PETROLOGICAL STUDIES ON PLAGIOCLASE TWINS*

MASAO GORAI†

ABSTRACT

The differences in the type of plagioclase twinning in igneous and metamorphic rocks are described. Plagioclase twins are divided, from a petrological point of view, into the C-twin and the A-twin. Frequencies of untwinned plagioclase and twin types in various endogenous rocks are described and the genesis of the C-twin which characterizes the volcanic and plutonic rocks is interpreted. Lastly, a plagioclase twin method for determining the origin of various granitic rocks is proposed and discussed.

INTRODUCTION AND ACKNOWLEDGMENTS

The present study has been under investigation since 1944 for the purpose of determining the petrological significance of plagioclase twins. As a result of this investigation it was found that there exists a clear difference in plagioclase twinning in igneous and metamorphic rocks.

Thus albite and pericline (acline) twins are present commonly in the igneous as well as in the metamorphic rocks, while the other twins (Carlsbad, etc.) are confined to, or characteristic of, the volcanic and plutonic rocks. This difference in the type of plagioclase twinning may be attributed to the difference in the mechanism of plagioclase crystallization.

According to the above interpretation the writer has tried to deduce the mechanism of plagioclase crystallization in some rocks formed near the boundary between magmatic and metamorphic processes, and from this also to postulate the environmental conditions under which these rocks were formed.

It is hoped that the plagioclase twin method proposed in the present paper may throw new light on the so-called "granite problem."

The writer wishes to express his sincere gratitude to the late Dr.

* Preliminary reports of this study were published in the following articles:

Study of plagioclase twins, considered from a petrological point of view (in Japanese): *Jour. Assoc. Geol. Collaboration*, **1**, No. 1, 3–6 (1947).

Plagioclase twins in the igneous and metamorphic rocks (in Japanese): *Jour. Geol. Soc. Japan*, **54**, No. 635, 89 (1948).

Proposal of twin method for the study of the granite problem: *Jour. Geol. Soc. Japan*, **56**, No. 655, 149–156 (1950).

Method of distinguishing C-twin and A-twin of plagioclase under ordinary polarization microscope (in Japanese with English summary): *Jour. Geol. Soc. Japan*, **56**, No. 660, 441–443 (1950).

The features of plagioclase twinning in various granitic rocks: *Jour. Geol. Soc. Japan*, **56**, No. 663, 515–518, 1950.

† Geological and Mineralogical Institute, Tokyo Kyōiku-Daigaku (Univ. of Education), Tokyo, Japan.

Kenichi Sugi who kindly guided him during this study, and also to Dr. Shōji Ijiri, Mr. Akiho Miyashiro, Dr. Tatsurō Matsumoto, Mr. George Kojima, Dr. Kenzo Yagi and Mr. Hiroshi Kanō for their many valuable suggestions and criticisms. His thanks are also due to Dr. N. L. Bowen and Dr. F. Chayes for their critical reading of the manuscript. Lastly, he is indebted to Mr. Yono Sotozaki and Miss Takako Ishikawa who assisted him in the preparation of the article.

Approximate Frequencies of Each Twinning Law in Various Endogenous rocks

The chief purpose of this study is to indicate the difference between plagioclase twins characteristic of igneous and metamorphic rocks. Up to the present time the twinning laws of about 1500 plagioclase twins from various endogenous rocks have been determined by the Fedorov method.[1]

Table 1. Approximate Frequencies of Each Twinning Law in the Plagioclases of Volcanic and Allied Rocks

An%		Ab	Pe	Ac	Pe or Ac	Sum	Ca	Ab-Ca	AlB	Ab-AlB	Ma	AlA (Ma-Ac)	Ba	X	Sum	Whole sum
0– 24	P	4	—	—	2	6	2	2	—	—	—	—	—	—	4	10
	G	5	—	—	—	5	3	4	—	—	—	—	—	—	7	12
25– 49	P	85	3	2	26	116	24	23	1	5	3	3	—	4	63	179
	G	19	—	—	4	23	14	10	—	—	—	—	—	—	24	47
50– 74	P	71	6	3	15	95	44	24	1	1	5	3	2	1	81	176
	G	68	—	1	6	75	36	25	—	1	2	—	—	—	64	139
75–100	P	56	5	2	13	76	37	29	1	2	1	1	2	1	74	150
	G	30	—	4	4	38	30	12	—	1	—	1	—	—	44	82
Sum	P	216	14	7	56	293	107	78	3	8	9	7	4	6	222	515
	G	122	—	5	14	141	83	51	—	2	2	1	—	—	139	280
Whole sum		338	14	12	70	434	190	129	3	10	11	8	4	6	361	795

Ab = albite, Pe = pericline, Ac = acline, Ca = Carlsbad, Ab-Ca = albite-Carlsbad, AlB = AlaB, Ab-AlB = Albite-AlaB, Ma = Manebach, AlA (Ma-Ac) = AlaA (Manebach-acline), Ba = Baveno, X = unknown twin, P = phenocrystic plagioclase, G = groundmass plagioclase.

Table 1 shows the approximate frequencies of different types of twins in various volcanic rocks (including so-called hypabyssal rocks such as

[1] Index of hemisphere is 1.516, that of immersion liquid (cedarwood oil) 1.518 at 21° C. Angle of inclination (*h*) was not compensated. The observations with the universal stage and the plotting of Wulff's net were carried out simultaneously. The twinning laws were determined according to Reinhard's diagrams.

quartz-porphyries, porphyrites, diabases, and gabbroic rocks of volcanic origin). As seen from the table, albite, pericline (plus acline),[2] Carlsbad and albite-Carlsbad twins are very common, while the other twins are of relatively rare occurrence. It is noteworthy that there are no marked differences between the type of twinning in the phenocrysts and groundmass of the plagioclases, except that the former are somewhat richer in pericline (acline) and the rare twins (Manebach, etc.).

TABLE 2. APPROXIMATE FREQUENCIES OF EACH TWINNING LAW IN THE PLAGIOCLASES OF PLUTONIC ROCKS

An%	Ab	Pe	Ac	Pe or Ac	Sum	Ca	Ab-Ca	Ca or Ab-Ca	Ab-AlB	Ma	AlA or (Ma-Ac)	Ba	X	Sum	Whole sum
0– 24	31	—	—	3	34	—	—	17	—	—	1	—	1	19	53
25– 49	35	7	2	8	52	—	—	28	—	—	1	—	1	30	82
50–100	103	18	7	40	168	40	35	—	2	1	1	1	—	80	248
Sum	169	25	9	51	254	40	35	45	2	1	3	1	2	129	383

Table 2 shows the frequencies of each form of twin in the plagioclases of various plutonic rocks (gabbroic to granitic rocks occurring as so-called batholiths and stocks). As in the volcanic rocks mentioned above, albite, pericline (acline), Carlsbad and albite-Carlsbad twins are common, while the other twins are very scarce.

TABLE 3. APPROXIMATE FREQUENCIES OF EACH TWINNING LAW IN THE PLAGIOCLASES OF SCHISTS AND GNEISSES

An%	Ab	Pe	Ac	Pe or Ac	Sum	Ca	Ab-Ca	Sum	Whole sum
25– 49	62	2	1	18	83	—	1	1	84
50– 74	18	3	1	2	24	—	—	—	24
75–100	13	27	1	1	42	1	—	1	43
Sum	93	32	3	21	149	1	1	2	151

Table 3 shows the frequencies of twin forms in the plagioclases of various schists and gneisses of amphibolite facies.[3] As seen from this table the type of plagioclase twinning in these metamorphic rocks is quite different from that in the volcanic and plutonic rocks. Although

[2] As the differentiation of pericline from acline twins is not always easy, especially in the case of intermediate plagioclases, these twins are treated together.

[3] Excluding the gneisses of marked migmatitic appearance (so-called injection gneiss, etc.).

albite and pericline (acline) twins are common, the other twins are very scarce, Carlsbad and albite-Carlsbad twins being rarely encountered. Pericline (acline) twins are more common in extremely calcic plagioclases than in the sodic varities. The same tendency is also observed in the plagioclases of volcanic and plutonic rocks above described, although it is not shown in Tables 1 and 2.

TABLE 4. APPROXIMATE FREQUENCIES OF EACH TWINNING LAW IN THE PLAGIOCLASES OF HORNFELSIC ROCKS

An%	Ab	Pe	Ac	Pe or Ac	Sum	Ca	Ab-Ca	Ab-AlB	Sum	Whole sum
25– 49	32	1	1	9	43	3	1	—	4	47
50– 74	43	5	2	10	60	6	3	1	10	70
75–100	9	2	1	3	15	—	2	—	2	17
Sum	84	8	4	22	118	9	6	1	16	134

Table 4 shows the type of plagioclase twinning in hornfelsic rocks, probably of pyroxene-hornfels facies. As seen from this table the frequencies of different plagioclase twins in these hornfelsic rocks are rather similar to those in the schists and gneisses above described. It is noteworthy, however, that the hornfelses are somewhat richer in Carlsbad and albite-Carlsbad twins than the schists and gneisses, although the frequencies of these twins shown in table 4 are somewhat overestimated.

The above described features of plagioclase twinning in various endogenous rocks may be summarized as follows:

(i) Albite and pericline (acline) twins are very common in the igneous as well as in the metamorphic rocks.

(ii) Carlsbad and albite-Carlsbad twins are common in the volcanic and plutonic rocks, while rare in the metamorphic rocks.

(iii) The other twins (Manebach, etc.) are almost entirely confined to the volcanic and plutonic rocks, where they are of relatively rare occurrence.

GROUPING OF PLAGIOCLASE TWINS FROM A PETROLOGICAL POINT OF VIEW

As indicated in the foregoing paragraph albite and pericline (acline) twins are commonly present in the igneous as well as in the metamorphic rocks, while the other twins are almost confined to, or are characteristic of, the volcanic and plutonic rocks. Accordingly, the plagioclase twins are divided, from a petrological point of view, into the following two groups:

C-twin. This includes twins according to the laws[4] that are restricted to, or characteristic of, the volcanic and plutonic rocks.

A-twin. This includes twins according to the laws[5] that are commonly present in the igneous as well as in the metamorphic rocks.

It is easy to determine the approximate frequencies of these C-twins and A-twins in each rock, because they are readily distinguished with the ordinary petrographic microscope (without universal stage).

First, twinned plagioclases are divided into the following four types:

Type 1. Polysynthetic twins (1, 2, 4 of Fig. 1) and their modifications (3, 5).

Type 2. Simple twins (6, 7) and their modifications (8, 9, 10).

Type 3. Complex twins and their modifications; this is subdivided into *3a* (11–15) and *3b* (16–20).

Type 4. Penetration twins (21–25).

Fortunately there are intimate relations between these four types of twinned plagioclases and the twinning laws. Thus the twins of type 1 are almost always those according to the albite or pericline (acline) laws, and consequently fall in type A.[6] The twins of type 3 are almost always complex twins related to albite, Carlsbad and albite-Carlsbad laws, being rarely related to albite, Ala B and albite-Ala B laws. Therefore, they are always C-twins. The twins of type 4 are also C-twins, because they are always twinned after the laws characteristic of the volcanic and plutonic rocks (Carlsbad, etc.). However, the twins of type 2 include, in general, both C-twins and A-twins, and the differentiation of the former from the latter is not always easy. The following three cases may be distinguished for the twins of type 2:

(i) The different twin units of a crystal show different retardation when the twinning line is placed in or near the 45° position with reference to the cross hairs.

(ii) The twin units show, in that position, nearly equal retardation, but show different retardation when a gypsum plate is inserted.

(iii) The twin units show, in that position, equal retardation even when the gypsum plate is inserted.

Of these the first two cases are C-twins (Carlsbad twin), while the third case is practically indeterminate.[7]

[4] Carlsbad, albite-Carlsbad, Manebach, Baveno, AlaB, albite-AlaB, AlaA or Manebach-acline laws. Of these the first two are the most common.

[5] Albite and pericline (acline) laws.

[6] Excepting rare instances in some basaltic rocks, in which the twins of Type 1 are sometimes twinned after the Carlsbad law.

[7] The twins of the third case are either A-twin (albite or pericline) or C-twin (albite-Carlsbad); the differentiation is impossible without universal stage.

The approximate frequencies of C-twins and A-twins in each rock are thus easily estimated from those of the above four types of twinned plagioclases determined with the ordinary petrographic microscope. The frequencies of these four types are determined by counting successively the grains of each type (generally 100–200 grains in each slice) which

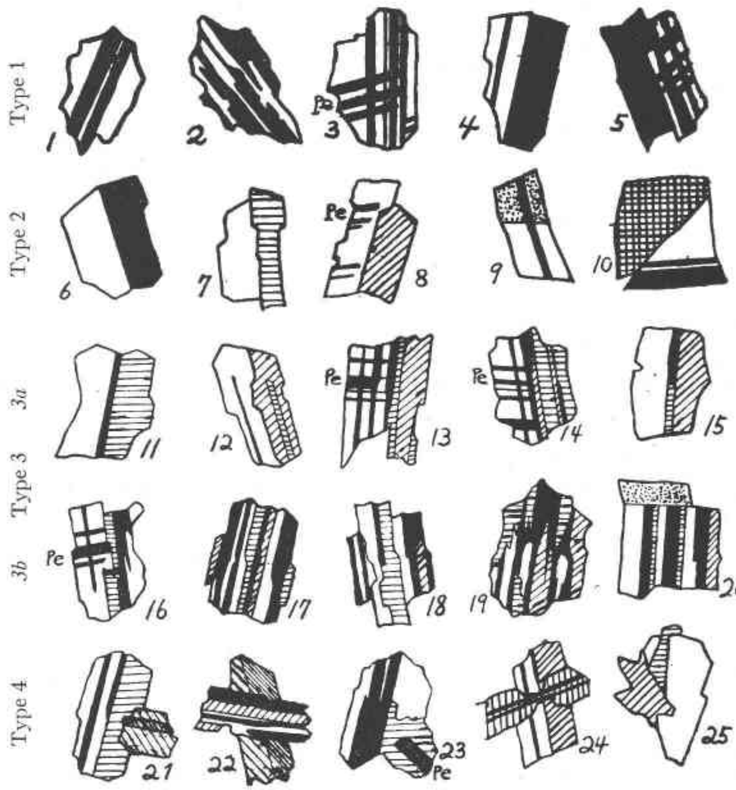


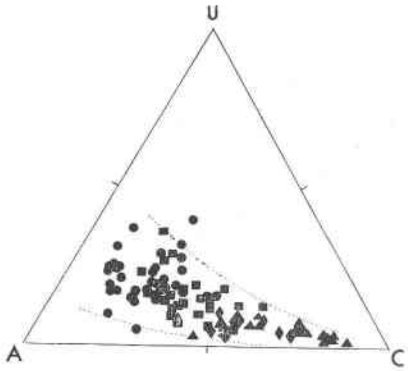
FIG. 1. Four types of twinned plagioclases.
Type 1. Polysynthetic twins and their modifications.
Type 2. Simple twins and their modifications.
Type 3. Complex twins and their modifications.
Type 4. Penetration twins.

pass the central portion of the field of microscope, moving the slice regularly on a mechanical stage.[8] The frequencies of untwinned plagioclases are also recorded together with those of the two twin types.

[8] Therefore large grains may sometimes be counted twice or more.

Frequencies of Untwinned Plagioclase and Twin Types in Various Endogenous Rocks

Figure 2 shows the ratios of untwinned plagioclase (U), C-twin (C), and A-twin (A), of the phenocrystic plagioclases in various volcanic and related rocks. As seen from this diagram each point (each rock) falls in a narrow field, more basic rocks being relatively richer in C-twins. The same features are observed in the groundmass plagioclases of volcanic and allied rocks (Fig. 3). The frequencies of U, A and C depend, however, on the average compositions of the plagioclase rather than on



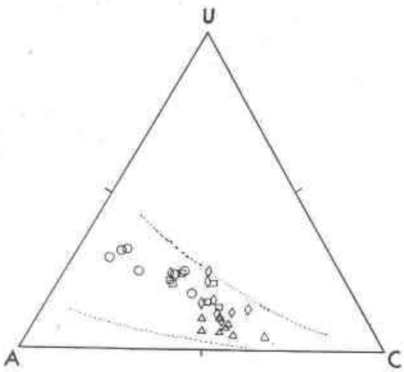


Fig. 2 (left). U:A:C ratios in the phenocrystic plagioclase of volcanic and allied rocks.
Fig. 3 (right). U:A:C ratios in the groundmass plagioclase of volcanic and allied rocks.
Triangle = basalts and related types.
Rhomb = Pyroxene andesites and related types.
Square = hornblende andesites, dacites, and related types.
Circle = liparites, trachytes, and related types.

the chemical compositions of the entire rocks. Thus, as seen from Fig. 4, there are regular relationships between the average compositions of plagioclase and the frequencies of untwinned plagioclase and twin types in each rock. This relationship is more pronounced in Fig. 5, which shows the relationship between the average compositions of plagioclase and the frequencies of C-twin in the labradoritic to anorthitic feldspars in andesitic to basaltic rocks.

The U:A:C ratios in various plutonic rocks[9] are shown in Fig. 6. Figure 7 illustrates the relations between the average compositions of plagioclase and the frequencies of U, A and C. As seen from these diagrams the features of plagioclase twinning in these plutonic rocks are

[9] Gabbroic to granitic rocks occurring in batholiths and stocks, rocks with marked shearing effects being excluded.

very similar to those in the volcanic and allied rocks described above.

The ratios of U, A and C in various schists and gneisses[10] of amphibolite facies are shown in Fig. 8. As seen from this figure the features of plagio-

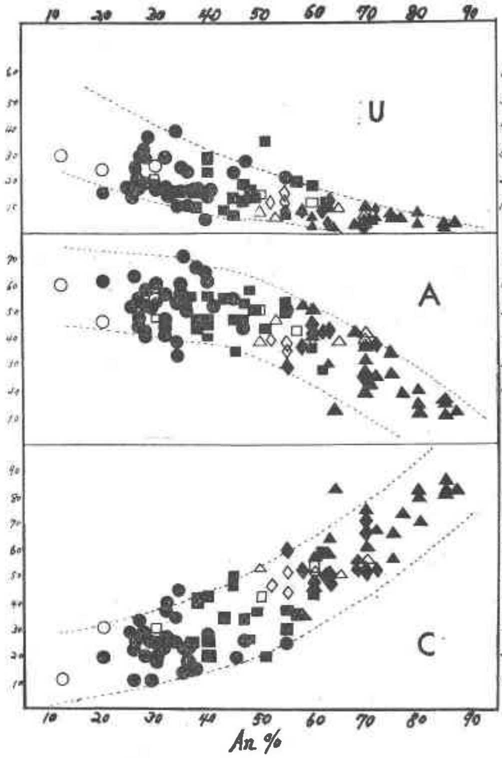


FIG. 4. Relationship between the average An% of plagioclase and the frequencies of U, A and C in volcanic and allied rocks.

clase twinning in these metamorphic rocks are quite different from those of the plagioclases in the volcanic and plutonic rocks, C-twins being almost lacking.[11]

It is noteworthy, moreover, that the frequency of twinned plagioclase (A-twin) in these metamorphic rocks has nothing to do with the average composition of the plagioclase, but depends on the average grain size of the plagioclase in each rock (Figs. 9 and 10).

[10] Excluding the gneisses of marked migmatitic appearance.

[11] Universal stage determinations show that the Type 2 twins (simple twins) in these metamorphic rocks are always albite or pericline (acline) twins, namely A-twins.

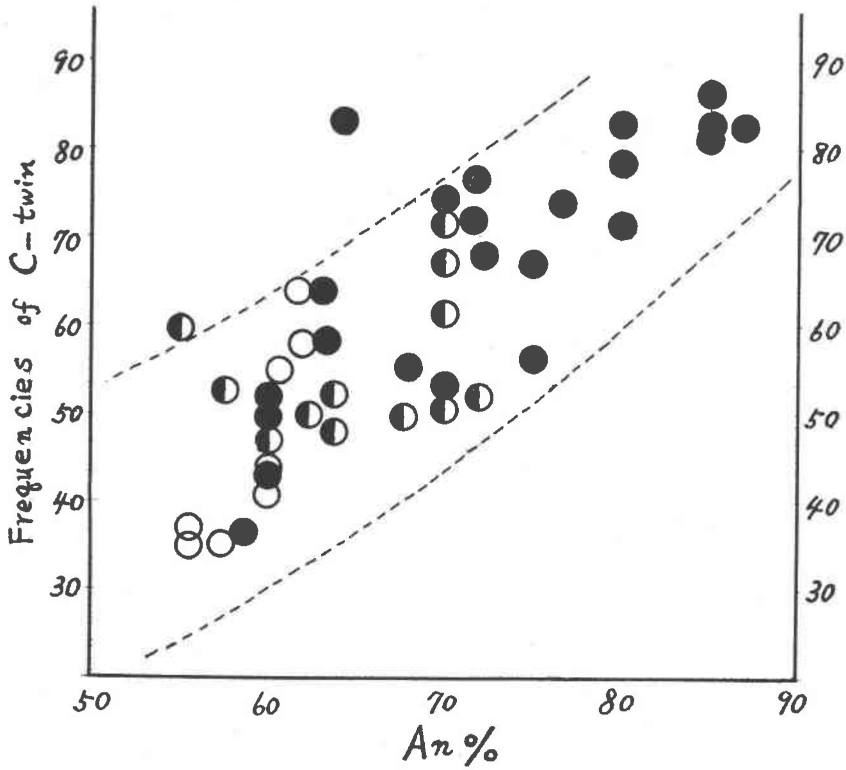


FIG. 5. Relationship between the average An% of plagioclase and the frequencies of C-twins in the basaltic and andesitic effusives and related rocks.
Solid circle = basalts and related types.
Semi-solid circle = pyroxene andesites and allied types.
Open circle = hornblende andesites and allied types.

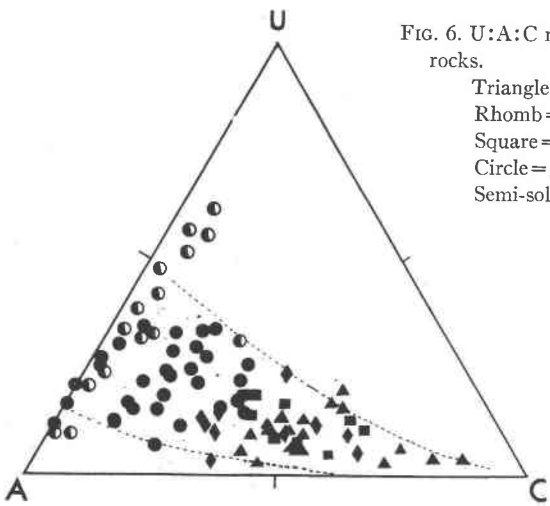


FIG. 6. U:A:C ratios in the plagioclase of plutonic rocks.
Triangle = gabbros.
Rhomb = diorites.
Square = quartz diorites.
Circle = granites, granodiorites.
Semi-solid circle = aplites, pegmatites.

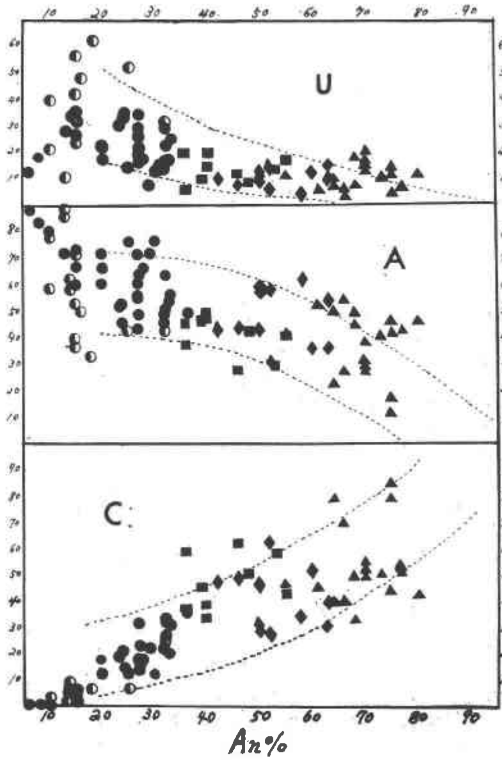


FIG. 7. Relationship between the average An% of plagioclase and the frequencies of U, A and C in plutonic rocks.

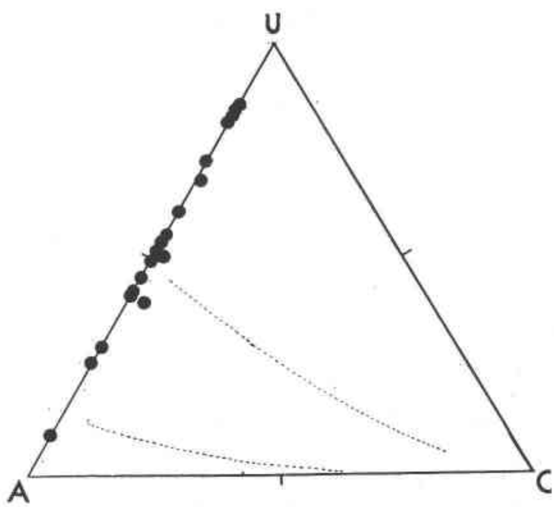


FIG. 8. U:A:C ratios in the plagioclase of schists and gneisses.

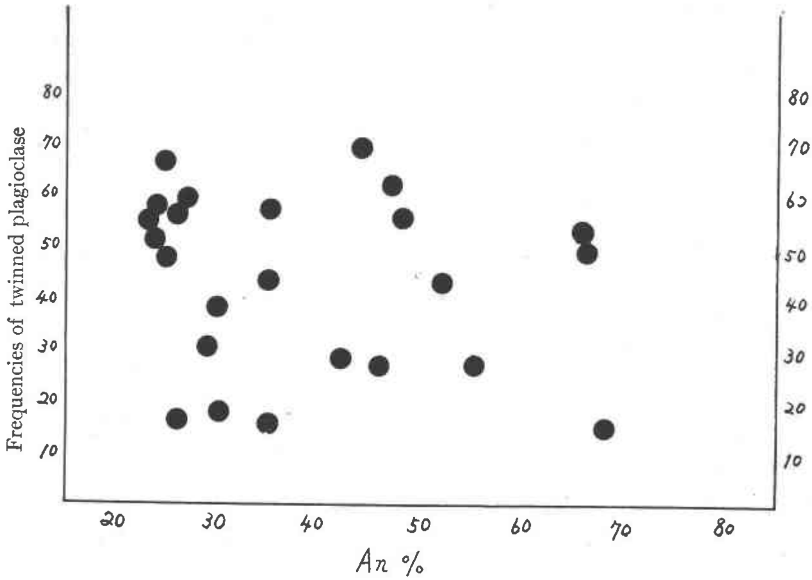


FIG. 9. Relationship between the average An% of plagioclase and the frequencies of twinned plagioclase in schists and gneisses.

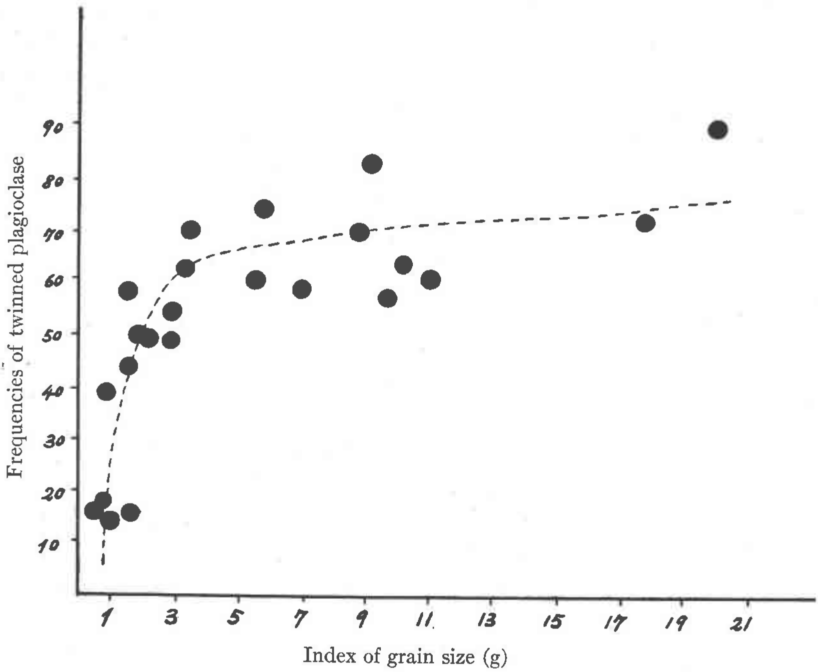


FIG. 10. Relationship between the average grain size (g) of plagioclase and the frequencies of twinned plagioclase in schists and gneisses.

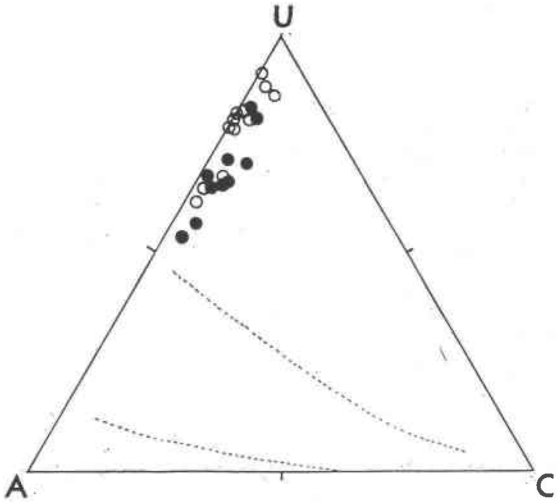


FIG. 11. U:A:C ratios in the plagioclase of hornfelsic rocks.
Open circle = Rocks constituting metamorphic aureoles.
Solid circle = Rocks occurring as xenoliths in the plutonic rocks.

Figure 11 shows the U:A:C ratios in hornfelsic rocks probably of pyroxene-hornfels facies. As seen from this figure each point (each rock) falls, as in the schists and gneisses above described, on or near the U-A line. The hornfelses are, however, generally richer in untwinned plagioclase,[12] and somewhat richer in C-twins as compared with schists and gneisses. It is noteworthy, moreover, that the hornfelses occurring as xenoliths in the plutonic rocks are generally richer in C-twins than those constituting the metamorphic aureoles surrounding the plutonic masses.

SOME CONSIDERATIONS ON THE GENESIS OF C-TWINS

As described in the foregoing paragraphs, some kinds of twins are commonly present in the igneous as well as in metamorphic rocks, while others are confined to, or characteristic of, the volcanic and plutonic types. The genesis of C-twins, which characterize the volcanic and plutonic rocks, is, therefore, a matter of particular interest. It is almost unquestionable that most of the plagioclases in the volcanic rocks are of igneous (magmatic) origin. However the origin of plagioclases in the plutonic rocks is not so definite. The plagioclases of the schists, gneisses, and hornfelses discussed in the preceding paragraphs may be considered as representatives of the plagioclases of metamorphic (recrystallization) origin.

[12] This is due to the circumstance that plagioclase twinning in the hornfelses is generally finer than that in the schists and gneisses.

As already mentioned the difference in plagioclase twinning between the volcanic and metamorphic rocks is most pronounced in the twins grouped under C-twins. This relation is expressed as follows: The plagioclase of igneous (magmatic) rocks exhibits, in general, fairly high relative frequency of C-twins, while the plagioclase of metamorphic (recrystallized) rocks rarely shows this type of twinning. The factor which controls the formation of C-twins (it will be called C-factor subsequently) is apparently connected with physical, chemical, or physicochemical circumstances at the time of plagioclase formation. These circumstances differ obviously in the crystallization of plagioclase in rock magma from those in the so-called recrystallization resulting in the formation of metamorphic rocks. Accordingly, it is conceivable that the C-factor is connected with the crystallization of plagioclase from rock magma.

This interpretation at once raises, however, the question of why C-twins occur at all, though rarely, in some metamorphic rocks.[13] This problem is difficult to solve conclusively, because at present little is known about the details of recrystallization in rock metamorphism.

As many authors have stated, the constituents of the metamorphic rocks may gradually dissolve under favorable conditions, resulting in the formation of a solution phase. If this is true, one can expect the occasional occurrence of plagioclases crystallizing directly from a melt phase in such high grade metamorphics as gneisses or hornfelses. The existence of C-twins in these high-grade metamorphics is thus not incompatible with the interpretation of the C-factor mentioned above.

As already described, the frequencies of C-twins in the volcanic rocks depend on the average compositions of the plagioclase in each rock, the rocks with more calcic plagioclase being, in general, relatively richer in C-twins. The writer proposes as a working hypothesis that the C-factor is connected with the crystallization of plagioclase from a melt phase and that its frequency of realization is controlled by the composition of the crystallizing plagioclase.

Proposal of Plagioclase Twin Method

The chief purpose of the present study is to determine the petrological significance of plagioclase twins. The discovery of the difference in twinning, between the igneous and metamorphic plagioclases is, in this connection, very significant.

One of the outstanding unsolved problems of petrology is the origin of rocks generated near the boundary between the magmatic and

[13] It is evident, from various petrographic observations, that C-twins in these metamorphic rocks are not relicts of original constituents.

metamorphic processes, which involves the so-called "granite problem." The study of plagioclase twins may throw new light on this problem.

On the basis of his interpretation of the C-factor above mentioned, the writer has tried to deduce the mechanism of plagioclase crystallization in rocks of this type and also the mechanism of formation of such rocks.

(a) *The features of plagioclase twinning in various granitic rocks of Japan.*

As already described, plagioclase twinning in the granitic to granodioritic rocks[14] occurring as batholiths and stocks is very similar to that in the volcanic (liparitic to dacitic) rocks. Relative frequencies in the two suites are shown in Figs. 13*a* and 14*a*.

FIG. 12. Outline map of Japan showing localities of the granitic rocks studied.
1. Kitakami Mountainland.
2. Abukuma Plateau.
3. Tsukuba District.
4. Jōetsu District.
5. Ryōke Region.
6. Hida Plateau.
7. Chyūgoku Mountainland.

The features of plagioclase twinning in the granitic rocks[15] occurring as dikes and sheets (minor intrusions) associated with the granites above mentioned are shown in Fig. 13*b* and Fig. 14*b*. As seen from these figures the features of plagioclase twinning of these granitic rocks are, as in the granites above mentioned, similar to those of typical igneous rocks, excepting three rocks whose types of plagioclase twinning are metamorphic.

[14] Of these granitic rocks, 4 are from Kitakami Mountainland, 13 from Abukuma Plateau, 3 from Jōetsu District, 6 from Ryōke Region, and 2 from Chūgoku Mountainland (Fig. 12).

[15] Of these, 20 are from Abukuma, 5 from Jōetsu.

Figure 13*c* and Fig. 14*c* show the features of twinning of the granitic to aplitic rocks[16] occurring as lit-par-lit veins in so-called injection gneisses formed from pelitic sediments. The features of twinning in these granitic

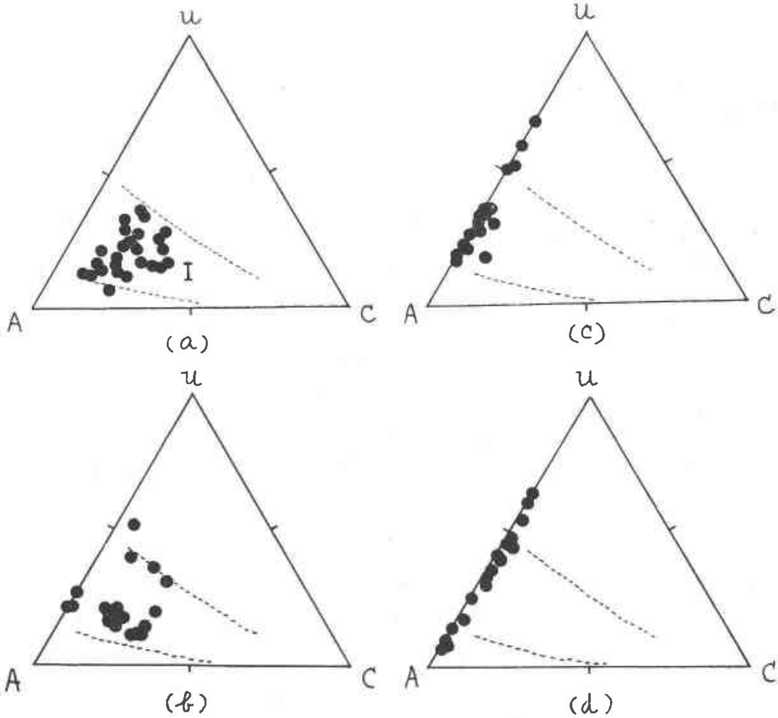


FIG. 13. U:A:C ratios in the plagioclase of various granitic rocks.
(*a*) Granitic rocks occurring as batholiths and stocks.
(*b*) Granitic rocks occurring as dikes and sheets.
(*c*) Granitic rocks occurring as lit-par-lit veins of injection-gneisses.
(*d*) Plutonic-looking rocks of Hida Plateau.
I = Field of typical igneous plagioclase.

rocks are fairly similar to those of typical metamorphic rocks, excepting two rocks which carry some C-twins.

Figure 13*d* and Fig. 14*d* show the features of twinning in the plutonic-looking (nebulitic) rocks of Hida Plateau. These plutonic-looking rocks include granitic, monzonitic, and quartz dioritic rocks which are at a glance indistinguishable in mineral composition and texture from typical plutonic rocks. They are intimately associated with gneissic rocks of

[16] Of these, 12 are from Abukuma, 2 from Tsukuba, and 13 from Ryōke.

TABLE 5

	1	2
U	12	9
A	88	44
C	0	47
An%	30	35

1—Granitic rock.
2—Tonalite.

more metamorphic appearances in transitional fashion, and have been commonly accepted as orthogneisses injected into gneisses of sedimentary origin. As seen from the figures the features of twinning in these plutonic-looking rocks are, as in the granites of lit-par-lit veins, fairly similar to those of typical metamorphic rocks.

Table 5 shows the modes of twinning in the granitic and tonalitic

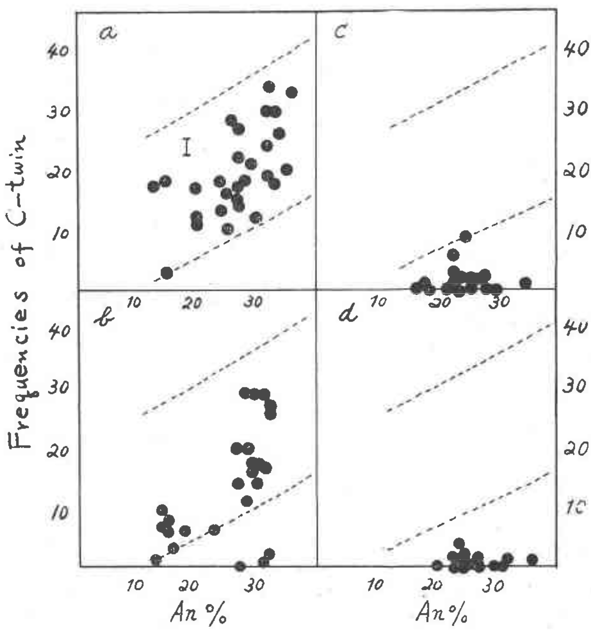


FIG. 14. Relations between the average An% of plagioclase and the frequencies of C-twins in various granitic rocks.
a, *b*, *c*, *d* correspond to those in Fig. 13.
I = Field of typical igneous plagioclase.

rocks at a gneiss-tonalite contact zone of Takanuki District, Abukuma Plateau. Here biotite-gneiss is invaded by tonalite, the marginal part of the former adjacent to the latter being non-gneissose and granitic in appearance. The junction of the granitic rock and the tonalite is fairly distinct, while the relation between this granitic rock and biotite-gneiss is gradational. Under the microscope the granitic rock closely resembles the tonalite in mineral composition (oligoclase, quartz and biotite) and texture (ordinary granitic texture), the two being almost indistinguishable by ordinary petrographic observations. However, as seen from the table these two rocks are quite different with respect to the type of plagioclase twinning. Thus the feature of twinning in the granitic rock is clearly metamorphic, that of the tonalite being markedly igneous.

(b) *Two types of granitic rocks, with respect to the type of plagioclase twinning.*

As described above some granites are igneous, while the others are metamorphic, with respect to the type of plagioclase twinning. Accordingly the granitic rocks may be divided into the following two types:

(i) I-granite, in which the type of plagioclase twinning is igneous.

(ii) M-granite, in which the type of plagioclase twinning is metamorphic.

It is interesting to note that there exist intimate relations between the types of occurrence and the features of plagioclase twinning. Thus most of the granitic rocks occurring as definite intrusive bodies (batholiths, stocks, dikes, and sheets) are I-granites, while the granitic rocks intimately associated with gneissic rocks in transitional fashion (lit-par-lit veins in injection gneisses, plutonic-looking rocks of Hida Plateau, etc.) largely belong to the M-granites.

It seems permissible, therefore, to infer that the I-granites above mentioned are of magmatic origin, while the M-granites are products of some metamorphic processes (granitization). There is no evidence unfavorable to this interpretation.[17]

The so-called "granite problem" which has attracted the attention of many petrologists during the past twenty years is, in short, whether granites are igneous (products of magmatic consolidation) or metamorphic (products of granitization). The plagioclase twin method proposed in the present paper may throw new light on this problem.

[17] It is noteworthy, in this connection, that the three exceptional rocks (M-granites) of minor intrusions previously described occur as sheet-like bodies intercalated with biotite gneisses of pelitic sedimentary origin. These M-granites might be products of granitization, probably of sandstones intercalated with pelitic sediments.

Summary

(i) Albite and pericline (acline) twins are commonly present in the igneous as well as in the metamorphic rocks, while the other twins are confined to, or characteristic of, volcanic and plutonic rocks, Carlsbad and albite-Carlsbad twins being the most common.

(ii) Plagioclase twins are divided, from a petrological point of view, into the following two types:

C-twins that include twins after the laws which are confined to, or are characteristic of, the volcanic and plutonic rocks.

A-twins that include twins after the laws which are commonly present in the igneous as well as in the metamorphic rocks.

(iii) The approximate frequencies of untwinned plagioclase and the above twin types in each rock can be estimated with the ordinary petrographic microscope, without the universal stage.

(iv) The plagioclase of volcanic rocks carries untwinned plagioclase, C-twins, and A-twins, C-twins being relatively abundant in the rocks with more calcic plagioclase.

(v) The features of plagioclase twinning of most plutonic rocks are fairly similar to those of the volcanic rocks.

(vi) The plagioclase of metamorphic rocks is mainly composed of untwinned plagioclase and A-twins, C-twins being absent or inconspicuous. The frequency of A-twins in these rocks depends on the average grain size of plagioclase in each rock.

(vii) The difference in plagioclase twinning between the igneous and metamorphic rocks may be attributed to differences in the mechanism of plagioclase formation in these rocks. The factor which controls the formation of C-twins seems to be related to the crystallization of plagioclase from a melt phase, the frequency of the development of this twin being controlled by the composition of the crystallizing plagioclase.

(viii) On the above interpretation as to the genesis of C-twins, one may be able to deduce the mechanism of plagioclase crystallization in the rocks formed near the boundary between the magmatic and metamorphic processes, and thus establish the mechanism of formation of the rocks themselves.

(ix) Granitic rocks are divided, with respect to the mode of plagioclase twinning, into the following two types:

I-granite, in which the mode of plagioclase twinning is igneous.

M-granite, in which the mode of plagioclase twinning is metamorphic. Most of the granitic rocks occurring as definite intrusive bodies are I-granites, while the granitic rocks intimately associated with gneissic rocks are mostly M-granites.

(x) It is suggested that I-granites are of magmatic origin, while M-granites are products of some metamorphic processes (granitization).

Manuscript received May 15, 1951.