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Replacement of cordierite by basic plagioclase

ABSTRACT: The process is described of the replacement of cordierite by basic plagioclase associated with subordinate chlorite and sporadical biotite. It took place during regressive metamorphism of the metamorphic Krynki series (Precambrian substrate of NE Poland) developed in the hornfels facies, with calcium and alkalies supplied probably under a low pressure and temperatures ranging from 330 to 580° C. The recognized plagioclase has been analysed on a universal stage for its composition, facial development and orientation in relation to the cordierite being replaced.

INTRODUCTION

The formation of cordierite at the expense of plagioclase by a metasomatic supply of magnesium (Bugge 1943) is a commonly known fact. The present writer has, however, observed an opposite phenomenon, *i.e.* the development at the expenses of cordierite, by the introduction of calcium and alkalies, of a strongly basic plagioclase, belonging mostly to bytownite, associated with relatively scarce chlorite and sporadical biotite. A small-scale process of this kind occurred locally during regressive metamorphism of a rock assemblage developed in the amphibole-hornfels and pyroxene-hornfels facies (Krynki series, *cf.* Ryka 1964) pierced near the village Plebanowo, E of Białystok (NE Poland).

The regressive metamorphism of this rock complex is expressed by the replacement of: cordierite by anorthite, chlorite, pinite; of plagioclase by calcite, muscovite, quartz, sericite, epidote; of potash felspars by sericite; of amphibole by biotite, chlorite, talc; of garnet by biotite and chlorite; of biotite by chlorite; of sillimanite and andalusite by chlorite and colourless fine-grained mica. The banded arrangement of the particular products of regressive metamorphism is observable in the rock complex investigated. The replacement of cordierite by basic plagioclase has taken place exclusively in the bottom parts of the rock complex, at a depth between 684 and 725 m, within the cordierite-biotite-plagioclase gneisses (*cf.* Pls 1—2). Most probably it represents the highest temperature phase of cordierite in the regressive metamorphism of the above rock complex.

TRANSFORMATION OF CORDIERITE

Various stages of the replacement of cordierite by basic plagioclase have been observed in the rock complex under consideration. This process starts at the rim of cordierite grains and consists in the development, at the expenses of cordierite, of a narrow fine-aggregate plagioclase zone intercalated by thin plates of chlorite and sporadic biotite and invading cordierite by an uneven inter-toothed surface (Pl. 1, Fig. 1). This zone widens (Pl. 1, Fig. 2) and, here and there, it closes up isolated cordierite relics (Pl. 1, Fig. 3). Finally, the cordierite is fully replaced by a fine--grained aggregate of heterogenic plagioclases with delicate chlorite intercalations (Pl. 1, Fig. 4). The irregular intricate boundaries of the plagioclase grains reasonably suggest that the aggregates have not attained their state of equilibrium. Here and there the occurrence is observed of plagioclase aggregates, more coarse-grained and with more regular grain boundaries (Text-fig. 1 and Pl. 2).

Chlorite accompanying plagioclases belong to clinochlore or prochlorite. It occurs as extremely thin plates, undeformed and enclosed in plagioclases, also as thicker plates, often polisynthetically twinned, isolated, sometimes with a fan-like arragement. The sporadic biotite formed in place of cordierite displays minute undeformed plates pleochroic in brown.

CHARACTER OF PLAGIOCLASES

The plagioclases formed at the expenses of cordierite are anhedral and heterogenic. They have been studied under strong (× 32) magnification on the universal stage, with dual marking of the position of the crystallographic and optical directions. The composition of plagioclases has been determined on the *α'/010* angle in section $\perp$ [100] and verified on the basis of full optical orientation using the Burri, Parker & Wenk (1967) diagrams. The composition of some grains has also been determined on the position of the rhombic section. These investigations show that the composition of the plagioclases here considered ranges from An_{36} to An_{100} *[*$\sphericalangle\, \alpha'/010 = 47°$*]* in most cases belonging to the An_{70-80} bytownite. The majority are untwinned and form incidental jointing, less often they are with rare albite and pericline twins. The albite twins consist of rare lamellae, varying in thickness, often fairly irregular, often not traversing the whole grain and ending blindly without thinning out. It is doubtless

Table 1

Composition of plagioclases presented in Text-figs 1—3 and Pl. 2

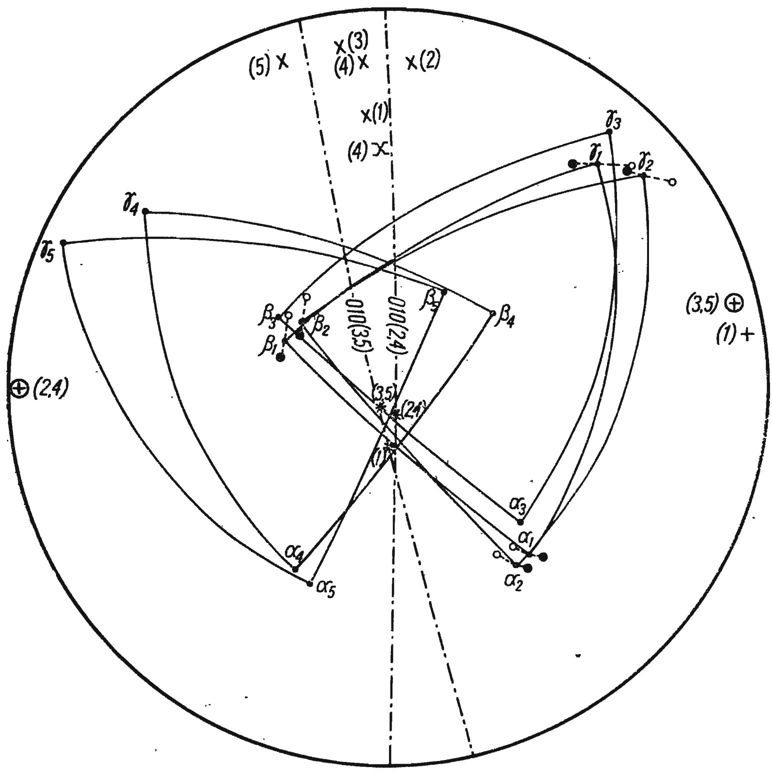
Aggregate	Grain no.	Anorthite content in plagioclase grains					
		minimal		most common		maximal	
		$\sphericalangle\alpha'/010$ $\perp[100]$	An %	$\sphericalangle\alpha'/010$ $\perp[100]$	An %	$\sphericalangle\alpha'/010$ $\perp[100]$	An %
I /Pl.2, fig.1/	1	36.8°	67	40.5°	77	43.6°	87
	2	33.3°	61.5	39.8°	75	41.8°	80.5
	3	33.8°	62	38.2°	71	40.0°	75.5
	4	30.7°	57.5	34.5°	63	34.6°	63
		-	-	-	-	-	96*
	5	35°	63.5	37.5°	67.5	39°	73
II /Pl.2, fig.2/	1 i 2	-	-	23.3°	43.5	-	-
	3'	-	-	40.6°	78	-	-
	3 i 4	36°	65	39.0°	73	39°	73
	5	-	-	-	80**	-	-

* Determined on the position of rhombic section which meets plane *001* at an angle of —17°.
** Determined on the position of rhombic section which meets plane *001* at an angle of —9°.

that the albite twins are primary in character, *i.e.* they formed during the growth of plagioclase. The pericline lamellae are thinner than those of albite, in some spots of the grain fairly numerous and often thinning out. The jointings of plagioclases are illustrated by the example of two aggregates marked *I* and *II* in Pl. 2, while the orientation of the crystallographic and optical directions is given on stereographic projections (Figs 1 and 2) oriented identically as in the photographs. Parts of aggregates differing in orientation are marked on the photographs with numbers corresponding to the numbers on projections referring to the crystallographic and optical directions of those parts. The composition of plagioclases in the aggregates here considered is shown in Table 1.

In aggregate *I* (Text-fig. 1; Pl. 2, Fig. 1) the parts marked *1, 2, 3* form incidental jointings. Their *010* planes meet at angles of 5—14°, the *001* planes at angles of 12—14° and the [100] directions at angles of 6—13°. Fields *2* and *4,* also *3* and *5* form albite twins united by well developed *010* planes (plotted onto the projection) and by other less well developed planes (not plotted onto the projection), situated approximately within the [100] zone. Within parts *4* and *5* there are very thin pericline lamellae. In section oblique to the composition plane these occur as blurred streaks. Hence in aggregate *I* there are three parts with haphazard but similar orientation, reasonably suggesting that the aggregate developed out of three nuclei having a similar orientation.

Aggregate *II* (Text-fig. 2; Pl. 2, Fig. 2) consists of homogenic andesine with Manebach twins (*1* and *2*) which occurred in association with cordierite, and of a younger non-homogenic aggregated bytownite (*3—5*) with albite and pericline twins formed at the expense of cordierite. Under the microscope this aggregate might possibly suggest that bytownite encasing the older andesine used it as a nucleus. A more detailed analysis shows, however, that andesine had no strong bearing on the orientation of bytownite. The mutual position of the various parts of bytownite is shown in diagram (Fig. 3). As microscopically seen the aggregate might suggest that parts *4* and *5* of the bytownite grow on part *1* of andesine. The *001* planes of parts *1* and *5* are concordant, while the orientation of the optical vectors reveals that part *5* occupies a position which may be obtained from part *1* by a rotation of 180° round the [100] direction. Within part *5* there is a thin pericline lamella. Part *4* turns at an angle of *c.* 15° from part *5* round a direction approaching [100]. Part *3* is in the position of albite twinning in relation to part *4*. In some places they are united by



•*1* ○*2* ●*3* ○*4* ×*5* +*6* ×*7* ✱*8* ------*9* *(1-5) 10*

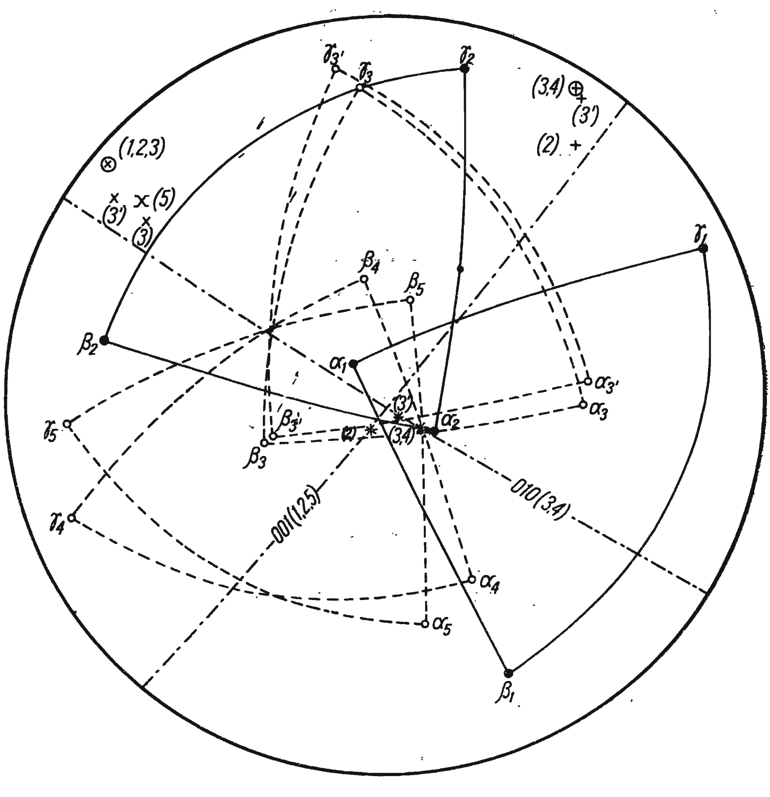
Fig. 1

Stereographic projection of the basic plagioclase aggregate *I* (presented in Pl. 2, Fig. 1; orientation of the projection identical as that in the photograph)

1 optical vectors of the plagioclase parts with composition predominant within the given grain (An_{63-77}), *2* optical vectors of plagioclase parts poorest in anorthite (An_{58-67}) within the given grain, *3* optical vectors of plagioclase parts richest in anorthite (An_{75-87}) within the given grain, *4* axes of albite twins, *5* normals of *010* planes, *6* normals of *001* planes, *7* normals of the planes of pericline lamellae (rhombic section), *8* — [100] directions, *9* composition planes of albite lamellae, *10* numbering of the various plagioclase parts identical as in Pl. 2, Fig. 1

well developed *010* planes, in others by less well developed planes lying approximately in belt [100]. Part *3'* is slightly turned from part *3*, so that their *010* planes meet at an angle of *c.* 2°, and their *001* planes at an angle of *c.* 7°. Part *3* of bytownite is slightly turned from part *2* of the andesine, so that their *010* planes meet at an angle of *c.* 9°, and the *001* planes at an angle of *c.* 13°. Parts *3'* of the bytownite and *2* of the andesine are so mutually placed that their *010* planes meet at an angle of *c.* 8° and the *001* planes at an angle of *c.* 7°.

Thus, the plagioclase here described consists of three parts of bytownite haphazardly but similarly oriented in disconformity with the orientation of older andesine. This may suggest that the aggregate developed from three bytownite nuclei formed within cordierite, while andesine associated with cordierite had not been



•1 ∘2 •3 ⊗4 ⊕5 +6 ×7 ×8 ----9 (1-5)10

Fig. 2

Stereographic projection of the plagioclase aggregate *II* (presented in Pl. 2, Fig. 2; orientation of projection identical as that in photograph)

1 optical vectors of primary andesine, *2* optical vectors of bytownite formed at the expense of cordierite, *3* optic axis, *4* axis of the Manebach twinning of andesine, *5* axis of albite twinning of bytownite, *6* normals of *010* planes, *7* normals of *001* planes, *8* normals of the composition plane of the pericline lamellae of bytownite (rhombic section), *9* — [100] directions, *10* composition planes of twins, *11* numbering of various parts of plagioclase identical as thet in Pl. 2, Fig. 2

used as a nucleus. Hence, it may be concluded that during a certain phase of regressive metamorphism of the rock association under investigation, there was a tendency for the formation of bytownite nuclei within cordierite.

Of special interest is the fact that in both the above cases, the bytownite nuclei, produced independently of each other within the cordierite, are similarly oriented. This might suggest that the bytownite nuclei used for their development certain lattice elements of cordierite.

A large monocrystalline cordierite grain, the various parts of which represent particular phases of replacement (Pl. 1, Figs 1—3) was selected for investigating the interdependence of the orientation of cordierite and that of plagioclase. The orientation of the *010* and *001* planes of plagioclases (An_{36}—An_{100}) replacing cordierite, to the principal optical vectors of cordierite, was determined on the universal stage. The results are shown in the stereographic projection (Fig. 4), onto which — on data from the literature (Dana 1904) have also been plotted the cordierite planes. In this projection, the (010), (001) and [100] directions of plagioclases are grouped within fields the angular centres of which coincide with the normals of the potential cordierite planes. The (001) directions of plagioclases are grouped around the (342) direction of cordierite, the distance between them being up to c. 30°. The (010) plagioclase directions are concentrated around the (1 10 4) cordierite direction, never being deviated by more than c. 22 degrees.

The above data reliably indicate a connection between the orientation of cordierite and that of plagioclase, *i.e.* that the determined crystallographic directions of plagioclases coincide with the determined, relatively big cluster of the crystallographic directions of cordierite.

THE SUPPOSED DEVELOPMENTAL CONDITIONS

The development of the bytownite + chlorite association at the expense of cordierite was made possible in a hydrated environment by the introduction of Ca and Na and the expulsion of SiO_2. This is illustrated by the reaction of the metamorphic changes of cordierite (having a theore-

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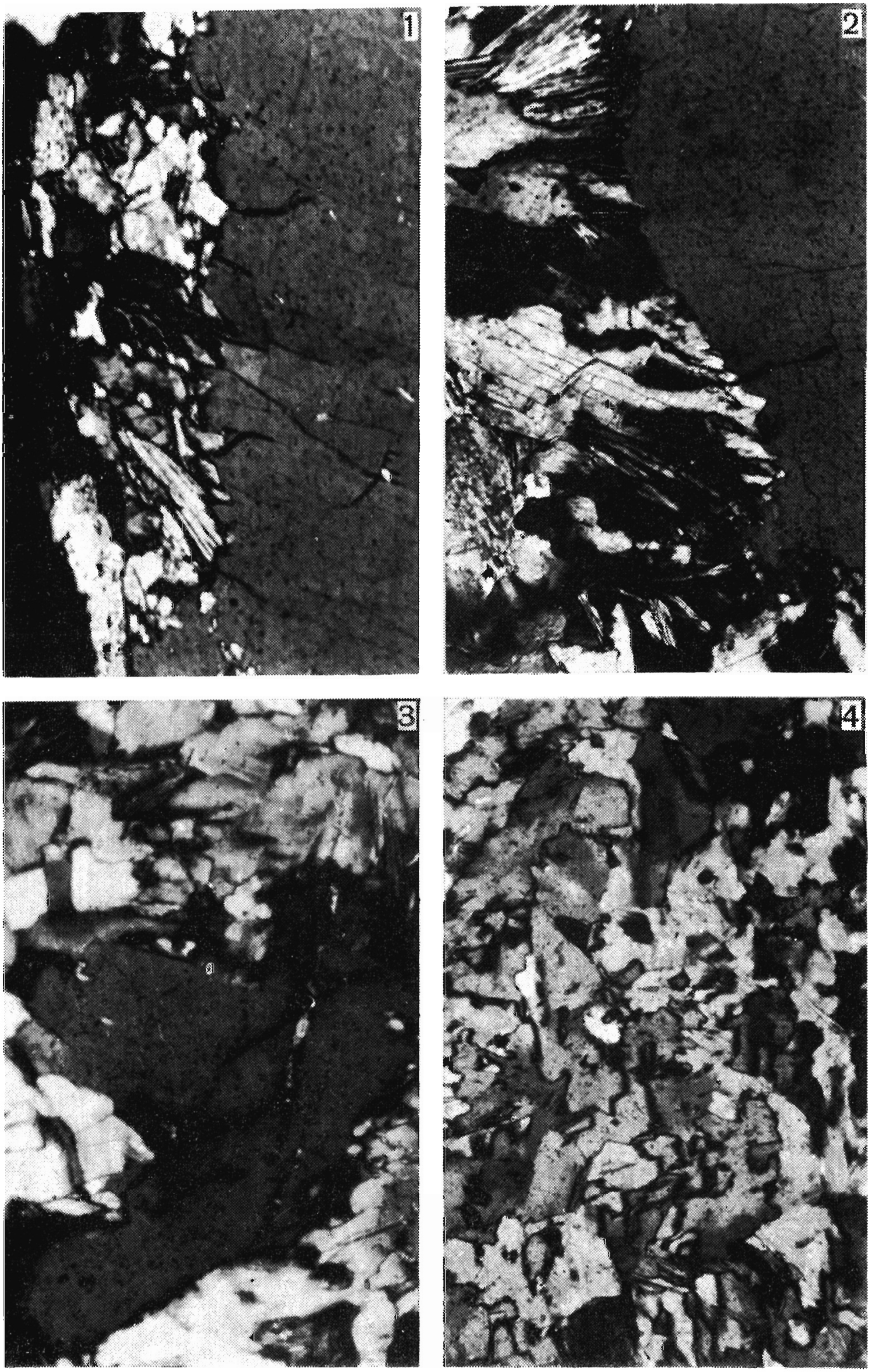
PLATE 1

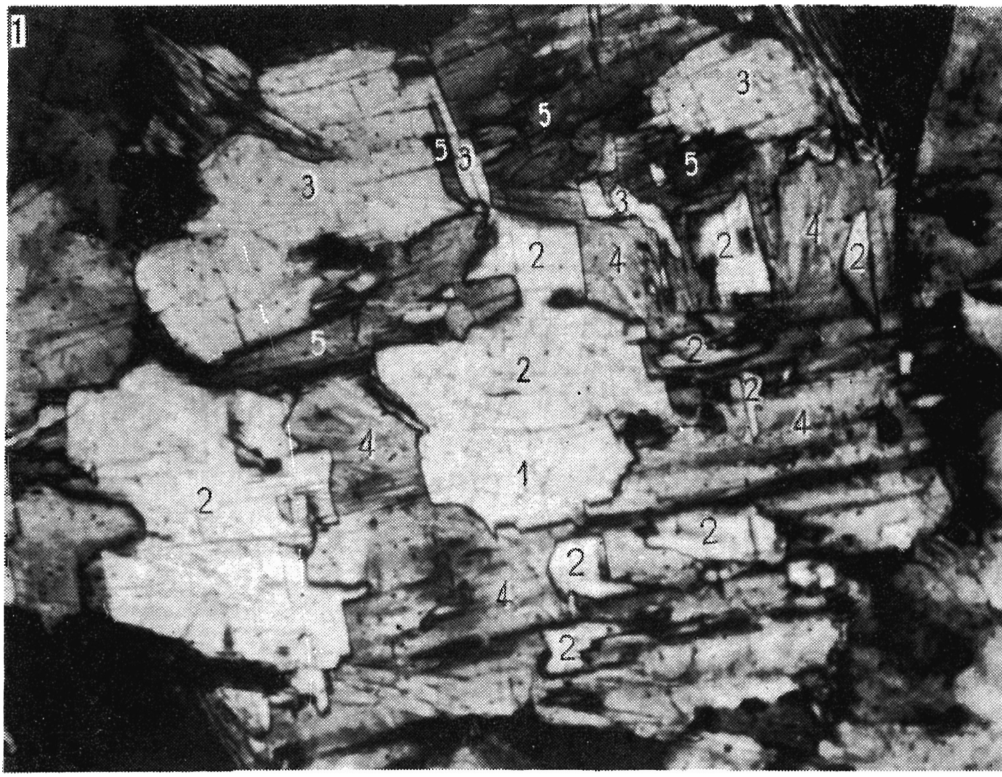
1 — Narrow zone of small aggregates, built of basic plagioclase, scarce klinochlore and sporadic biotite, formed at the expense of cordierite. To the right: fragment of a large cordierite grain, to the left — quartz. Cordierite-biotite-plagioclase gneiss; × 103, nicols crossed.

2 — Wide zone consisting of basic plagioclase, chlorite and sporadic biotite, formed at the expense of cordierite: fragment of a strongly altered part of a cordierite grain presented in the preceding photo; × 103, nicols crossed.

3 — Relic cordierite (bottom of photo) embedded among finely aggregated association of basic plagioclase associated with chlorite: fragment of a very strongly altered part of the cordierite grain presented in photos 1—2 of this plate; × 175, nicols crossed.

4 — Assemblage of fine-grained basic plagioclase with delicate chlorite ingrowths, formed at the expense of cordierite; × 103, nicols crossed.

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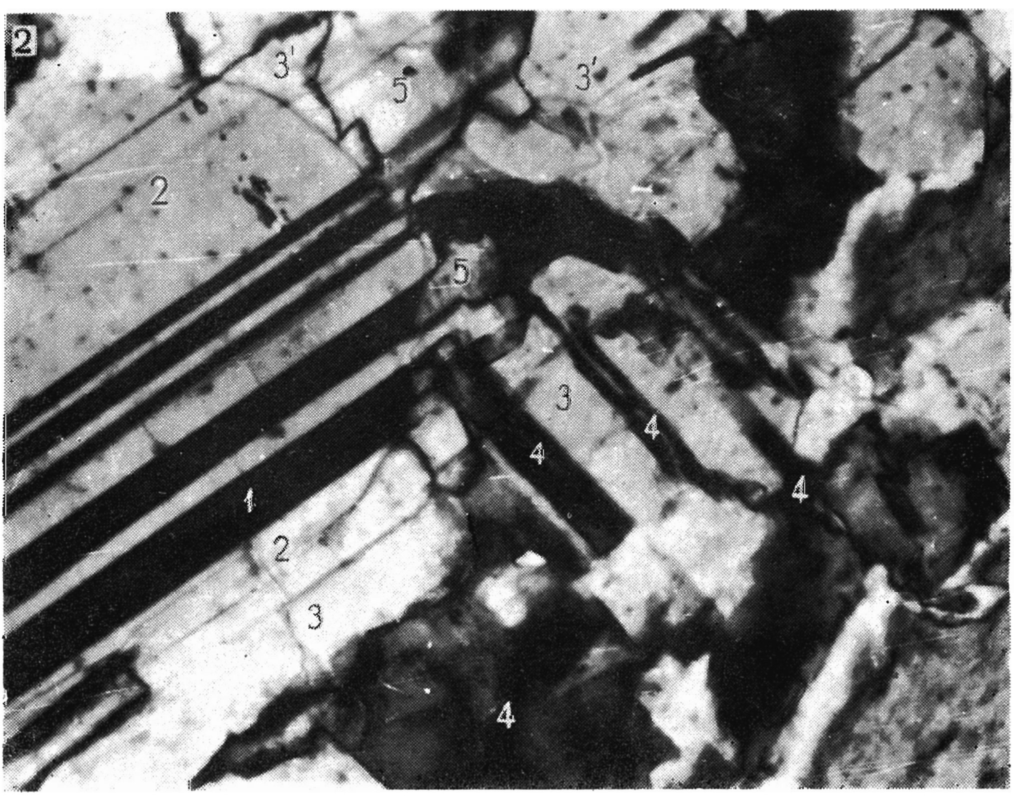
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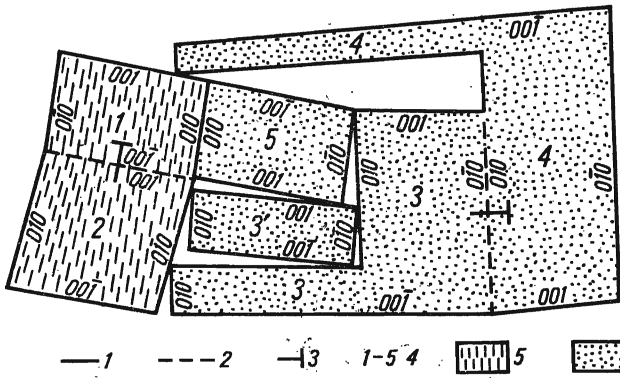

Fig. 3

Diagram showing the mutual orientation of various parts of the plagioclase aggregate *II* (*cf.* Pl. 2, Fig. 2 and projection in Text-fig. 2)

1 planes, *2* composition planes of twins, *3* axes of twins, *4* numbering of the particular parts of plagioclase identical as in Text-fig. 2 and Pl. 2, Fig. 2, *5* primary andesine, *6* secondary bytownite formed at the expense of cordierite

tical composition) into the bytownite (c. An_{82}) + chlorite + quartz association

$$\underset{\text{cordierite}}{10\ Mg_2Al_4Si_5O_{18}} + 9\ CaO + Na_2O + 20\ H_2O \rightarrow$$

$$\rightarrow \underset{\text{bytownite (c. An}_{82})}{9\ CaAl_2Si_2O_8 \cdot 2\ NaAlSi_3O_8} + \underset{\substack{\text{septochlorite}\\ \text{(amesite)}}}{10\ Mg_2Al_2SiO_5(OH)_4} + \underset{\text{quartz}}{16\ SiO_2}$$

If the composition of the plagioclase replacing cordierite was c. An_{33}, an analogous reaction would produce a quartz-less association made up exclusively of plagioclase and chlorite. The formation of a more basic plagioclase leads to excess of SiO_2. The absence of quartz in the bytownite + chlorite association here described suggests the removal of excess of silica during the transformation of cordierite.

PLATE 2

1 — Aggregate *I* of basic plagioclase, formed at the expense of cordierite, with delicate chlorite ingrowths (hardly detectable in the photo): parts *2* and *4*, also *3* and *5* are with albite twinning, within parts *4* and *5* occur thin pericline lamellae, hardly detectable in the photo as blurred streaks; parts *1*, *2* and *3* are haphazardly united; × 103, nicols crossed.

2 — Aggregate *II* of basic plagioclase (*3—5*), formed at the expense of cordierite, coating a grain of older andesine (*1—2*) with Manebach twinning; parts *3* and *4* of the bytownite form albite twins, a thin pericline lamella is visible in part *5*; parts *3*, *3′* and *5* are haphazardly united; × 582, nicols crossed.

The question now arises under what physical conditions the above reaction could take place.

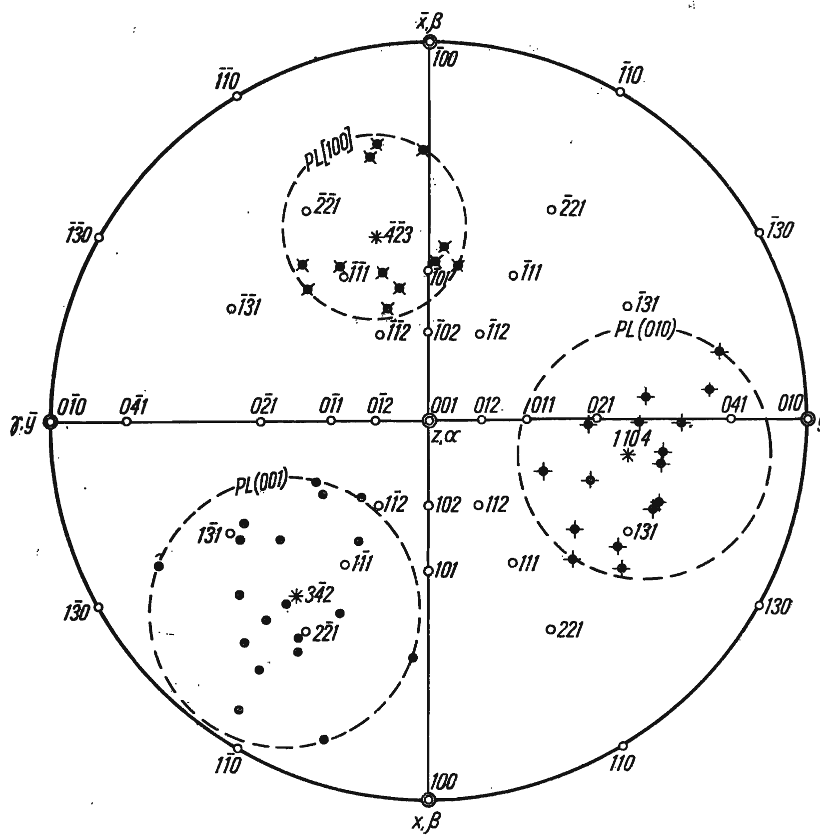

Fig. 4

Orientation of basic replacement plagioclase in relation to cordierite

1 crystallographic axes of cordierite, 2 chief crystallographic planes of cordierite, 3 planes of cordierite (*after* Dana 1904), 4 — [100] directions of plagioclases, 5 normals of *010* planes of plagioclases, 6 normals of *001* planes of plagioclases, 7 line delimiting the occurrence field of a given crystallographic direction of plagioclase, 8 direction of cordierite coinciding with the angular centre of the area delimiting the occurrence field of a given crystallographic direction of plagioclases, 9 plagioclases

During the progressive metamorphism of the rock sequence under consideration one of the associations then formed was sillimanite + andalusite + potash felspar, while the muscovite + quartz association was unstable. According to Hess (1969) the above stable association should have formed under a temperature > 675° C and pressures < 4.1 kb.

In the stage of the replacement of cordierite by basic plagioclase and chlorite during the regressive metamorphism of that rock association there occur no signs of deformation to indicate the static character of the prevalent pressure. It seems reasonable to suppose that this pressure was not higher, but more likely lower than that prevalent during the progressive metamorphism of the rock sequence; Fig. 5 showing the lower

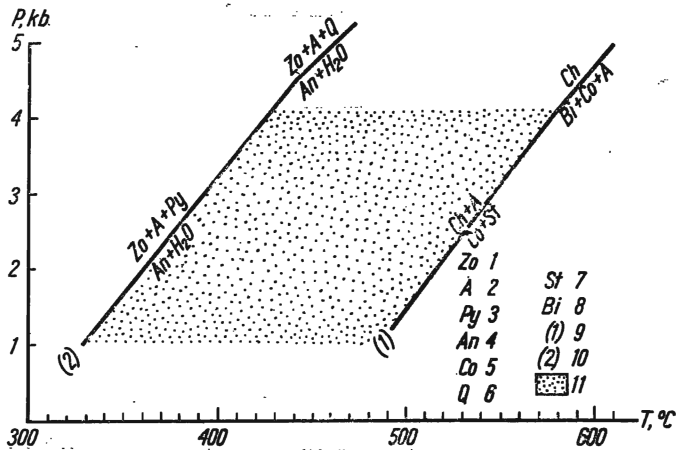

Fig. 5

Supposed field with the stable anorthite+chlorite association, and unstable cordierite under a pressure of < 4.1 kb

1 zoisite, *2* Al_2SiO_5, *3* pyrophyllite, *4* anorthite, *5* cordierite, *6* quartz, *7* staurolite, *8* biotite, *9* line delimiting the fields of the associations: chlorite + andalusite, and cordierite + staurolite, also biotite + cordierite + andalusite and chlorite (*after* Hess 1969), *10* line delimiting the stability fields of anorthite + H_2O and zoisite + pyrophyllite + Al_2SiO_5 (*after* Nitsch 1971), *11* supposed stability field of the anorthite + chlorite association

boundaries of the stability fields of anorthite (Nitsch 1971) and cordierite (Hess 1969) suggests that under a pressure of < 4.1 kb, the temperature of the formation of the basic plagioclase + chlorite association ranges from 330 to 580°C.

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ZASTĘPOWANIE KORDIERYTU PRZEZ ZASADOWY PLAGIOKLAZ

(Streszczenie)

Dotychczas znany był fakt rozwoju kordierytu kosztem plagioklazu na drodze metasomatycznego doprowadzenia magnezu (Bugge 1943). Autor zaobserwował zjawisko odwrotne, a mianowicie zastępowanie kordierytu przez zasadowy plagioklaz (An_{36}—An_{100}) należący przeważnie do bytownitu, a stowarzyszony ze stosunkowo nielicznym chlorytem i sporadycznym biotytem (por. pl. 1—2). Proces ten rozwinął się na niewielką skalę w toku regresywnych przemian krynkowskiej serii metamorficznej przewierconej w Plebanowie k. Białegostoku; przebiegał on przypuszczalnie pod niskim ciśnieniem ($<$ 4,1 kbar) w temperaturach mieszczących się w zakresie 330—580°C (fig. 5), w warunkach doprowadzenia wapnia i alkaliów. Zasadowy plagioklaz powstający kosztem kordierytu ma tutaj budowę agregatową. Dwa agregaty plagioklazowe (por. pl. 2) zbadano na stoliku uniwersalnym, charakteryzując ich skład (tab. 1), orientację (fig. 1—3) i wykształcenie, oraz stwierdzając, że istnieje związek między orientacją kordierytu i zastępującego go plagioklazu (por. fig. 4). Zwrócono też uwagę, że panujące w czasie omawianych przemian warunki fizykochemiczne szczególnie sprzyjały tworzeniu się zarodków zasadowego plagioklazu w kordierycie, podczas gdy kwaśniejsze plagioklazy kontaktujące z ziarnami kordierytu, nie były wykorzystywane jako tego typu zarodki.

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