The Yŏnch'ŏn System Containing Cyanite and Andalusite Deposits

Takao YAMAGUCHI

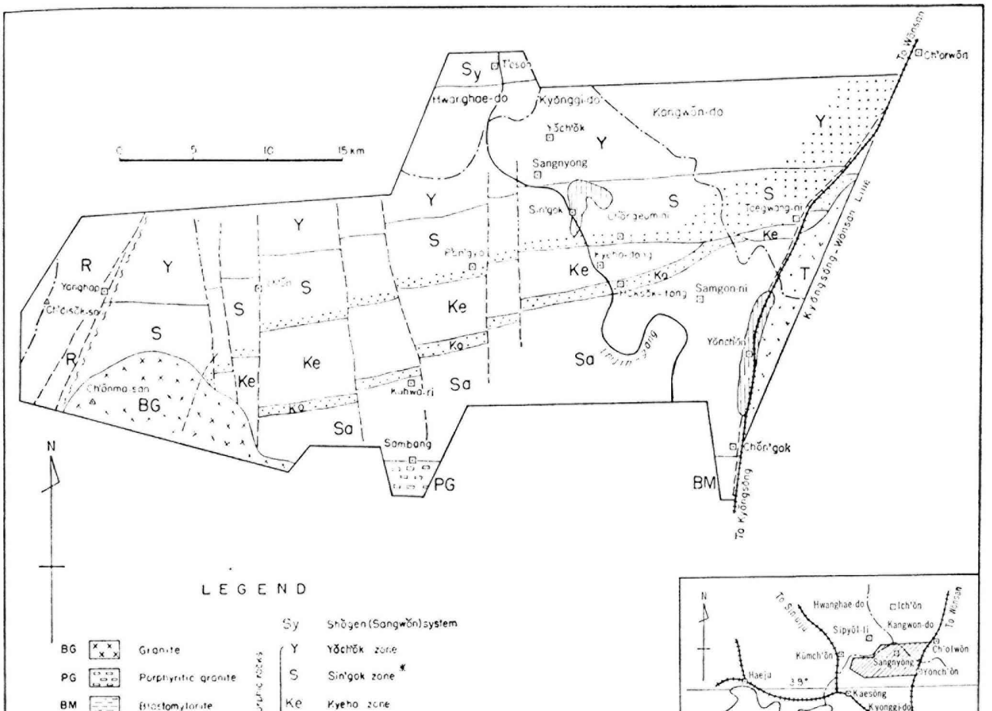


Fig. 1. Geological Map of the Sangnyŏng-Yŏnch'ŏn District, Kyŏnggi-do, South Korea.
Note: S zone is divided into three subzones (see figs. 15 and 16). The author sometimes refers to these subzones by using the symbols SI, SII, and SIII.

1. Introduction

Several localities of cyanite, andalusite, and sillimanite deposits have been found in Korea. The rocks of these localities are generally considered to be Archean or Proterozoic: the Yŏnch'ŏn, Okch'ŏn, and Sangwŏn systems (YAMAGUCHI, 1941, 1952) and the gneisses in Ŭiju-gun, P'yŏngan-pukdo (TAKAHASHI, 1940) and in Kangsŏ-gun, P'yŏngan-namdo (MIYAZAWA, 1940).

The deposits generally consist of cyanite, andalusite and sillimanite concentrated in veins or pockets with smaller amounts of other minerals or other easily separable minerals.

The fact that the deposits are distributed in remarkably metamorphosed regions indicates that they are closely related genetically to the metamorphism of their country rocks.

It has not been proved that these country rocks geologically and petrologically belong to the Archean or Proterozoic system; we have the old unsolved problems:

1. What are the kinds and ages of the original rocks?
2. What are the nature and ages of the metamorphism?

The same questions also apply to the so-called Yŏnch'ŏn system.[1]

The area covered in this paper is the type locality of the Yŏnch'ŏn system, which Shigetaro KAWASAKI (1918) reported upon earlier.

After 1939[2] the deposits in this region became known to the miners in Korea: Y. KINOSAKI (1938) had surveyed them for the mineral resources and I later surveyed the area (1941).

2. Geology

A. The Relation of the Yŏnch'ŏn Metamorphic Group to Other Geological Members

No evidence has been found in this region to prove that this metamorphic group belongs to the Archean system. As shown in Fig. 1, this group is in contact with the Sangwŏn system in the north, probably without faulting, and is in contact with granite and gneiss in the south where the relation is that of intrusions and injections. In the east and west the geological extensions of the group are such that they cannot be described clearly.

The members clearly overlying this metamorphic group are the tuff-breccia (near Yŏnch'ŏn), the plateau basalts (near Yŏnch'ŏn and Sin'gok), and the alluvial sediments.

Relations to the blasto-mylonite (BM), *the porphyritic granite* (PG), *and granite* (BG)

(i) Western side of the southern margin (of the area of this report)—near Chung'-bang.

The porphyritic granite (PG) is injected in the Samgot granulite zone. Near the plane of contact, the rock distributions are from north to south as follows:

[1] I prefer the name Yŏnch'ŏn metamorphic group to the Yŏnch'ŏn system, because no evidence suggesting that this "system" is Archean has been found.

[2] The mining of these cyanite deposits increased from 1937 to 1943; many amateur prospectors and miners actively worked these deposits.

the Yŏnch'ŏn metamorphic group
Granulite[3] (Samgot zone)
Alternation of granulite and melanocratic gneiss[4], approx. 150 m thick
Injection of aplite veins in melanocratic gneiss, approx. 150 m thick
Augen-gneiss, grading southward into PG
Porphyritic granite (PG)

The rocks have a similar orientation of schistosity and show gradual transition from one to another. The forming of PG (injection of basic magma in the earlier stage and injection of aplite veins in the later stage), therefore, is considered to have occurred simultaneously with the dynamometamorphism of the Samgot granulite.

(ii) Eastern side of the southern margin—near Chon'gok.

The blasto-mylonite[5] BM, named according to petrographic textures and structures, has an almost parallel schistosity orientation to the Samgot granulite. The contact relation is not that of a fault. Sheet-like melanocratic gneisses are also distributed in that part of the granulite near the contact. The blasto-mylonitization, therefore, is considered to have occurred simultaneously with the dynamometamorphism of the Samgot granulite.

(iii) The granite BG[6] in the southwest.

This granite undoubtedly intruded the metamorphic group.

(iv) The relation between PG, BM, and BG.

The field relations between them have not been clarified, but the succession of their intrusions is considered to be as follows:

(Intrusion or injection of the original rock of BM)—(injection of PG—simultaneous with the dynamometamorphism of the Yŏnch'on metamorphic groups)—(intrusion of BG).

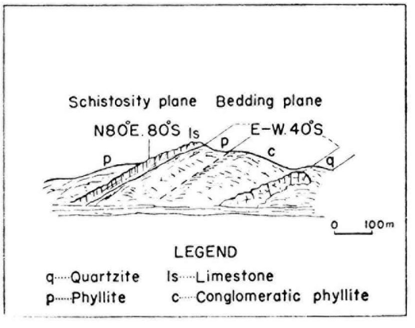


Fig. 2. Difference between the Schistosity Plane and the Bedding Plane in the Sangwŏn System Near To'san.

[3] According to Harker's definition.
[4] Granoblastic gabbro under the microscope.
[5] According to Sander's nomenclature.
[6] The Pulguksa granite?

The relation to the so-called Sangwŏn system, in the northern side.

The Yŏch'ŏk mica schist zone of the metamorphic group is in contact with the Proterozoic Sangwŏn system in the northern side. The contact relation is not considered a fault, as they alternate on a small scale near the contact and show an almost similar orientation of schistosity.

Conglomeratic phyllite, the characteristic key bed of the upper formation of the Sang'wŏn system in Middle Korea, is found near the contact (T'osan). The striking fact is that the plane of stratification and the plane of schistosity differ distinctively[7] (see Fig. 2).

The stratigraphic succession of the Sang'wŏn system (T'osan—Ich'ŏn) is as follows[8]:

Kuhyŏn Series	Phyllite P_5
	Limestone L_2
	Conglomeratic phyllite P_4
	Quartzite Q_3[9]
Sadangmol Series	Phyllite P_3
	Limestone L_1
	Ottrelite slate P_2
Chikhyŏn Series	Quartzite Q_2
	Phyllite P_1
	Quartzite Q_1

..........Unconformity..........

Gneiss (Blasto-mylonite)

The thickness of the quartzites and the limestones varies from place to place along those horizons.

B. The Internal Construction of The Yŏnch'ŏn Metamorphic Group

The zone distribution of the several rock types

Every rock type occupies an area extending almost E-W, with zone-to-zone changes from north to south. All rock types are easily distinguishable by eye in the field.

The orientations of their schistosity planes and the existence of cyanite-andalusite deposits are shown in the following table.

7) Such facts are also often observed in the Yŏnch'ŏn metamorphic group (see Figs. 4, 7).

8) The correlation of the Sang'won system of several localities has been shown in: YAMAGUCHI (1943), *Min. Journ. of Korea*, vol. XXVI, no. 4, p. 209.

9) Near Namjŏng-ni (a village between Kumch'on and Sibyon), I found one species each of *Monograptus* and *Cypridea* in the sandy slate and limestone correlated to P_3 and L_1 respectively. These fossils are well-known index fossils of Gotlandian Period.

The upper formation of the so-called Sang'won system in Middle Korea is therefore considered to be Silurian.

Zone (symbol)			Strike and dip of schistosity plane	Cyanite-andalusite deposits
Yŏch'ŏk mica schist zone (Y)			N70–90°W, 60–90°N	Few in the eastern area
Sin'gok	,,	zone I (SI)	N70–90°W, 70–80°Q	None
,,	,,	zone II (SII)[10]	N70–90°W, 70–80°N	None
,,	,,	zone III (SIII)	N70–90°W, 60–70°N	Many
Kyeho biotite-hornfels zone (Ke)			N-E, 80–90°N (Schistosity planes generally less developed)	None
Hŭksŏk mica schist zone (Ko)			N50–70°E, 50–70°S	Some
Samgot granulite zone (Sa)			N50–70°E, 50–70°N	None
Yanghap chlorite-schist zone (R)			N50°E, 60–70°N	None

Boundaries of the zones

Excluding the Yanghap zone, every zone shows transition from one to the other, without any fault and within a short distance. In fact such a transition from the highly metamorphosed zone SIII to the low metamorphosed zone Ke can be observed on the road cut between Sin'gok and Kyeho-dong.

The boundary planes (between the zones) differ genetically from the schistosity planes, although the two seem generally to be parallel. As seen in the occurrence of the Ke zone in the eastern part, the boundary is serrate (see Fig. 3).

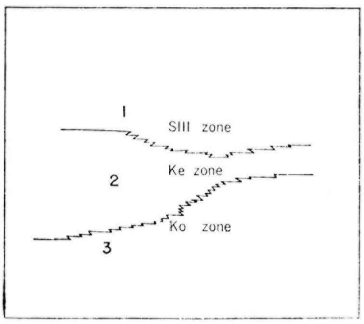
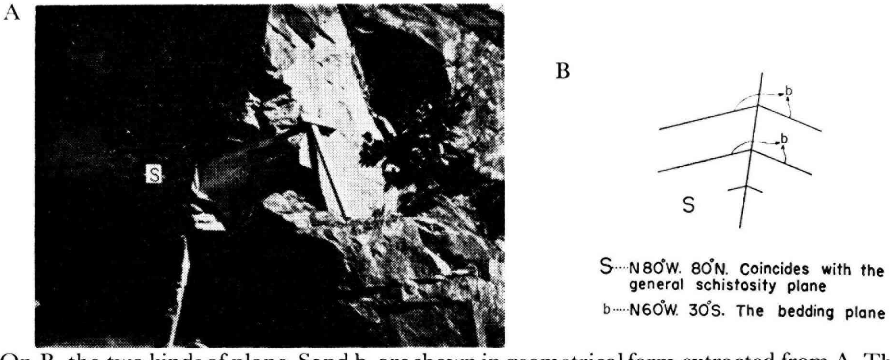


Fig. 3. Schematic Representation of the Serrate Countering of Zones.

The plane of stratification of the original formation and the plane of schistosity

The fact that the two planes generally differ from each other in the metamorphic region is often evident in the zones Ke and Y (see Figs. 4, 7).

10) See Fig. 16.



On B, the two kinds of plane, Sand b, are shown in geometrical form extracted from A. The plane b inclines gently as seen near the hammer on A.

Fig. 4.

The thickness of the zones

The common stratigraphic conception of thickness has no significance for the metamorphic group because of the difference between the plane of schistosity and that of stratification[11]. However, since each zone has its own nature of metamorphism, the "thickness of each kind of metamorphic zone" is shown in the following table:

	Thickness in meters	
Zone	Eastern part	Western part
Y	About 10,000	15,000
SI, SII, SIII	4,000	4,000
Ke	0 to 4,000	4,000
Ko	0 to 4,000	1,000
Sa	8,000	4,000
Total	28,000	28,000

Cyanite-andalusite deposits

These deposits are generally distributed only in the SIII and Ko zones, which have well-developed schistosity. The main deposits of large quantity and good quality are found in the SIII zone. They surely have some close relation to the remarkable metamorphism of the country rock.

[11] The stratigraphic succession and thickness of the Yŏnch'ŏn system has been shown by KAWASAKI (1918) as follows:

Upper	Mica schist, phyllite	12,290 m
	Cyanite-bearing mica schist	2,260 m
Lower	Amphibolite, hornfels	12,990 m
	Quartzite, amphibolite	
	Total	27,540 m

But, in the writer's opinion, these are the thicknesses of metamorphic zones.

Green schist and gabbro

Near T'osan, the gabbroic intrusive rocks change to green schist similar to the Mikabu green schist of Japan. Gabbroic rocks containing garnets are injected in the form of sheets of tongues into the Samgot zone.

Faults

There are some parallel step faults striking almost N-S in the metamorphic region; these faults do not cut the granite BG. A few faults striking northeast cut BG. The former are considered to have occurred simultaneously with the metamorphism, and the latter, after the metamorphism.

3. Petrology of Rocks and Ore Deposits

A. Development of Schistosity Petrofabrics or Gefügekunde

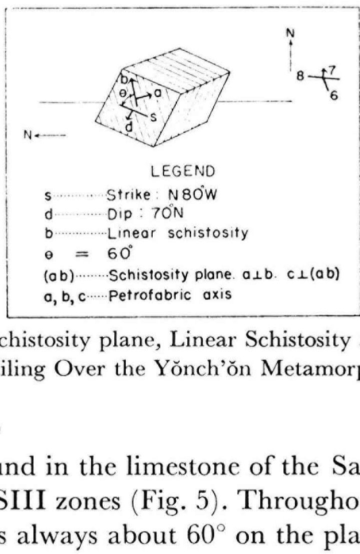


Fig. 5. The Schistosity plane, Linear Schistosity and Petrofabric Axis Prevailing Over the Yŏnch'ŏn Metamorphic Group.

(i) Linear schistosity[12)]

Linear schistosity is found in the limestone of the Sangwŏn system, and in the rocks of the SI, SII, and SIII zones (Fig. 5). Throughout these zones, the inclination of linear schistosity is always about 60° on the plane of schistosity.

(ii) The system

The phyllite and the conglomeratic phyllite have phyllitic cleavage; the quartzite Q_3 was disturbed and became angular blocks; and the limestone L_2 shows ptygmatic folding and linear schistosity.

The *Gefügeregelung* of the calcites in L_2 is shown in Fig. 6.

(iii) The Yŏch'ŏk zone

The foliation is generally slaty or shaly, and no phyllitic cleavage is seen. The term granulite[13)] may be preferable to schist as a name for the rocks in this zone.

Some rock has three kinds of cleavage and traces of the schistosity of the former stage and of the original stratification (see Fig. 7).

12) The linear schistosity is indicated by symbol "b", one of the petrofabric axes which are used as the co-ordinate axis in petrofabric analysis (Fig. 5).

13) According to Harker's definition.

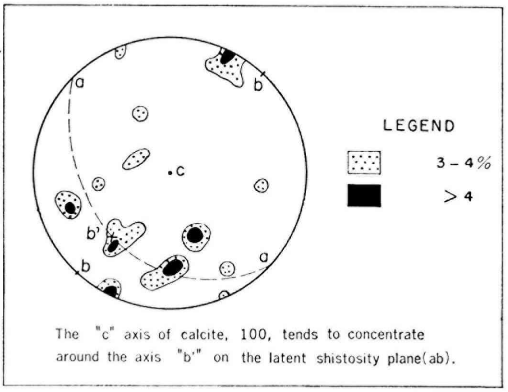
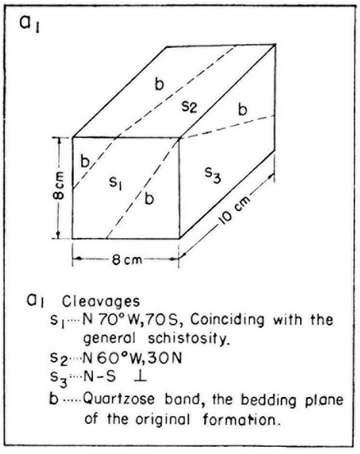


Fig. 6. The "Gefügeregelung" of Calcite in the Limestone of the Shōgen System (South of Tosan).



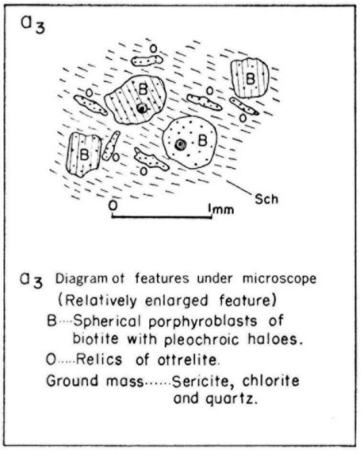


Fig. 7. a_1, a_3 Rock in the Yŏch'ŏk Zone (Specimen No. 106).

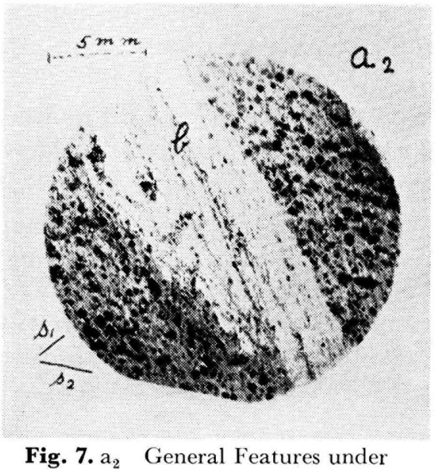


Fig. 7. a_2 General Features under Microscope.

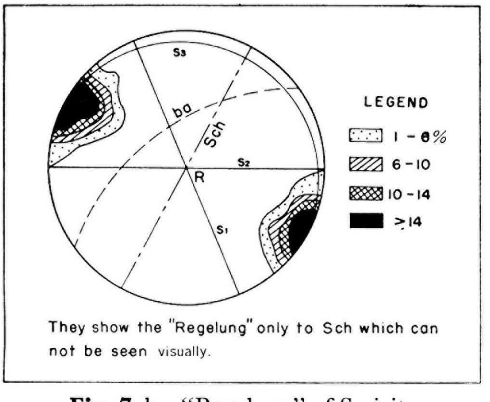


Fig. 7. b "Regelung" of Sericite 50 Poles of the Flakes.

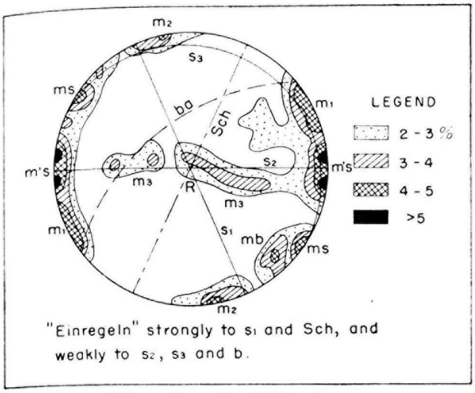


Fig. 7.c "Regelung" of Biotite 100 c-Axis.

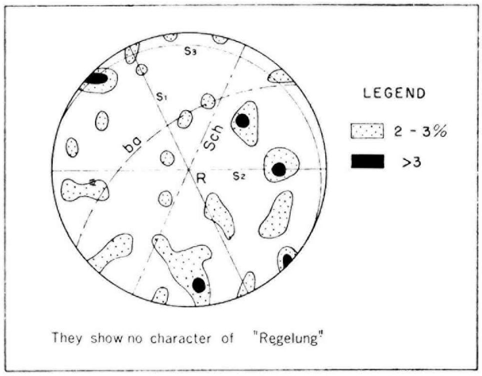


Fig. 7.d "Regelung" of Quartz 150 c-Axis.

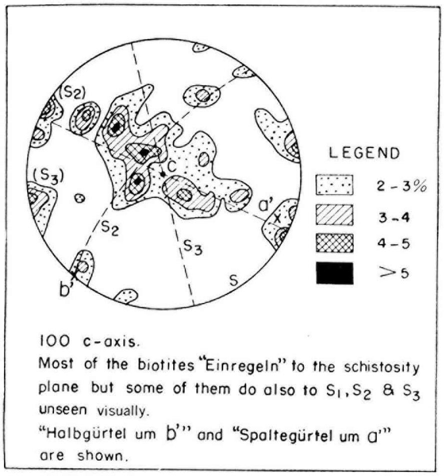


Fig. 8. "Regelung" of Biotite in a Specimen (No. 109) of the Yŏch'ŏk Zone.

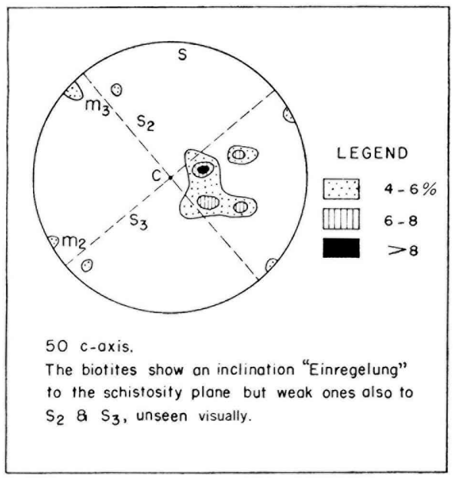


Fig. 9. "Regelung" of Biotite in a Specimen (No. 18) of the Yŏch'ŏk Zone.

The *Gefügeregelungen* in the three rocks is shown in Figs. 7–9.

(iv) The Sin'gok zone

The linear schistosity is relatively weak in the Sin'gok I zone and relatively strong in II and III; in III, it becomes weaker when cyanite and andalusite appear as constituent minerals.

The *Gefügeregelungen* in I, II, and III are shown in Figs. 10–13.

(v) The Kyeho zone

In this zone the schistosity is not generally clear, but traces of the original stratification are often found (see Fig. 4). Mica schists are sometimes intercalated.

(vi) The Hŭksŏk zone

The schistose cleavage is perfect but the plane of schistosity is often bent, and the linear schistosity is not seen.

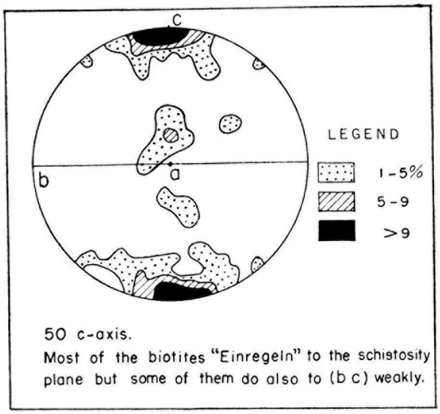
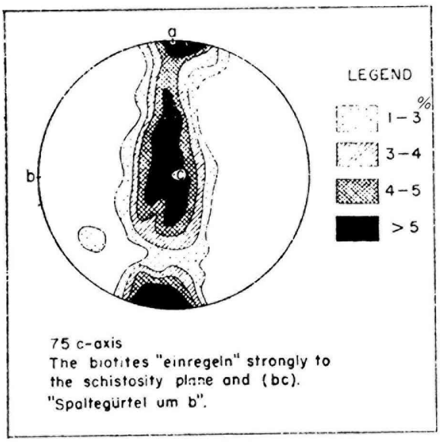
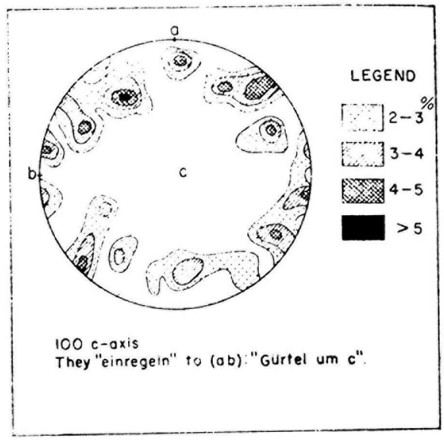


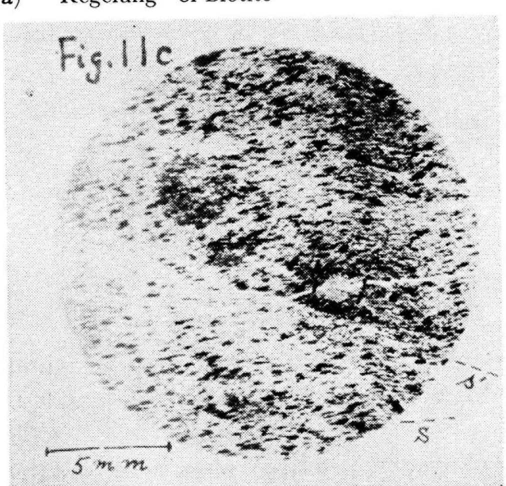
Fig. 10. "Regelung" of Biotite in a Specimen (No. 48) of the Sin'gok Zone I.



a) "Regelung" of Biotite



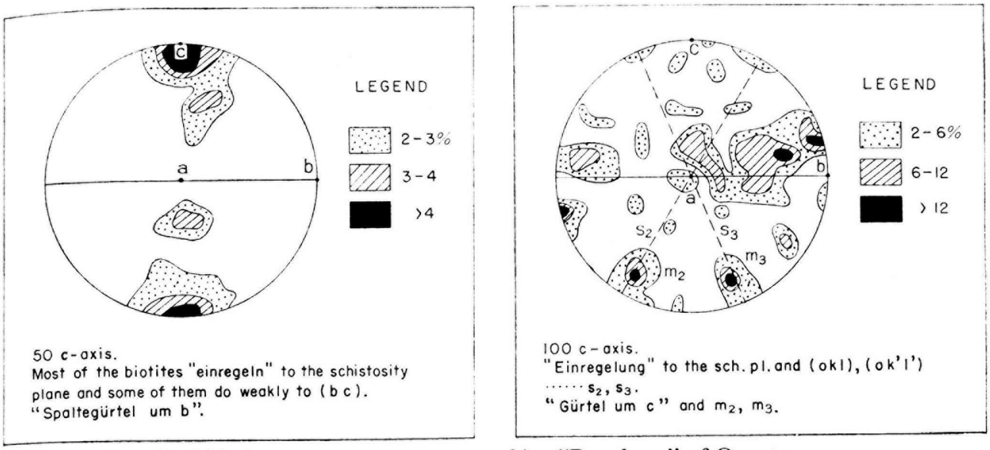
b) "Regelung" of Quartz



c)
The Texture Under the Microscope
S' ...... Bedding plane of the original rook
S .... Schistosity plane
In the broken circle........ garnet

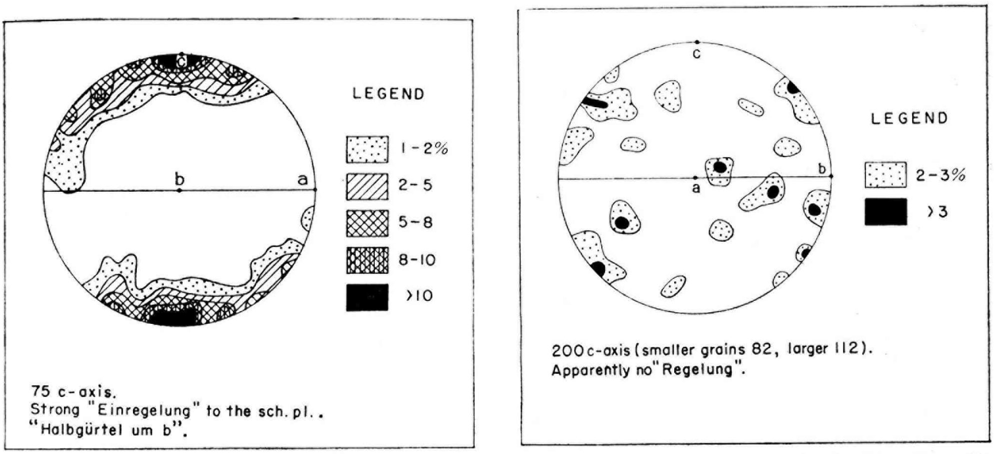
The porphyroblasts are garnet and biotite, and the groundmass consists of chlorite, sericite and quartz.

Fig. 11. Examples of "Gefügeregelung" from the Sin'gok II Zone.

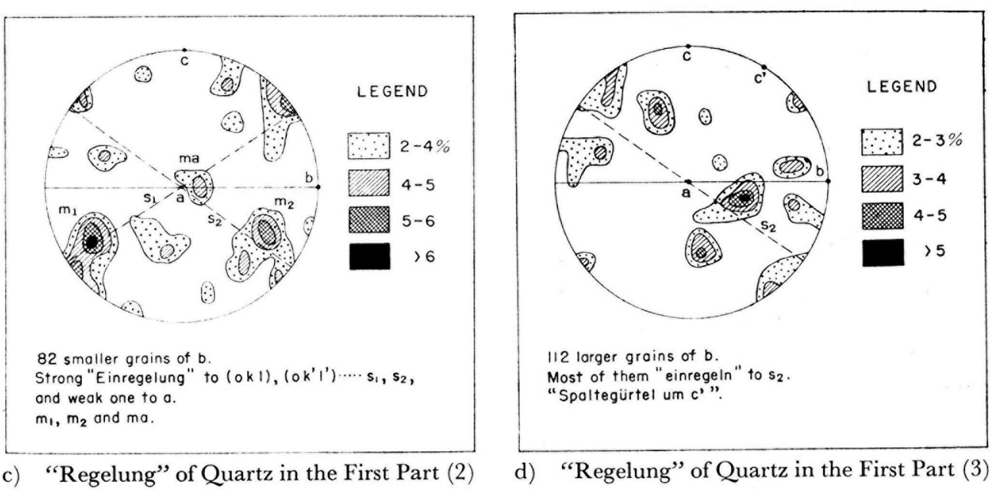


a) "Regelung" of Biotite b) "Regelung" of Quartz

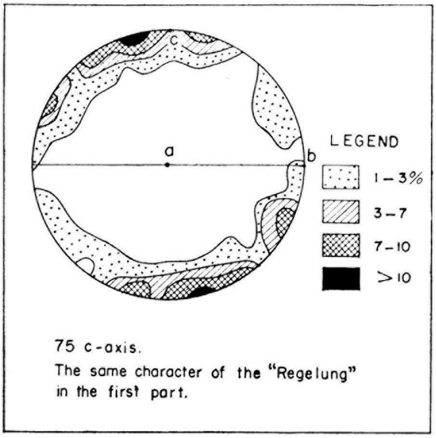
Fig. 12. G-schist in the Sin'gok III Zone (Specimen No. 32).



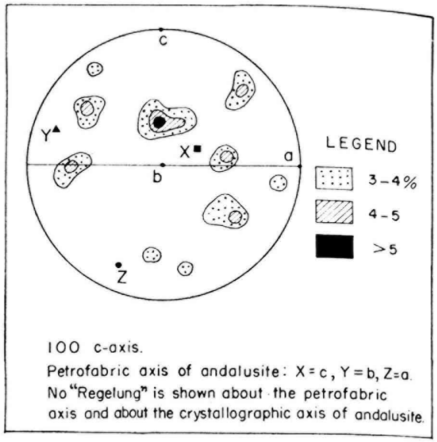
a) "Regelung" of Biotite in the First Part b) "Regelung" of Quartz in the First Part (1)



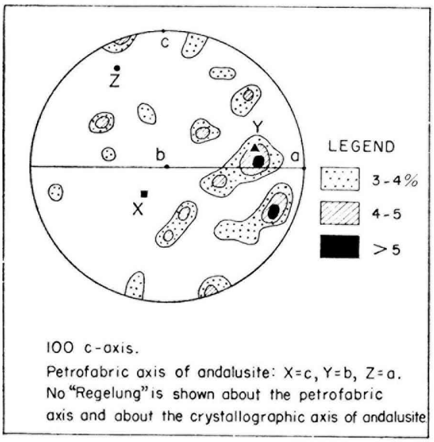
c) "Regelung" of Quartz in the First Part (2) d) "Regelung" of Quartz in the First Part (3)



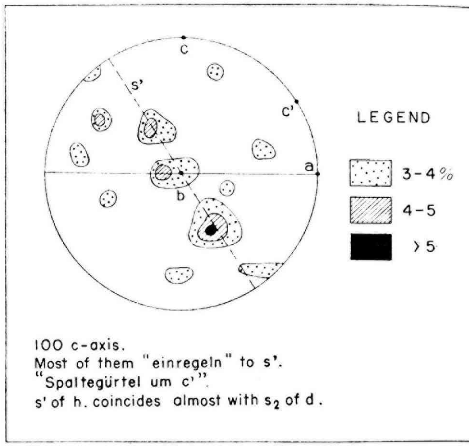
e) "Regelung" of Biotite in the Second Part



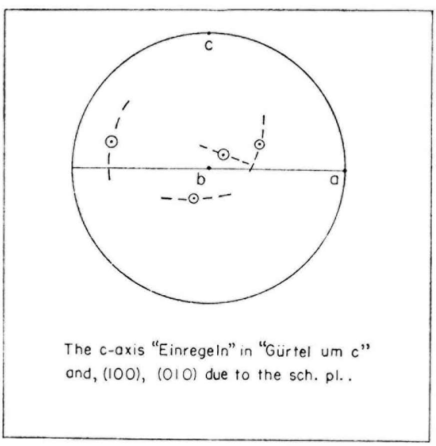
f) "Regelung" of Quartz in the Second Part



g) "Regelung" of Quartz in the Second Part



h) "Regelung" of Quartz in the Third Part



i) "Regelung" of Andalusite

Fig. 13. A-Schist in the Sin'gok III Zone (Specimen No. 43).

(vii) The Samgot zone

The cleavage is shaly and the schistosity plane is very platy, but no linear schistosity is seen. The *Gefügeregelungen* is shown in Fig. 14.

(viii) The Yanghap zone

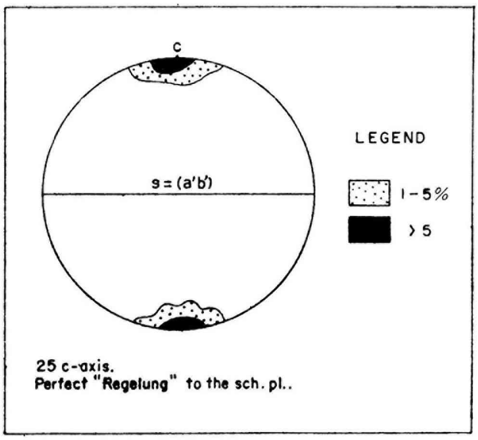
The cleavage is phyllitic. No linear schistosity is seen.

(ix) The blasto-mylonite and the *Augen*-gneiss

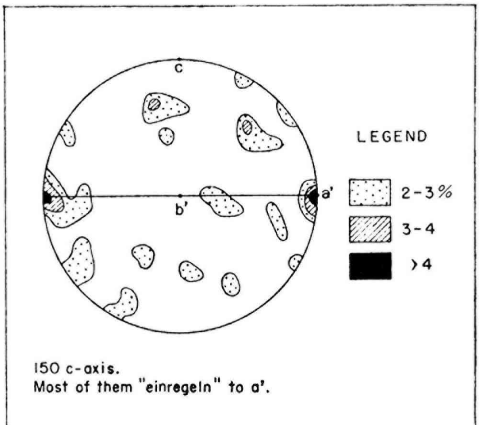
The gneissic schistosity is not developed so clearly.

(x) The nature of the dynamometamorphism as interpreted from the *Gefügeregelungen* of the minerals.

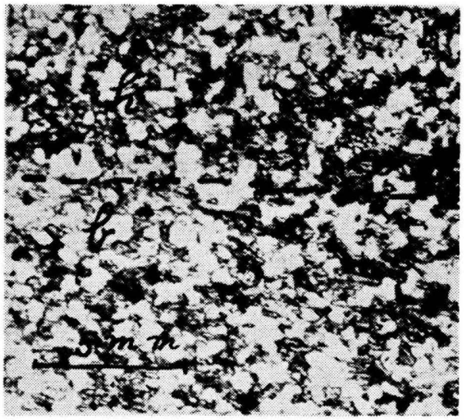
Interpreting the *Gefügeregelungen* shown in Figs. 8–14, the nature of the internal movements in the rocks is summarized in Table 1.



a) "Regelung" of Biotite in the Biotite-Granulite Layer



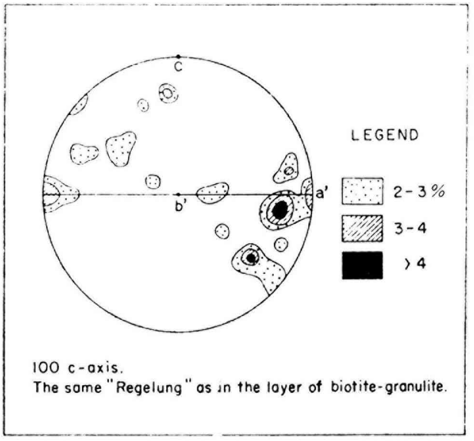
Hornblend layer



b) "Regelung" of Quartz in the Biotite-Granulite Layer

Biotite layer

Fig. 14. Examples of "Gefügereglung" from the Samgot Zone (Specimen).



c) "Regelung" of Quartz in the Hornblende-Granulite Layer

Table 1. Internal Movements Caused by the Dynamometamorphism.

Zone	Conspicuous kinds of internal movement					
	Gliding of schistosity plane in the earlier stage	Rotation around b axis	*Plättung nach* c axis	Gliding of plane (bc)	Shearing of (okl) & (ok'l')	Differential movement to a axis
Y	Sericite ((+++)) Biotite ((++))	Biotite ((++)) (±)	Biotite (++)	Biotite (±)	Biotite (±)	
SI			Biotite (++)	Biotite (±)		
SII		Biotite (+)	Biotite (++) Quartz (++)	Biotite (++)		
SIIIg		Biotite (±)	Biotite (++) Quartz (+)		Quartz (+)	
SIIIa		Biotite (+)	Biotite (++) Andalusite (+)		Quartz (+)	Quartz (±)
Sa			Biotite (+++)			Quartz (+)

(+++)....Very strongly, (++)....Strongly, (+)....Considerably, (±)....Weakly *geregelte*.
Plättung nach c:——c—— (( ))....Some cases.

The characters of the internal movements in each zone may be summarized as follows:

Y zone: The principal movement of *Plättung* in direction c is not so strong and the movements of several planes have some influence upon the *Regelung* of biotite. Sometimes, planes (okl) and (ok'l') actually appear.

SI zone: The *Plättung nach* c appears to have moved strongly and plane (bc) has glided weakly.

SII zone: The types of *Regelung* of biotite show proof of the following movements: rotation around axis b, *Plättung nach* c and gliding of plane (bc) which by hammering can be made to appear. For quartz, the *Plättung nach* c is much stronger than the other movements.

Table 2. Mineral Assemblage.

Zone	Specimen no. \ Minerals	Sericite	Chlorite	Biotite	Muscovite	Ottrelite	Garnet	Staurolite	Cyanite	Andalusite	Anorthite	Diopside	Green hornblende	Zoisite	Apatite
Y	109	+	+	+°		(+)	±								
,,	106	+	+	+°		(+)									
,,	85	+	+	+											
,,	88	+	+	+°											
,,	92	+	+	+											
,,	18	+	+	+°		±	±								
SI	15	+	+	+°			+°							[+]	[±]
,,	48	+	+	+°										[+]	[±]
SII	53	±	+	+°			+°							[±]	[+]
,,	54	±	+	+°			+°							[+]	[±]
SIII	26		±	+	+		±°								[+]
,,	32		±	+	+		+°								[+]
,,	39			+	+		+°	+°							[+]
,,	42			+	+		+°	+°	+°						[+]
,,	43			+	+		+°	+°	+°	+°					[+]
Ke	68	+	+	+											[+]
,,	72	+	+	+											[+]
Ko	145			+			±								[+]
Sa	273			+								+	+		
,,	266			+							±	+	+		[+]
,,	250*			+											
,,	,, **												+		
,,	264			+							±	+	+		[±]
,,	262			+			+				+	+	+	+	

The specimens are arranged according to zones and from north to south.
+ . . . . much,
± . . . . less,
° . . . . porphyroblast.
( ) . . . . relict.
[ ] . . . . accessory.
Quartz is + in specimens other than no. 264 which is [±].
Tourmaline, magnetite or ilmenite, and zircon occur [+] in all the specimens.
* . . . . biotite layer,
** . . . . hornblende layer.

SIII zone: "A-schist" shows very complicated *Regelungen*. The representative *Regelung* of quartz is the one of the smaller grains in the first part: shearing of planes (okl) and (ok'l'), and differential movements in direction a. The *Regelung* of biotite informs us that the *Plättung nach* c accompanied by micro-folding around b is conspicuous.

Sa zone: For biotite, the *Plättung* in direction c and the differential movement in direction a for quartz is conspicuous.

(xi) General view on the internal movement in the metamorphic region.

The behavior of the Y zone shows considerable properties of a solid[14]. One subzone of the S zone has the properties of both a solid and liquid. One subzone of the Sa zone is almost liquid and less viscous.[15] The Ko zone is considered to have behaved in almost the same manner as the S zone while the Ke zone is a solid. The Yŏnch'ŏn metamorphic group, therefore, is considered to have behaved more liquidly toward the south.

B. Mineral Assemblage

In the metamorphic region, several index minerals appear and disappear zone-by-zone and facies-by-facies[16] (see Table. 2, Fig. 15).

In the Samgot zone, Ca0-bearing minerals are common. It is quite possible that these rocks are the products of several kinds of contamination of some basic magma into common argillaceous sediments[17]. No relict of limestone was found.

Cummingtonite rocks[18] are often found in the SIII zone.

C. The Modes of Occurrence of some Characteristic Minerals

(1) Ottrelite and Biotite in the Y Zone

In this zone there commonly exist relicts of ottrelite, whose shapes were generally so severely altered that the original shapes could not be discerned.

The porphyroblasts of biotite show rounded, spheritic forms with rotating or recumbent micro-folded structures. The biotite, therefore, can be considered to have been formed a stage later than the ottrelite and the minerals (sericite and chlorite) in the ground-mass; the metamorphic process forming the biotite may be a combination of two processes as follows:

Ottrelite + K_2O → Biotite

Chlorite + Sericite → K_2O → Biotite.

These formulas of the metamorphic processes are not a perfect representation

[14] I assume when shearing by deformation occurs the material behaves as a solid, and when it does not, it behaves as a liquid.

[15] When the material is highly viscous, the biotite must show a rotating "Regelung". The word "highly viscous" means that the product of (viscosity) × (velocity gradient), is high. The larger the product is, the greater the influence of the internal movement to the constituent minerals.

[16] Barrow-Tilley's classification of "metamorphic" zone is suitable for this metamorphic group.

[17] Refer to II. A. (i).

[18] Cordierite-anthophyllite-garnet rocks exist in the Okchon system.

but only indicate the succession of transitions. In the above processes, "$+K_2O$" means some addition of K_2O, that is, a positive metasomatism of K_2O.

(2) Several Aluminous Minerals in the SIII Zone[19]

(garnet, staurolite, cyanite and andalusite)

i. The distribution of schists within zone SIII is as follows (also see Fig. 16):

	Schist	Plane of schistosity
(m)	2M—Q Schist	Silky luster; even
(g)	G—2M—Q ,,	↑
(s)	S—G—2M—Q ,,	Transitional
(c)	C—S—G—2M—Q ,,	↓
(a)	A—C—S—G—2M—Q ,,	Brownish; micro-folded

Legend. Q...Quartz, 2M...Biotite and muscovite, S...Staurolite, C...Cyanite, A...Andalusite, G...Garnet.
From (m) to (a), the amount of muscovite decreases and the amount of biotite increases.

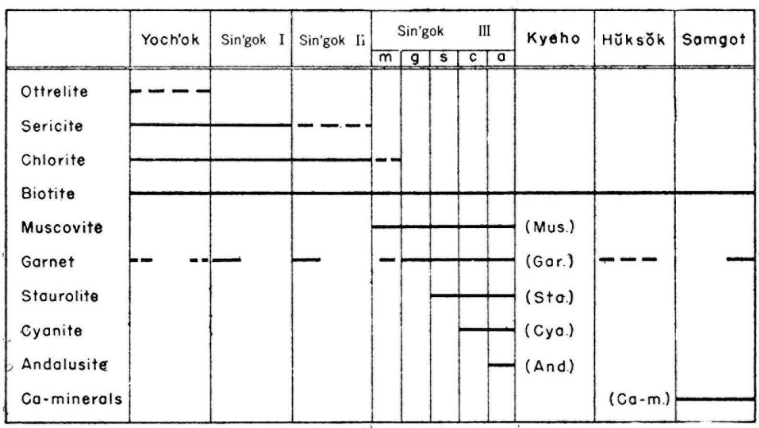


Fig. 15. Zone-distribution of "Index Minerals".

ii. The modes of occurrence of the minerals are observed representatively in a-schist. Two kinds of layers are found: in one mica is concentrated and in the other quartz. These layers were perhaps separated by metamorphic differentiation. Each layer is 0.3 to 1.0 mm thick, and folds around petrofabric axis b and is sometimes flexed along axis a. The garnet, staurolite, and cyanite often exist at the flexure along axis a (Fig. 17).

The aluminous minerals occupy their own spaces in a very regular manner as schematically shown in Fig. 18, with garnet and andalusite in the quartzose layer, and staurolite and cyanite in the micaceous layer.

19) Subzone number III of the Sin'gok zone.

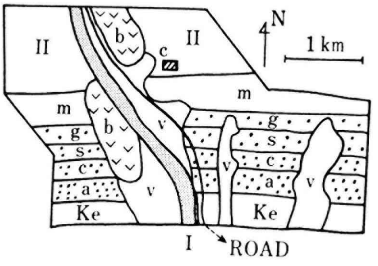


Fig. 16. The Zone-distribution of Schists near Chin'gok-ni.

II......S-II Garnet-biotite-sericite-chlorite-quartz schist

m, g, s, c, a......S-II

m. Two mica-quartz schist

g. Garnet-two mica-quartz schist

s. Staurolite-garnet-two mica-quartz schist

c. Cyanite-staurolite-garnet-two mica-quartz schist

a. Andalusite-cyanite-staurolite-garnet-two mica-quartz schist

Dots show distribution of cyanite-andalusite-bearing veins.

b. Basalt flow v. Alluvial

c. Chingok-ni I. Imjing-gang

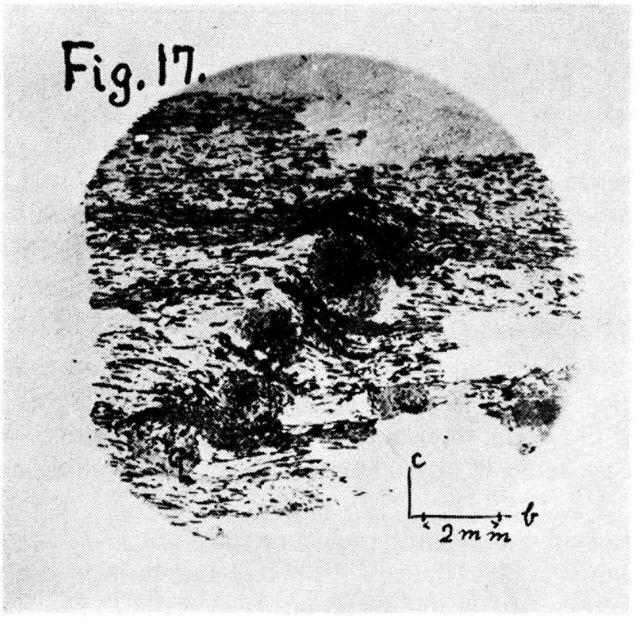


Fig. 17.

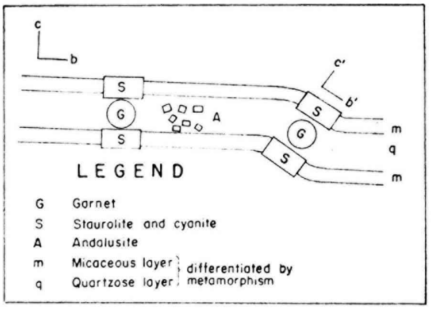


Fig. 18. Schematic Diagram of the Mode of Occurrence of Minerals in a-schist.

The interior of a-schist must be divided petrographically into three parts: (1) a representative part which consists of cyanite, staurolite, garnet, micas, and quartz; (2) the quartzose layer which consists of andalusite, cyanite, staurolite, garnet, micas and quartz and (3) the micaceous layer, in which micas are abnormally chloritized[20].

Each part is a 2–3 cm irregular mass.

iii. Microscopic structures of the minerals

Garnet In thin section the garnet shows rounded hexahedrons, and is therefore, considered to be a dodecahedron crystal. In general, it is accompanied by abnormal chlorite[20] (Fig. 19). Its formative process, therefore, may be as follows:

Micas→abnormal chlorite→garnet

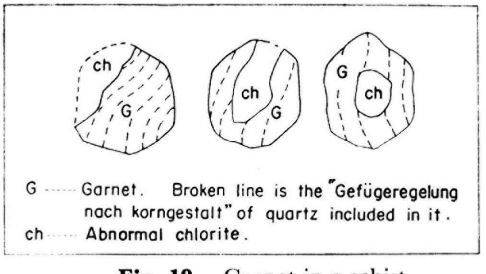


Fig. 19. Garnet in a-schist.

It contains a considerable amount of small grains of quartz *geregelt nach Korngestalt*[21]. This fact shows that the formation of garnet was accompanied by some kind of movement[22].

20) It has the relicts of cleavages of micas, is severely flexed, and is dirty yellowish-green. The amount of optical retardation γ-α is about 0.02.

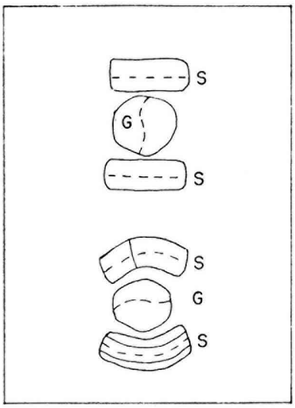
21) The more or less elongated grains of quartz are ranged in the form of S-shaped "inclusion-vortex."

22) The movements can be considered to be rotation by differential movement (the writer, 1947) or recumbent folding by compression (the writer, 1952).

Staurolite It exists generally in contact with garnet. Staurolite is found in the space of the micaceous layer while garnet is found in the space of the quartzose layer (Figs. 17, 18). It shows twin-like intergrowths which is not the characteristic twinning of staurolite. Its shape is irregular. It contains a considerable amount of quartz *geregelt nach Korngestalt* in the schistosity plane and is sometimes continuous to the inclusive-vortex in the neighboring garnet. Its modes of occurrence are shown in Fig. 20.

Cyanite Its mode of occurrence is almost similar to staurolite (Fig. 21).

A. Staurolite (S) and Garnet (G) in a-schist



B.

Fig. 20.

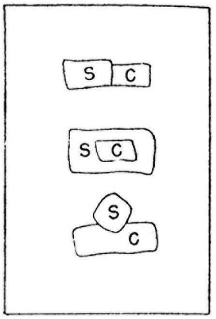
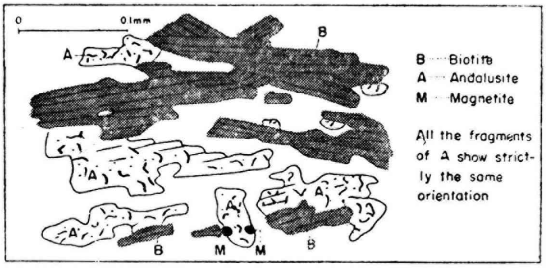


Fig. 21. The Equal Relation between Cyanite (C) and Staurolite (S).

Andalusite It exists as fragments in the quartzose layer. Sizes and shapes are almost the same as the fragments of biotite. All the fragments in the area of about 200 grains of quartz in a thin section show an identical orientation. This fact may show that the fragments of andalusite in this area are really from one crystal and that the quartz and micas in this area are its inclusions, the amount of which is so large that the one crystal of andalusite was separated into many fragments. The *Gefügeregelung* of the biotite in the area is almost the same as in the first part (Fig. 13E). The *Gefügeregelung* of the quartz in the area shows no regularity (Fig. 13G, H).

The andalusite has a tendency for its prismatic plane to lie on the plane of schistosity (Fig. 13I). It sometimes seems to have behaved in a way similar to the staurolite (Fig. 22B). The andalusite is therefore considered to have been formed simultaneously with staurolite and cyanite; the genetic difference seems to be the field of recrystallization; the material, $SiO_2+Al_2O_3$ ($+Fe_2O_3$), recrystallizes to andalusite if in the quartzose layer, or recrystallizes to cyanite or staurolite if in the micaceous layer. The modes of occurrence of the andalusite are shown in Fig. 22.

A. Mode of Occurrence of Andalusite in a-schist



B. Mode of Occurrence of Andalusite in a-schist

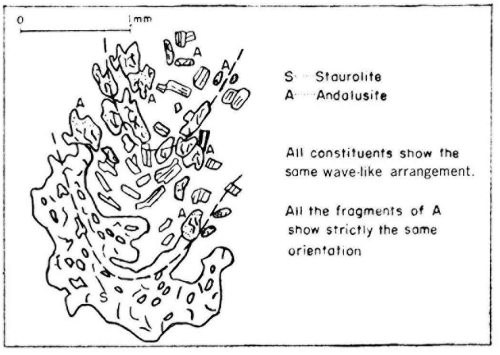


Fig. 22.

D. Sequence of Mineral Formation, Progressive Metamorphism and Metasomatism

(1) Metamorphic Progressions

As previously mentioned in C, the following metamorphic process can be viewed as the most probable.

Micas→abnormal chlorite→garnet

The chemical relations of those processes are as follows:

i. For the process, micas→abnormal chlorite, subtraction of K_2O is necessary.

ii. The measured data of the chemical composition of micas, abnormal chlorite, and garnet are shown in Table 3 and Fig. 23 (in molecular ratio).

Fig. 23 shows us the following five informative items:

The ratio of Al_2O_3 to $(FeO+MgO)$ of the micas is larger than that of the soluble component of the abnormal chlorite.

In Fig. 23a BCK is on a line.

The ratio of FeO to MgO in the micas and in the soluble component of the abnormal chlorite is almost equal.

The ratio of Al_2O_3 to $(FeO+MgO)$ in the garnet and the soluble component of the abnormal chlorite is almost equal.

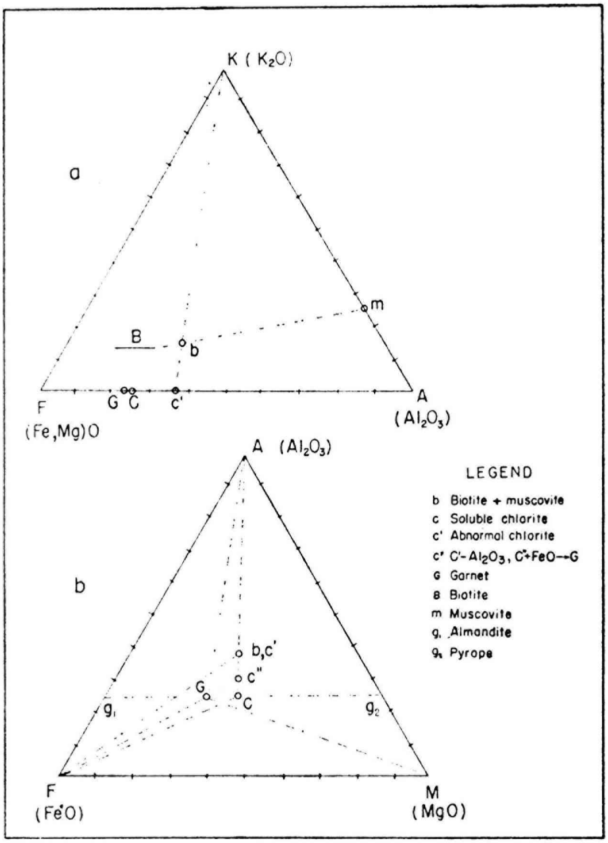


Fig. 23. Chemical Relations between the Minerals.

Table 3. Chemical Relation between Mica, Abnormal Chlorite and Garnet.

	Micas biotite + muscovite + quartz			Soluble component of abnormal chlorite		Garnet
	Wt. %	mol. ratio		Wt. gm	mol. ratio	mol. ratio
SiO_2	63.4					
Al_2O_3	14.4	37.8	32.8	0.30088	25.8	25
FeO	7.9	31.4 }		0.2554	38.3	47
MgO	4.3	30.8 }	52.1	0.1342	35.9	28
K_2O	6.2		15.1			
Total	95.2	100.0	100.0	0.6984	100.0	100

Analyzed by the writer

1. In FeO, Fe_2O_3 is included.
2. In K_2O, Na_2O is included. CaO is negligible.
3. Refractive index of the garnet is $n=1.793$; almandine: Pyrope=68:32 (mol. ratio).
4. The soluble component of abnormal chlorite was obtained by using dil. HCl to dissolve the abnormal chlorite out of the powder from which magnetite had been previously taken out by means of a magnet.
5. After 4, mica-quartz was separated by means of flotation in a heavy liquid (sp. gr. 3.0) from the heavier minerals (garnet, staurolite, cyanite and andalusite).

The ratio of FeO to MgO in the soluble component of the abnormal chlorite is smaller than the one in the garnet. SiO_2 and H_2O were not considered.

From the first three, $2M-K_2O \rightarrow ch+Al_2O_3$ .....

From the last two, $ch+FeO \rightarrow G-MgO$ .....

or, $ch+Al_2O_3+FeO \rightarrow G$ .....

From the first, $ch' = ch+Al_2O_3$ .....

The symbols used above are as follows:

2M .... Micas, ch' .... Abnormal chlorite,

ch .... Its soluble component, G .... Garnet.

From these, the following conclusions were made: by means of the subtraction of K_2O, the micas change to a supermicroscopic aggregation of chlorite and perhaps sillimanite[23]. These supermicroscopic needles of sillimanite may migrate, recrystallize, and form several aluminous minerals. The garnet is considered to be formed under the process 6. It is clear in Fig. 23B that Al_2O_3 derived from the micas is present in larger amounts than are necessary for the formation of the garnet:

$$2M-K_2O+FeO \rightarrow G+Al_2O_3$$

(FGC" in Fig. 23B)

The source of +FeO may be magnetite in the schist. Al_2O_3 may have recrystallized as staurolite, cyanite, and andalusite. The process is summarized as follows:

Micas + Magnetite − K_2O → Garnet + Staurolite,
Cyanite,
Andalusite.

The K_2O migrates into the outer part of the parent schist bodies.

Table 4. Migrating Materials and Products of Recrystallization.

			Excess of	SiO_2......C + Q......(1)
			some	SiO_2......C ....(2)
			very little	SiO_2......C + R ......(3)
			no	SiO_2......R ....(4)
recrystallization of muscovite	(SiO_2, Al_2O_3, K_2O)	no excess of K_2O		
		no excess of Al_2O_3		Q + K_2O...(5)
		no excess of SiO		R + K_2O...(6)

Final mineral assemblages (Products of Recristallization):

(1)	(2)	(3)	(4)	(5)	(6)
M+C+Q	M+C	M+C+R	M+R	M+Q	M+R

K_2O in (5) and (6) migrates out far-away.

C......Cyanite and andalusite Q......Quartz

R......Corundum M......Muscovite

[23] This interpretation agrees with the fact that retardation γ-α of the abnormal chlorite and sillimanite is almost equal. This can be observed in several rocks in Korea.

(2) Metamorphic Differentiation

As mentioned above, K_2O must and Al_2O_3 may migrate. SiO_2 and H_2O are the materials most likely to migrate[24]. In the case where these materials migrate into the fissures or cavities and recrystallize, the mineral assemblages are as shown in Table 4.

All the final mineral assemblages are observed in veins or pockets in the schist zone of SIII as stated in III, E.

(3) Other Examples of Metamorphic Differentiation

A rare example is cummingtonite-quartz rock found in zone SIII. This rock is like a sheet or tongue, several centimeters thick, parallel to the schistosity of the country rock, and is therefore considered to have been formed by dynamo-metamorphism. It is primarily composed of SiO_2, FeO, and MgO. It is therefore possible that this rock was derived from the mica schist by the following process[25]:

$$\text{Micas}-K_2O-Al_2O_3\rightarrow\text{cummingtonite} \ldots\ldots \quad 10$$

(4) Progressive Metamorphism Accompanied by Metasomatism and Metamorphic Differentiation

It can be summarized that two kinds of processes of progressive metamorphism accompanied by metasomatism occurred in the two zones:

One was in zone Y,

$$\text{ottrelite}+K_2O\rightarrow\text{biotite},$$
$$\text{chlorite}+\text{sericite}+K_2O\rightarrow\text{biotite},$$

The other was in zone SIII,

$$\text{micas}+\text{magnetite}-K_2O\rightarrow\text{garnet}+\text{staurolite}, \text{cyanite}, \text{andalusite}.$$

It is quite possible that K_2O migrates from zone SIII into zone Y as one of metamorphic differentiation.

(5) Some Properties of Biotite

The quantitative relation between biotite and muscovite and the quality of the biotite seem to be related to the grade of metamorphism. The quantitative ratio of the biotite to muscovite increases from m-schist to a-schist (III.C. (2). i.), The refractive indices ($\beta\doteqdot\gamma$) of the biotites are as follows:

m-	g-	s-	c-	a-schist
1.625	1.625	1.625	1.627	1.629

The refractive index ($\beta\doteqdot\gamma$) of the biotites in each zone varies zone by zone:

zone	Y	SI	SII	Ke	Sa
average →	1.628 ⟶	1.625 ⟶	1.633 ⟶	1.625 ⟶	1.630

The relation between the value $\beta\doteqdot\gamma$ and the chemical composition has not been clarified.

24) "Kieselsaure ist das mobilste Material bei der Metamorphose." (Eskola: Entstehung der Gesteine, p. 407).

25) In this process, subtraction of K_2O and Al_2O_3 occurred. In the zone of mica schist of the Okch'ŏn system, (garnet)-anthophyllite-cordierite rocks are found. In such a rock, subtraction of Al_2O_3 is considered to have occurred imperfectly.

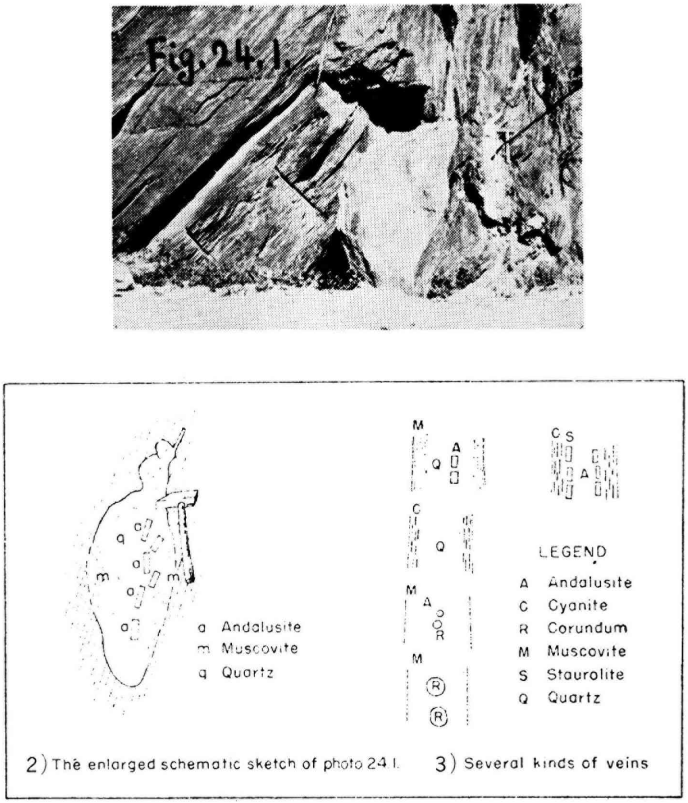


Fig. 24. Modes of Occurrence of the Ore Deposits.

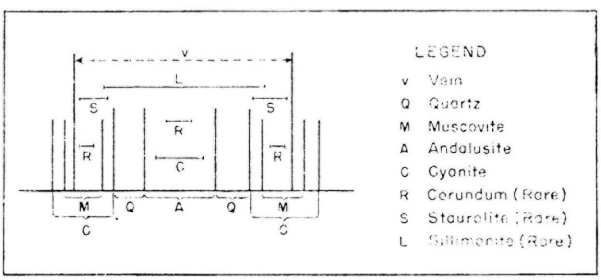


Fig. 25. Synoptic Representation of the Situations of Minerals in Veins.

Fig. 26. Some Minerals in a Small Quartz Vein.
G......Garnet A......Andalusite C......Cyanite

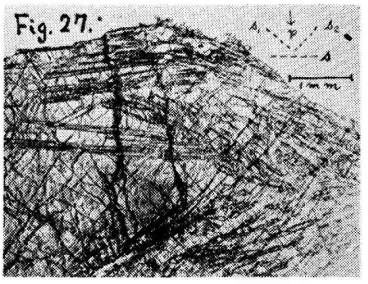


Fig. 27. Cracks and Cyanite Flakes in a Crystal of Andalusite.

E. Cyanite-andalusite Deposits

(1) Deposits which are in the form of veins or pockets containing cyanite and andalusite are one of the proofs of metamorphic differentiation (III. D. (2)).

The modes of occurrence of the minerals in the veins or pockets show some regularity as shown in Fig. 24. This regularity can be diagrammed as in Fig. 25.

Sometimes small quartz veins containing garnet, cyanite, and andalusite are found parallel to the plane of schistosity of the schist. In the schist in contact with the small veins, almost no quartz exists (Fig. 26). This may be one positive example of segregation by means of metamorphic differentiation. Cyanites are regularly found in the relatively large crystals of andalusite (Fig. 27). This informs us that the cyanites were formed regularly under a *Plättung* accompanied by shearing.

(2) The deposits are more concentrated in the eastern area of the Imjin-gang, where the reserve of cyanite and andalusite was estimated to be about 300,000–500,000 metric tons.

As mentioned in the introduction, the residual blocks from the veins or the pockets were collected during the first stage of mining; in the next stage, the veins or the pockets were prospected and mined. During World War II, the residual blocks seem to have been exhausted[26].

4. Summary

1. In the region covered by my study, I found no evidence supporting the proposal that the Yŏnch'ŏn system is Archean. The original formations of this "system" may be the formations succeeding the uppermost member of the Shōgen (Sangwŏn) system in Middle Korea. The dynamometamorphism occurred simultaneously with the injection of the porphyritic granite in the southern region. The plane of schistosity differs distinctively from the plane of stratification of the original formation. I consider the name Yŏnch'ŏn metamorphic group to be preferable to Rensen (Yŏnch'ŏn) system.

2. The Yŏnch'ŏn metamorphic group shows a well-developed zonal structure. Each zone has its own characteristic metamorphism.

3. The metamorphism is a typical progressive metamorphism accompanied by metamorphic differentiations (migrations of some materials) and metasomatism. The principal dynamic factor of the metamorphism is *Plättung*.

4. The cyanite-andalusite deposits are one proof of metamorphic differentiation.

REFERENCES

KAWASAKI, S. (1918); Mineral Resources of Chōsen, v. 6 (North part of Kyonggi-do) (J).

YAMAGUCHI, T. (1941); Cyanite-Andalusite Deposit in the Rensen system, *Chōsen Kōgyō (Mining of Korea)*, v. 8, no. 11 (J).

—— (1947); Analysis of Inclusion Vortex, *Jour. Geo. Soc. Japan*, v. 53, nos. 616–621.

—— (1952A); Cyanite Deposit in Yokusen system, *Geol. and Min. Resources of the Far East*, v. 1 (J).

—— (1952B); Cyanite Deposit in Shōgen system, *Geol. and Min. Resources of the Far East* (J).

—— (1952C); S-shaped Curve of Inclusions in Porphyroblast and Role of Compression in Schistose Rocks. *Jour. Geo. Soc. Japan*, v. 58, no. 680 (J).

[26] After the Mining Law of Korea was revised (1941) until August, 1945, the mining and the sale of cyanite (including andalusite, sillimanite, and corundum) was controlled by Chōsen Kōgyō Shinkō Co. (Mining Promotion Company of Korea), but the actual working of the mines was generally assigned to small-scale civilian miners. Because of the simple mining (requiring only the collection of the residual blocks), the low cost of mining (5–10 yen/ton in 1941), and the high selling price (100–150 yen/ton in 1941), large profits were obtained in a relatively short period. Accordingly, many civilian miners or brokers crowded to the cyanite mines to profit from this boom.