and it might have been dissolved again.

**** The contamination after the intrusion is inconspicuous.

have already been lowered and this probably has been caused by the volatile substances in the magma.

The Muroto magma might have absorbed the volatile constituents in the course of its intrusion to a certain degree and it, together with the original volatiles, might have caused the oxidation in the magma and prevented the normal differentiation of the magma seen in the case of the magma in *Kratogen*. The concentration of the volatiles may have been, on the other hand, the cause of the pegmatite formation of a large scale, etc.*.

B. The comparison between the Muroto rock and other similar rocks

As written above, the Muroto rock is different from the gabbros in *Kratogen* in its mineral assemblage and in the course of differentiation: especially it must be noticed that from the Muroto magma, the calc-alkaline suite are formed. In this respect, the Muroto gabbro is more alike to the basaltic lava[13) 4)] of the Keweenawan Series, performing the differentiation in situ, than the allied rocks of other regions, but the Muroto gabbro is a little more alike to the calc-alkaline suite than the lava is: the lava was formed by the fractional crystallization of its magma and the oxidation by H_2O contained in it, but it is different from the Muroto rock in the respects that it has no evidence of contamination and that it is, perhaps, formed by the crystallization at a higher temperature, because, judging from the descripition, it is considered to contain pigeonite and no hornblende, biotite etc., except in its pegmatitic and granitic phase. It is, the writer considers, of the hydrous magma type with the lowered crystallization-temperatures, but the temperatures are higher than those of the Muroto magma.

In Japan, the basic plutonites have been studied, but generally the details are not yet made clear. Presumably they are generally of the lower temperature crystallization, judging from their descriptions, though difficult to say so decisively. The detailed comparison between these rocks and the Muroto rocks from the petrological standpoint must depend on future studies, but it seems that the influence of sialic materials upon the Muroto magma, judging from the mineral paragenesis, probably is weaker than upon the other members.

There have been various studies on the origin of the calc-alkaline suite, and Wager and Deer[15)] considered that the calc-alkaline series of igneous rocks are, in the main, the result of the mixing of basic and acid material, and Edwards[16)] said that the great part of calc-alkaline rock can have arisen only by the assimilation by tholeiitic magma of large quantities of sialic materials, coupled with crystallization differentiation in subjacent chambers. Walker and Poldervaart[17)] considered that the calc-alkaline suite may be produced by fractionation of

* The pegmatitic facies occupy 25 vol % of the whole rock body.

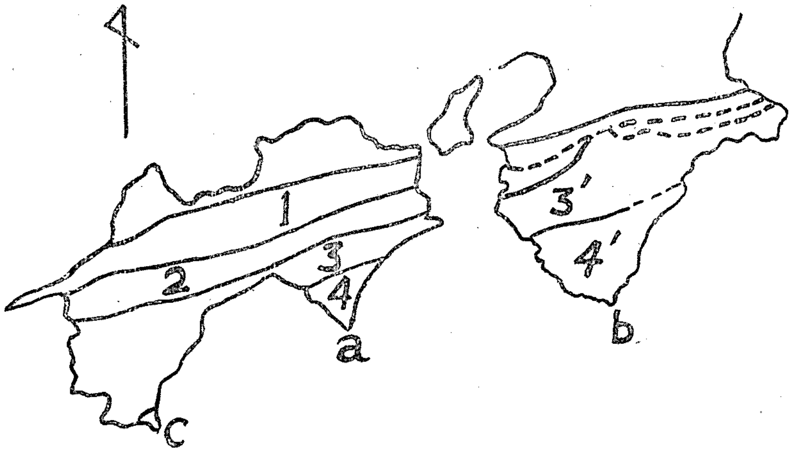

Fig. 6 The Zonal Arrangement of the Outer Zone of West Japan 1....Nagatoro Zone 2....Chichibu Zone 3....Shimantogawa Zone 3′....Hidaka Zone 4....Nakamura Zone 4′....Muro Zone a....Cape of Muroto b....Cape of Shionomisaki c....Cape of Ashizurizaki

basaltic magma, though they do not exclude the possibility of assimilation of sialic material, followed by crystallization-differentiation of the hybrid magma. Kuno[18] classified the basic volcanics of the rock type contaminated with sialic material (the hypersthenic rock series) and those of the rock type differentiated from the primary olivine-tholeiitic magma (the pigeonitic rock series) and he considered the cause of the formation of the former series in the differentiation and the contamination. Cornwall, as said before, sought the origin of the calc-alkaline rock in the differentiation and in the oxidation of basaltic magma by the H_2O included in it. Muroto magma differentiates into calc-alkaline suite at the comparatively low temperature which has been influenced by volatile substances, though the influence of the contamination by sialic materials were weak.

C. The relations with the igneous intrusives of the outer zone of Shikoku Island.*

In the north of the Outer Belt of Shikoku Island, mainly Nagatoro metamorphic zone, there are intrusion of many ultrabasic and basic rocks such as dunite, serpentine, gabbro, diabase, etc., zonally arranged. According to Kobayashi,[19] the Nagatoro metamorphism of the Sakawa orogenic cycle in the periods arounds the Jurassic Period was accompanied by these intrusions, but according to Kojima, who investigated on the supposition that the movements of the

* The volcanic rocks are not described here.

Akiyoshi orogenic cycle, pre-Sakawa cycle, of the Inner Zone have influence upon the Outer Zone, these intrusions are considered to have been the syntectic action with the Sambagawa metamorphism, which was genetically related to the southerly upthrusting movement* of the Ryoke *Kratogen*[20] and the successive Mikabu tectonic Zone-formation.

There are also the intrusions of the basic rocks in the Chichibu zone which runs parallel to the former zone and lies to the south of it, the typical intrusion being Yokokura intrusive** rocks.[19] It has various species: plutonic and hypabyssal rocks with acidic or basic character, among which diabase and serpentine often develop along the tectonic line, and are supposed to have connection with those in the Nagatoro zone. All these rocks do not differentiate in situ, but seems to occur as masses separated from one another.

To the south of the Chichibu Zone, there lie the Shimantogawa, and Nakamura[21] zones which were successively formed, as the position of the above mentioned orogenesis moved southward, and consist of the geosynclinal sediments. The Nakamura geosyncline was formed during the late Cretaceous—Palaeogene, and the folding of the Nakamura area of the middle Tertiary is, perhaps, accompanied by the intrusion of Muroto gabbro, and at this period, the intrusion of many granitic rocks are comparatively large in their scales, though not batholithic, but the occurrence of the basic rock is very few, a conspicuous example of which is probably the Shionomisaki gabbro at the southern end of Honshu, with the exception of the Muroto gabbro. Generally speaking, the granitic rocks are stock-like or plutone-like, but the basic ones occur as sill in the modes of occurrence.

The Shionomisaki gabbro exists in the Muro Zone[22] geologically correlated to the Nakamura Zone, and by its mode of occurrence, the following geological conclusions[23][24] are reached: the gabbro was intruded into Shimozato Series as a sill, and then the granite-porphyry was injected between them. These intrusions probably took part in the period of the folding of the Shimozato Series. The two igneous rocks seem to have touched each other in the period of intrusion, because several diabase dykes, which have genetical relation with the main gabbro, is intruded into granite-prophyry. This gabbro differentiates in situ, like that of Muroto, which consists of hornblende-olivine-gabbro, hornblende-two pyroxene-gabbro, and hornblende-gabbro-porphyrite, etc., and it is, moreover, assimilated by the granite-porphyry magma. Judging from the mineral paragenesis and the relative amounts of various minerals, the properties of the gabbro magma and the mechanism of the differentiation are similar to those of Muroto gabbro.***

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* This occurred as the later act of the late Palaeozoic—early Mesozoic orogenesis.

** The Yokokura igneous bodies, Kobayashi says, were injected after Besshi intrusives, i. e. the plutonic types of the Nagatoro Zone.

*** The study of the precise age-relation between the two gabbros should be carried out in the future.

Moreover, in the granitic rock of Ashizurizaki at the southwest point of Shikoku Island, being considered to be an intrusive rock of the nearly same period as the rocks of Shionomisaki and Muroto, gabbroic xenolith is perceived.[25]

Judging from a recent study,[26] the granite-porphyry of Shionomisaki may belong to the same group as the Kumano- and Omine-acid rocks.

The study of the genetical relation between these acid rocks and the basic rocks is to be expected in the future, but it is an interesting fact that by the study of the gravity anomaly,* the concealment of some basic rock was assumed to underlie the area in which Shionomisaki gabbro and Kumano- and Omine-acid rocks develop.

As written above, in each area of the orogenesis which has successively moved southward in the Outer Zone, there are the intrusions of the basic rocks, and the injection of the Muroto gabbro is, probably, accompanied by the folding of the Tertiary age, and therefore, is obviously different from the basic intrusives in the Nagatoro zone from the geological standpoint.

These basic rocks have, the writer consideres, something in common with each other as the basic intrusive in *Orogen*, e. g. the influence of the volatiles, and the mode of occurrence, etc., though these rocks are different in their periods of intrusion.

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* Having previously computed the depth (40 km below sea-level) of the granodioritic batholith of the Pacific coast of Northest Honshu, Kumagai(27)(29) also has inferred from the general trend of the positive Bouguer anomalies and from the aid of a large positive isostatic anomaly at Kushimoto which is roughly estimated to be +101 mgal that the diorite—gabbro rocks cropping out at Shionomisaki and Kushimoto would extend below the earth's surface to NE direction.

From the extent of the protuberance of the said positive Bouguer anomalies extending from Shionomisaki as far as to Hase, Nara Pref., he has further noticed that the andesite at Hase lying in the direction would be an effusive facies of the diorite—gabbro rocks mentioned above. (Address by N. Kumagai at a seasonal meeting in 1951 of the Western Branch of the Geological Society of Japan)

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Revision in Part I

(1) In the Table 2, the indices of olivine are not β, but γ. (Sample 261, and 258 are the melanocrate of the pegmatitic phase.) Therefore, the ranges of the chemical composition, assumed from the index of the olivines in the normal facies of the Muroto gabbro is from Fa_{23} to Fa_{32}. One of the Fe-richest olivine in the pegmatite facies is Fa_{39}.

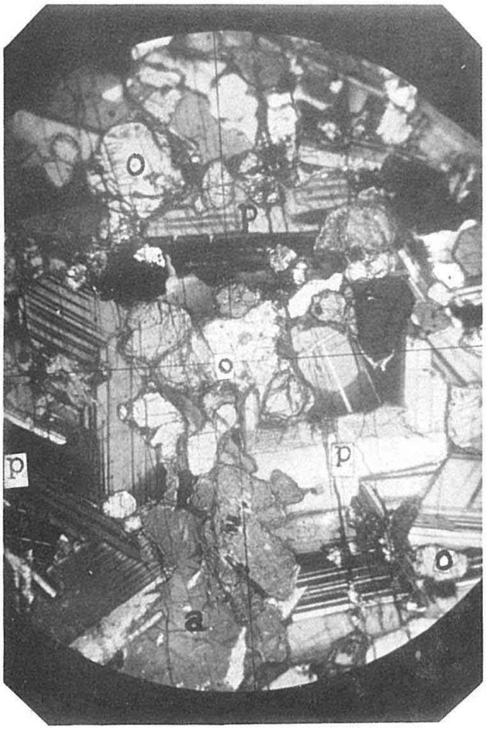
(2) ($\beta \gtrless 1.740$), written in the geological map, is revised to ($\gamma \gtrless 1.735$ ca.).

(3) In the table of the chemical composition of the monoclinic pyroxene, En is revised to Wo, and Wo to En.

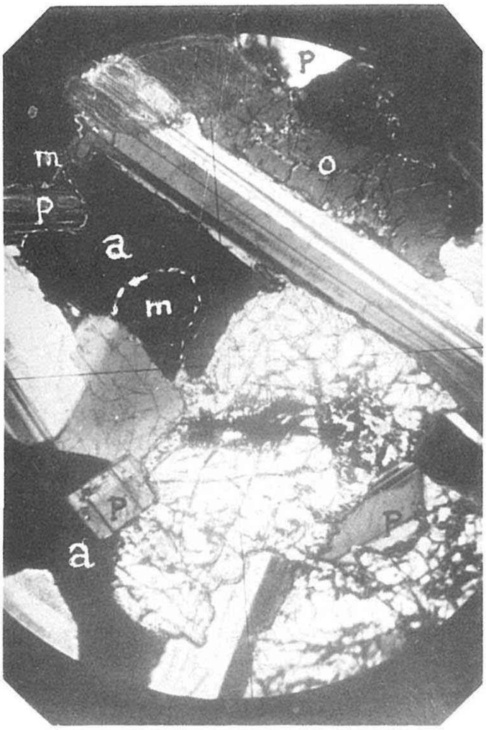
(4) The Muroto gobbro was considered in Part I to be correlated to the hypersthenic rock series, but the gabbro is to be assumed to have been formed by the lower temperature crystallization, i. e. the contamination of sialic materials was weak.

Plate II

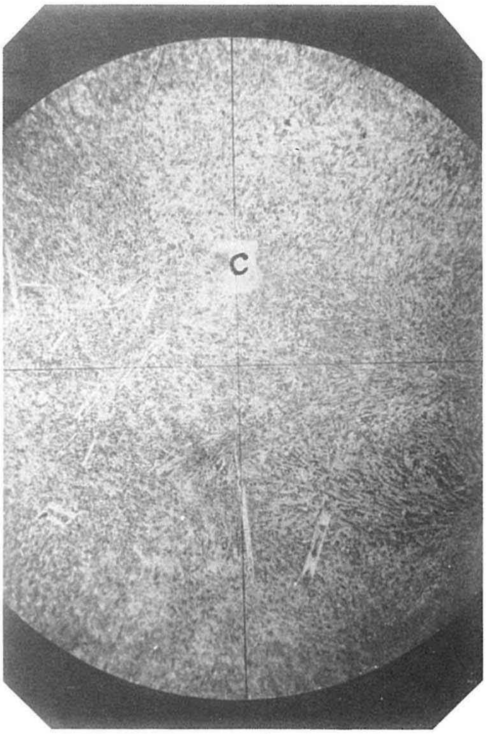
m........magnetite
o........olivine
a........augite
p........plagioclase
c........cavity



No. 1. Fine-grained
two pyroxene-olivine-gabbro.
Crossed nicols × 20



No. 2. Medium-grained.
two pyroxene-olivine-gabbro.
Crossed nicols × 20



No. 3. Intraformationally
intruded and chilled diabase.
Upper nicol opened. × 20