Some petrological aspects of order–disorder in feldspars.

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[Communicated by Dr. I. D. Muir; read 22 March 1962.]

Summary. The results are presented of some recent feldspar studies that relate the fundamental concepts of order–disorder series to petrological problems. New diagrams have been prepared with coordinates 'optical properties–chemical composition–structural state'. From direct observations made on natural minerals some conclusions have been reached about the sequence in which the solid-state transformations of ordering, unmixing, and twinning occur in feldspars.

A study has been made of the geological distribution of different structural types of alkali feldspars in single intrusive bodies (Tertiary granite, Palaeozoic syenite, Pre-cambrian charnockite), in magmatic complexes, and in different complexes of the Ukrainian Shield and the Caucasus Geosynclinal Province.

A RECONSIDERATION of feldspar mineralogy during the past decade was connected with order–disorder relations in this mineral group. During this period as many feldspar works were published as during the whole previous history of mineralogy.

After the main results of the structural-thermodynamical studies had been published (Taylor, Gay, Megaw, and co-workers; Laves, Goldsmith, and co-workers; Mackenzie and Smith)[1] these relations came to be investigated as geological phenomena (Barth, Gay, Guitard and Sabatier, Heier, Marfunin, Marmo, Muir, Oftedahl, and others).[1]

This paper presents the results of some studies based on universal-stage measurements that correlate the distribution of feldspar optical-structure types with geological mapping of large areas in the USSR. From these works observations were selected that complement the existing X-ray and experimental data used for interpretation of phase relations in feldspars and their petrological significance.

Before summarizing the results of this survey of the petrological problems, consideration should be given to a number of conclusions based on optical and mineralogical investigations.

Optical orientation of plagioclases. In the last 70 years there has been

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[1] See references in papers of the Feldspar-Symposium in Cursillos y conferencias, Instituto 'Lucas Mallada', 1961, Fasc., Madrid.

a great change in the accepted ideas of the phase relations in the plagioclases and an increased understanding of their relation to the optical orientation. Michel-Lévy[1] treated the plagioclases as a series of individual chemical compounds, each with its distinct optical orientation—a series of points; Nikitin[2] recognized that there is a series of solid solutions, with which the optical orientations may be correlated by a set of curves; Köhler[3] distinguished two series of plagioclases, high- and low-temperature, with two corresponding sets of optical-orientation curves; and Marfunin[4] recognized the continuity of the order–disorder relation, which spreads the optical-orientation curves into a divariant field that may be plotted as a network of isoplets.

Two recent diagrams based on Köhler's generalization are those of Burri[5] and of Zavaritskii, Sobolev, *et al.*[6] A diagram with divariant fields of isoplets seems to be the most unbiased method of treating the available composition data; it is also the first attempt at plotting optical properties against degree of order–disorder.

Further factors must now be taken into consideration. Peristerite unmixing results in complications owing to the cooperative action of two phases of different compositions. However, as the trend of variation of optical orientation that depends on the degree of order–disorder differs from that depending on composition, these two factors cannot be confused.

Scattering of optical orientation data of natural plagioclases seems to be the result of insufficient precision in the usual orthoscopic method of measurement, which exaggerates variations in such properties. Our conoscopic determinations of the orientation of the optic axis A in labradorites[7] from the Korosten pluton in the Ukrainian Shield showed

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[1] A. Michel-Lévy, Étude sur la détermination des feldspats dans les plaques, minces, 1984, Paris.

[2] V. V. Nikitin [В. В. Никитин], Tschermaks Min. Petr. Mitt., 1933, ser. 2, vol. 44, p. 117.

[3] A. Köhler, Tschermaks Min. Petr. Mitt., 1941, vol. 53, p. 24.

[4] A. S. Marfunin [А. С. Марфунин], Доклады Акад. наук СССР [Comp. Rend. Acad. Sci. URSS], 1958, vol. 118, p. 1183; Изв. Акад. наук СССР, Сер. геол. [Bull. Acad. Sci. URSS, Sér. géol.], 1960, no. 5, p. 88.

[5] C. Burri, Schweiz. Min. Petr. Mitt., 1956, vol. 36, p. 539.

[6] [A. N. Zavaritskii, V. S. Sobolev, L. G. Kvasha, V. P. Kostyuk, and A. P. Bobrievich] А. Н. Заварицкий, В. С. Соболев, Л. Г. Кваша, В. П. Костюк, и А. П. Бобриевич, Зап. Всесоюз. мин. общ. [Mem. All-Union Min. Soc.], 1958, vol. 87, p. 529.

[7] In labradorites it is only possible to observe one optic axis by inclining the universal stage when the trace of the (010) cleavage is visible and the twins are not superposed.

only small divergences in the direction normal to the migration curves.

The same cause results in overstating the difference between high- and low-temperature curves of anorthite-bytownites (compare this with the gradual decrease in difference of X-ray properties between high- and low-forms from albite to anorthite).

For greater completeness it is desirable that the new data for the optical orientation of plagioclases now being collected by Burri and Wenk[1] should be carried out using an improved technique of measurement, and should quote both Euler angles and the orientation of the optic axes A and B.

The optical orientation of alkali feldspars. It may seem unexpected, but with the help only of X-ray parameters it is impossible to determine the degree of order–disorder in alkali feldspars, and to identify petrographically known variants of alkali feldspars. The lattice angles and triclinicity are the result of a combination of the indistinguishable factors of order–disorder, submicroscopic twinning, and composition.

The optical orientation alone gives the possibility of unequivocal determination of alkali feldspars. The reason for this is the selective dependence of different optical parameters on different factors, which occurs in particular in potash–soda feldspars. Therefore crystal-structural data must be related to optical properties in order to be used in petrography.

The diagram of optical orientation,[2] and the diagrams of 2V against triclinicity and of 2V against extinction on (010) derived from that, show the dependence of 2V on order–disorder alone, of triclinicity on submicroscopic twinning with constant 2V, and of extinction on (010) on composition with constant 2V. There may be other interpretations of these parameters, but there are no other independent optical parameters in potash–soda feldspars to decide this. Nomenclature of alkali feldspars must therefore be linked with these parameters.

The diagram of 2V against triclinicity shows the limits of variation of optical properties of potash feldspars. It may be interpreted as showing the existence of a sequence in Al redistribution: Al first moves from A sites to B and then from B_1 to B_2 (fig. 1). Any divergence from the established limits would mean the existence of other structural types of

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[1] C. Burri and E. Wenk, Feldspar-Symposium, Cursillos y conferencias, Instituto 'Lucas Mallada', 1961, Fasc. 8, Madrid.

[2] A. S. Marfunin, 1961, Feldspar-Symposium, Cursillos y conferencias, Instituto 'Lucas Mallada', 1961, Fasc. 8, Madrid.

potash feldspars. But this must be proved by precise measurements of optical orientation (the conoscopic universal stage method).

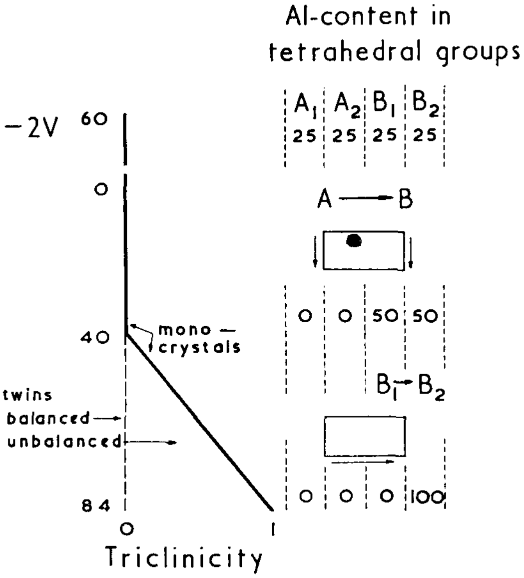

FIG. 1. The limits of variation of the optic axial angle and triclinicity in potash feldspars and their possible interpretation. 2V depends on the degree of order–disorder. Triclinicity is determined as $\gamma \wedge \perp (010)$ or as $\Delta = 12{\cdot}5\,(\alpha_{131} - \alpha_{1\bar{3}1})$ and depends both on the degree of ordering and on the existence of submicroscopic twinning. The heavy line corresponds only to single-crystal phases of potash feldspar. The dashed line corresponds to the resultant properties of balanced submicroscopic twins. Points lying in the area between these lines indicate the presence of unbalanced twins. No reliable data on potash feldspars have been observed to plot outside these limits.

Optical properties of submicroscopically twinned crystals. It is possible to calculate the resultant optical properties of twins if the properties of the untwinned crystals are known. The solution of this problem, raised as long ago as 1876 by Mallard, can be carried out as follows.

All crystals may be divided into five optical-symmetry classes: triclinic, monoclinic, orthorhombic, uniaxial, and cubic (or isotropic).

In the case of balanced twinning (where the left- and right-hand components of the twins are equal) the twin plane is a symmetry plane and the twin axis a diad axis of the twin. Taking into account the centrosymmetry of the optical properties the minimum resultant optical symmetry of sub-microscopically twinned crystals is monoclinic, while if any two similar axes of the optical indicatrix in each half of a twin are parallel, the optical symmetry is orthorhombic; sub-microscopical twins may only belong to these two optical groups of symmetry. The problem is to determine the resultant optical properties of sub-microscopically twinned crystals when the optical properties of the untwinned crystals are known.

In pseudo-orthorhombic twins, the indicatrices of the two individuals have one axis in common; the directions of the other two axes of the resultant indicatrix are the bisectors of the acute angles (ω) between corresponding axes of the individual indicatrices, while their magnitudes are given by Mallard's formulae:[1]

$$\gamma'_r = \tfrac{1}{2}(\gamma'+\alpha')+\tfrac{1}{2}(\gamma'-\alpha')\cos\omega, \qquad \alpha'_r = \tfrac{1}{2}(\gamma'+\alpha')-\tfrac{1}{2}(\gamma'-\alpha')\cos\omega.$$

The resultant 2V may be calculated from the resultant refractive indices.

In pseudomonoclinic twins one axis of the resultant indicatrix coincides with the twin axis, while the other two lie in the plane of symmetry. The directions of these latter two may be determined by the Biot–Fresnel construction: Draw the two great circles each containing one optic axis of one individual and the pole of the twin axis; by symmetry these great circles pass through the optic axes of the other individual. The principal directions for the section parallel to the twin plane, which will be the other two axes of the resultant indicatrix, are given by the poles midway between the points where the trace of the twin plane intersects these two great circles. The angles ψ_1 and ψ_2 from the pole of the twin axis to the two optic axes of either individual are then measured, taking the measurement in each case over γ, and the magnitudes of the two axes of the resultant indicatrix that lie in the plane of symmetry are calculated by Tsuboi's formulae:[2]

$$n^2_{r1} = 2\gamma^2\alpha^2/\{\gamma^2+\alpha^2+(\gamma^2-\alpha^2)\cos(\psi_1-\psi_2)\},$$
$$n^2_{r2} = 2\gamma^2\alpha^2/\{\gamma^2+\alpha^2+(\gamma^2-\alpha^2)\cos(\psi_1+\psi_2)\}.$$

The magnitude of the third axis of the resultant indicatrix, coinciding with the twin axis, is calculated by the same formulae when ψ_1 and ψ_2 are the angles between the two optic axes of either individual and the normal to that plane, parallel to the twin axis (or the normal to the twin plane), on which the extinction directions for the two

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[1] The common axis of the individual indicatrices may, of course, be α, β, or γ; γ'_r, α'_r, γ', and α' all lie in the plane normal to this common axis.

[2] S. Tsuboi, Min. Mag., 1923, vol. 20, p. 108.

members of the twin are parallel. This may conveniently be found with the help of the Wulff net: Draw the trace T of the twin plane (or plane normal to the twin axis) and the traces P and Q of planes normal

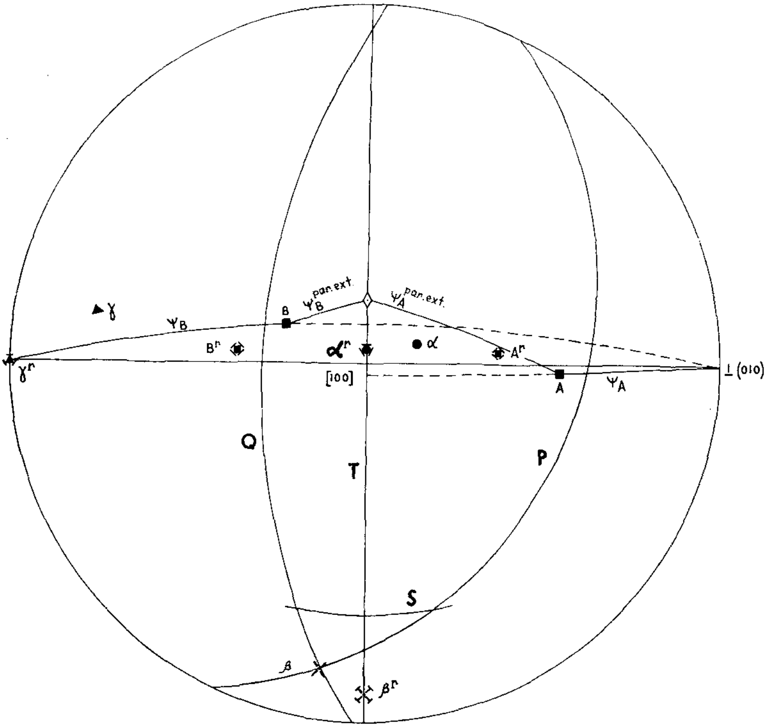

FIG. 2. Determination of the optical orientation of a pseudomonoclinic crystal, knowing that of the untwinned individual, exemplified for a potash feldspar. A, B poles, and P, Q traces of planes normal to the optic axes of one individual; α, β, γ axes of the indicatrix of one individual; $A^r, B^r, \alpha^r, \beta^r, \gamma^r$, optic axes and axes of the resultant indicatrix; T, trace of (010); S, trace of that plane, normal to (010), on which the extinction of both individuals is parallel to (010).

to the two optic axes of one individual, and then search by trial and error for a great circle S passing through the pole of the twin plane (or twin axis) and such that the segment of it intercepted between the traces P and Q is bisected by the trace T; this great circle is the trace of the required plane and its normal is the required direction. It will be evident that this construction, which is a polar variant of the

Biot–Fresnel construction, locates a plane on which extinction is parallel to the twin plane.

This method of calculation has been tested using examples where the resultant orientation was known (pseudo-monoclinic low- and high-temperature albites).[1]

Some general conclusions. The main results of optical mineralogy during the last 50 years consisted of composition–property diagrams. The example of the feldspars shows the new physical significance of crystal optics in relation to three-coordinate diagrams of composition–degree-of-ordering–optical-properties. In the last few years with the help of new methods of investigation the number of mineral groups in which order–disorder phenomena have been observed has grown. They are now known in elements, sulphides, sulphosalts, multiple oxides, carbonates, silicates (feldspars, cordierite, nepheline, serpentine, &c.).

The structural mechanism of the order–disorder transformation is different in silicates and in sulphides, for instance. But a general point of view exists that is very important for mineralogy: the thermodynamical point of view. Minerals can form continuous series with two end-components, one completely disordered and the other with maximum order; the first is the high- and the latter the low-temperature state. Intermediate states can be equilibrium ones. The term order–disorder series may be proposed for these relationships, which are as widespread as solid solution and polymorphism. The concept of mineral species must be complemented by that of order–disorder series.

In any isomorphous series the substitution may occur in a disordered or an ordered manner. Chemical compounds of the NaCl type, which cannot transform to a disordered state, must be distinguished from those types, e.g. CuZn or $MgAl_2O_4$ or Ag_2S, that form order–disorder series of the type of internal solid solutions.[2]

In the general case the degree of order–disorder must be described with the help of more than one parameter; but the various parameters are not independent. In equilibrium and near-equilibrium conditions the distribution of atoms that can be attained is the same at any given temperature, and gives rise to characteristic physical properties.

The intermediate states of order–disorder can persist (for instance in feldspars and cordierites) for a full geological epoch and can be as characteristic of a massif or rock complex as the limiting states.

[1] [A. S. Marfunin] А. С. Марфунин, Доклады Акад. наук СССР [Compt. Rend. Acad. Sci. URSS], 1959, vol. 127, p. 869.

[2] G. B. Bokii, Crystallochemistry, 1960, Moscow University Publishing House.

The sequence of solid-state transformations in feldspars.

It is possible to observe simultaneously in feldspars the results of ordering, unmixing, and twinning. An attempt is made here to correlate such observations independently of any other facts and assumptions. These observations give limited but quite definite conclusions about the occurrence of these processes under natural conditions, about the relative ages of particular phenomena, and about the possibility of a particular mechanical transformation. This simple method leads ultimately to unequivocal petrological results.

Ordering and crystallization. A particular order–disorder state may be formed in the course of crystallization, either at equilibrium in the stability field of the phase with the degree of order–disorder corresponding to a given temperature, or metastably, in the stability field of a more ordered (but not less ordered) phase—for instance, sanidine in the stability field of microcline but not vice versa; alternatively, a particular state may be arrived at in the course of ordering, either at equilibrium after attaining the temperature of the beginning of ordering, or after metastable crystallization of a disordered or intermediate phase.

Metastable crystallization of disordered potash feldspars (identified by 2V) is shown by the occurrence of such feldspars in environments with other indicators of at least the approximate temperature of formation. Well-known examples are crystals of the adularia habit that crystallize in the special environment of hydrothermal veins and embody different structural states, from cross-hatched microcline to feldspars with sanidine optics and composition. A still more convincing example has been observed in drusy cavities in the Tyrny–Auz granite (Caucasus) where high-orthoclase ($2V_\alpha = 45°–56°$) is associated with quartz crystals of a distinct low-temperature habit.

Do alkali feldspars crystallize in an ordered state? The difficulty of answering this question is due to the fact that it is nearly always possible to suppose that the observed structural state was attained either by crystallization or by solid-state transformation. It seems that only authigenic crystallization of maximum microcline occurs at a low enough temperature to exclude the possibility of diffusion in the solid state. Direct indication that ordering in natural feldspars occurs in the solid state may be seen from observations made on the intermediate to maximum microcline 'Taĭmyr II'.[1] In this specimen there are large regular

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[1] [A. S. Marfunin] А. С. Марфунин, Труды Мин. муз. Акад. наук СССР [Proc. Min. Mus. Acad. Sci. USSR], 1961, vol. 12.

veins of albite perthite and thin albite veins between the large ones. The degree of order–disorder increases gradually from the middle of the potash feldspar bands towards the large albite bands. This increase is accompanied by segregation of the thin albite veins. The ordering in this case appears to involve the participation of catalysts.

The widely distributed variations of the degree of order–disorder in alkali feldspars (detected by 2V) and the dependence of the morphology of these variations on the inclusions, perthites, deformation, and twinning also indicate transformation in the solid state.

Twinning and crystallization. Twinning of feldspars can be subdivided according to the number of individuals (simple or polysynthetic), the twinning law, crystal symmetry, the relative ages of twinning and crystallization, and the cause of twinning. All these subdivisions are interdependent.

Numerous observations show that repeated twinning in feldspars occurs only after the albite and pericline laws. These twins imitate monoclinic symmetry and are formed after the protoclase cracks (cracks that form before solidification) and also during plastic deformation in dynamometamorphosed rocks as wedges in bent crystals. Thin pericline twins are observed inside large albite twins and vice versa. This shows that twinning occurs repeatedly.

Simple twins occurring by any twin law possible in feldspars are often observed as penetration twins or as twins with unequal lengths of twin individuals, showing that their origin is during the course of crystallization.

Twinning depends also on the mode of crystallization. Statistical calculations of the prevalence of different twin laws in plagioclases, made with due regard for triad[1] interrelation and with the help of simple universal stage methods involving exact determination of twin law by eye without measurement,[2] show a decrease in the complexity of twinning with increase in the role of metasomatic processes in rock formation. The general trend is as follows: in effusive rocks complex pseudocubic, pseudohexagonal, or pseudotetragonal blocks[3] occur, in

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[1] [L. A. Vardanyants] Л. А. Варданянц, Триадный метод исследования двойников плагиоклаза [The triad method of determination of plagioclase twins]. Изд. Акад. наук Армен. ССР [Publ. Acad. Sci. Armenian SSR], 1951.

[2] [A. S. Marfunin] А. С. Марфунин, Известие выших учебных заведений, сер. геол. [Bull. higher educational inst., ser. geol.], 1959.

[3] [L. A. Vardanyants] Л. А. Варданянц, Комплексные двойники плагиоклаза. Изд. Акад. наук Армен. ССР [Publ. Acad. Sci. Armenian SSR], 1952.

normal intrusions twin triads, in metamorphic rocks albite and pericline twins and untwinned crystals.

Unmixing and twinning. Triclinic phases of perthites are always twinned in pseudomonoclinic blocks (if triclinic symmetry can be detected in the potash phase). Cross-hatched twinning of microcline is controlled by perthite veins. Perthite segregation is accompanied by enlargement of twins. The sub-microscopically twinned parts of crystals are usually also sub-microscopic perthites and such areas frequently appear to be relics within finely twinned and finely perthitic alkali feldspars.

Twinning and ordering. With decrease of obliquity in feldspars, untwinned crystals become rarer. While untwinned plagioclases occur only in special conditions, untwinned maximum microclines are still more uncommon. Furthermore, potash feldspars with intermediate order–disorder states and thus of very low obliquity indeed do not lie at all on the straight line which corresponds to monocrystal states in the diagram[1] of 2V against triclinicity (except for the special case of 'Taĭmyr II'). This agrees very well with dependence of the ease of twinning on the obliquity of the twin and with the increase of obliquity and triclinicity with ordering. Laves's conclusions about the formation of microcline-type twinning from the monoclinic structural states may be recalled here.[2]

Ordering and unmixing. Systematic investigations on specimens from extreme geological environments[3] have demonstrated that alkali feldspars showing any degree of ordering are always perthitic and, conversely, that the perthite phases have always an intermediate or maximum degree of order. Intermediate states correspond to cryptoperthites, maximum microclines to vein perthites. The simultaneous occurrence of order–disorder phenomena and perthite segregation has been established in above-mentioned specimen 'Taĭmyr II'.

The interdependence of solid state transformations in alkali feldspars.

The comparison of the observations leads to the following conclusions: Unmixing, ordering, and twinning are three simultaneous processes or three elements of the single process of rearrangement occurring only once in an alkali feldspar crystal. Such a crystal crystallizes metastably in

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[1] A. S. Marfunin, in Feldspar-Symposium, 1961 (loc. cit.).

[2] F. Laves, Journ. Geol. (Chicago), 1952, vol. 58, p. 548.

[3] [A. S. Marfunin] А. С. Марфунин, Зап. Всесоюз. мин. общ. [Mem. All-Union Min. Soc.], 1960, vol. 89, p. 623.

an intrusion as a homogeneous disordered form. The observed form is the result of solid-state transformations; it may be surmised that these transformations occur immediately after crystallization and do not usually recommence later.

The analysis of mineral parageneses and solid-state transformations.

How is it possible to represent the structural state of minerals in the composition–paragenesis diagrams of D. S. Korzhinsky? What are the relations between chemical and structural equilibria? Is equilibrium associated with a disordered mineral? Are cristobalite–sanidine, quartz–orthoclase, quartz–microcline equivalent associations?

A composition–paragenesis diagram that fixes the composition of coexisting minerals at a given temperature, pressure, and chemical potential of perfectly mobile components determines also the structural states of minerals that are in *equilibrium at the moment of formation.* The equilibrium of structural states means that such diagrams are completely applicable to the cases when the equilibrium state forms by direct crystallization. But in silicates, in accordance with the principle of the more ready crystallization of more simple forms, it is quite common to find the metastable crystallization of disordered or, more generally, of high-temperature phases in the stability field of low-temperature ones.

Equilibrium cannot be divided into chemical and structural parts. Disequilibrium from a structural point of view means that the association is generally a disequilibrium one. There are two simplifying circumstances: the energetic effects of ordering are usually very small, and transformation can occur immediately after crystallization, during the *PT* intervals corresponding to a given equilibrium stage. The possible (or necessary) availability of catalysts speeds up the establishment of equilibrium without its displacement. In this case only circumstantial evidence can show that a metastable state existed originally; signs of the rearrangement could not have remained. This relates to equilibrium only at the moment of crystallization.

But transformations can occur also after crystallization over a large range of changing conditions well outside the given temperature stage of equilibrium. After solidification a system breaks down into a number (as great as the number of minerals) of comparatively independent systems. Transformations in these systems are not connected immediately with conditions of chemical and structural equilibrium corresponding to the composition–paragenesis diagram. This is just such a late stage of the natural history of the minerals as is unmixing.

The geological distribution of different structural types of alkali feldspars.

The use of alkali feldspars for the purpose of distinguishing magmatic rocks of different ages was considered, following the example of the Caucasus, in D. S. Belyankin's work carried out during the period 1915–45.[1] The existence of feldspars intermediate between sanidine and microcline was also ascertained by him, and he called them potash-anorthoclase; he described as a special type the Caucasus Tertiary granite, granodiorite, syenite, or teschenite intrusions with potash–anorthoclase named by him 'neointrusions'. Further optical and petrological works about feldspars of young intrusions[2, 3] and of Palaeozoic intrusions in the Caucasus[4] and in the magmatic rocks of Kazakhstan[5] showed the significance of alkali feldspars in the geology of magmatic rocks.

The standard method of petrological investigation of alkali feldspars was used for the systematic study of their geological distribution in all magmatic and metamorphic complexes of the Ukrainian Shield and of the Caucasus.

Variations of optical parameters of alkali feldspars within intrusions.

In a number of petrographic works very large variations of optical orientation of alkali feldspars, and also the coexistence of very different variants in one intrusion or even in one thin section have been described. First of all such observations must be tested with the improved techniques of measurements, in different geological environments:

The Tertiary Tyrny-Auz intrusion (North Caucasus) is a small stock of normal porphyritic biotite-granite with local evidences of contamination near the contacts with xenoliths of sandstones and schists. The plagioclase is a structurally intermediate oligoclase-andesine, sharply zoned from 36–38 % An ($2V_\alpha = 86°$–$90°$) to 22–26 % An ($2V_\alpha = 70°$–$82°$). The alkali feldspar of the intrusion is a high-orthoclase crypto-

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[1] [D. S. Belyankin] Д. С. Белянкин, Изв. Акад. наук СССР, Сер. геол. [Bull. Acad. Sci. URSS, Sér. géol.], 1937, no. 2, p. 225; 1944, no. 5, p. 65.

[2] [L. A. Vardanyants] Л. А. Варданянц, Зап. Всеросс. мин. общ. [Mém. Soc. Russe Min.], 1937, vol. 66, p. 441.

[3] [V. P. Petrov] В. П. Петров, Труды Геол. Инст. Акад. наук СССР [Trans. Inst. Geol. Acad. Sci. USSR], 1955, vol. 167.

[4] [G. D. Afanasev] Г. Д. Афанасьев, Изв. Акад. Наук СССР, Сер. геол. [Bull. Acad. Sci. URSS, Sér. géol.], 1951, no. 7.

[5] [V. K. Monich] В. К. Монич, в Вопросы петрологии и минералогии, Акад. наук СССР [Problems of Petrology and mineralogy, Acad. Sci. USSR], 1953, vol. 2.

perthite with $2V_\alpha$ chiefly 43°–53°, and only occasionally low-sanidine ($2V_\alpha = 37°$–$40°$) or high-triclinic-orthoclase ($2V_\alpha = 50°$–$57°$); Or_{20-40} Ab_{80-60}; the albite phase of the cryptoperthites has an albite–pericline twin superstructure. Diffractometer traces of specimens from different parts of the intrusion are remarkably similar. The range of optical properties of the potash feldspars in the intrusion exceeds only by a little the range inside a particular specimen. There is no trend of variation from the centre of the intrusion towards the contacts.

The Palaeozoic Ortotokoi intrusion (Kirghiz SSR), about 300 km^2 in area, is made up of giant-grained and giant-porphyritic syenites. The rocks of the intrusion consist of orthoclase, plagioclase (andesine), diopsidic augite, barkevikite, rare biotite, and olivine, with accessory apatite, sphene, and magnetite. Orthoclase forms crystals up to 30 cm in size; Carlsbad, Baveno, and Manebach twins are common.

The optical orientation of the orthoclase is monoclinic; the observed deviation from monoclinic symmetry does not exceed 2° (γ to the normal to (010)); the range of $2V_\alpha$ in the whole intrusion is from 50° to 64° corresponding to high to intermediate orthoclase; $Or_{90-75}Ab_{10-25}$; the albite phase of the cryptoperthite has an albite-pericline superstructure. The variation of optical properties does not depend on the rock type or on the distance from the contacts, but a slow increase in average values of 2V is observed from west to east across the intrusion (from 52·5° in the west to 56·3° in the centre and to 64·2° in the east).

The Pre-Cambrian Novo-Ukrainian massif about 3000 km^2 in area has a special position in the Ukrainian Shield. This massif lies at the junction of three geological complexes: on the south and west it is in contact with charnockite, pyroxene–plagioclase gneisses, and migmatite, on the east with the Kirovograd porphyritic granites, and on the north with Rapakivi granites of the Korsun massif. It consists of trachytoid garnet–biotite granite, monzonite, and charnockites. Potash feldspar always forms Carsbad twins ranging in length from 3–5 cm to 10–15 cm. There are three types of potash feldspars in the massif:

The very rare Annovka type is an intermediate triclinic orthoclase ($2V_\alpha = 58°$–$73{\cdot}5°$), the Kapustino type an intermediate to low triclinic orthoclase ($2V_\alpha = 72°$–$82°$) occurring in trachytoid granites and some monzonites, and the Voinovka–Adabash type a crypto-cross-hatched maximum-microcline ($2V_\alpha = 82°$–$85°$) occurring in charnockites and monzonites. Within these types there is a remarkable constancy of optical properties and diffractometer traces and if variations of properties occur there is a constancy of the trend of these variations. Thus in the Annovka type variation is connected with movement of the optic axis A only (B is stationary), while in the Voinovka type both the A and B axes move equally.

The similarity between the Annovka feldspar and that from the garnet–cordierite migmatite, between the Kapustino type and that of the Rapakivi granites, between the Voinovka type and that of the Kirovograd granite give complementary evidence to the history of the massif and its relations with adjacent complexes.

Variations of optical structure types of alkali feldspars in magmatic and metamorphic complexes.

A comparison of alkali feldspars investigated with standard optical and X-ray methods was made with regard to the following relations:

Granites and migmatites. For the Ukrainian Shield it was observed that in migmatites connected with orthoclase–garnet–cordierite granites the potash feldspar is also an intermediate orthoclase; in migmatite connected with charnockites and monzonites, a crypto-cross-hatched microcline, and in migmatites connected with microcline-granites the feldspar is also a maximum microcline.

Granites and syenites, and pegmatites. In all microcline-granites of the Ukrainian Shield and the Caucasus the alkali feldspar in the associated pegmatites is maximum microcline. Pegmatites in orthoclase–garnet–cordierite granites of the Ukrainian Shield are orthoclase pegmatites. For the orthoclase-syenites of the Caucasus (Pambak region, Vakis–Dzhvari) the feldspar of the pegmatites is also orthoclase. Pegmatoid veins in migmatites of the Ukrainian Shield have the same type of potash feldspar as have the migmatites.

Granites and syenites, and porphyroblasts and druses. For the Tyrny-Auz intrusion the same high-orthoclase occurs in the porphyritic granites of the intrusion, in drusy cavities of the granites, in pegmatoid veins, and in porphyroblasts in xenoliths.

For the Ortotokoi intrusion the same high to intermediate orthoclase occurs in giant-grained syenites, syenites, porphyrys, hybrid syenite-diorite, and in xenoliths as porphyroblasts.

Porphyroblasts of alkali feldspars in the quartz–biotite–plagioclase part of migmatites are of the same type as in the leucocratic part of the migmatites. These observations show the constancy of the type of alkali feldspar in different derivatives of magmatic complexes. Independent of the mode of crystallization and the composition and textural variations of the rock the same optical-structure type of feldspar exists in granitoids and their related pegmatites, migmatites, and porphyroblasts. It would be desirable to confirm these conclusions with data from other regions.

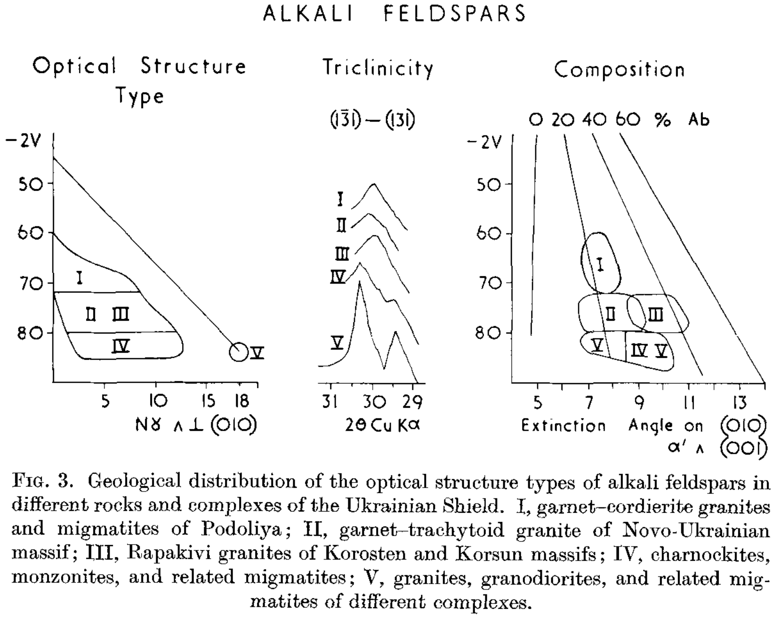

FIG. 3. Geological distribution of the optical structure types of alkali feldspars in different rocks and complexes of the Ukrainian Shield. I, garnet–cordierite granites and migmatites of Podoliya; II, garnet–trachytoid granite of Novo-Ukrainian massif; III, Rapakivi granites of Korosten and Korsun massifs; IV, charnockites, monzonites, and related migmatites; V, granites, granodiorites, and related migmatites of different complexes.

Regional distribution of alkali feldspars.

Ukrainian Shield. The specimens of alkali feldspar were selected from nearly all the magmatic and metamorphic complexes of the Ukrainian Shield and were studied by the new standard optical and X-ray methods. Different complexes need different numbers of specimens for their characterization: specimens need only be taken from two or three places in intrusions containing maximum cross-hatched microcline; on the other hand in the Novo-Ukrainian massif where the feldspars have comparatively more variable properties, the specimens were taken from more than 50 localities. The general scheme of the alkali feldspar distribution in the Ukrainian Shield is set out in fig. 3.

In most complexes, and over the largest area of the Ukrainian Pre-Cambrian, the alkali feldspar is maximum microcline with constant triclinicity, optic axial angle, and optic orientation. In comparatively special rock types, such as the Rapakivi granites, charnockites, and garnet–cordierite granites, there are other types of alkali feldspars. These types remain constant for large areas, of hundreds and thousands of square kilometres. This implies that the magmatic and metamorphic rocks here form large blocks of the earth's crust where the thermodynamic and kinetic parameters are essentially constant. The optical-structure types of alkali feldspar have in the Ukrainian Shield a regional distribution (with variation of properties within the types).

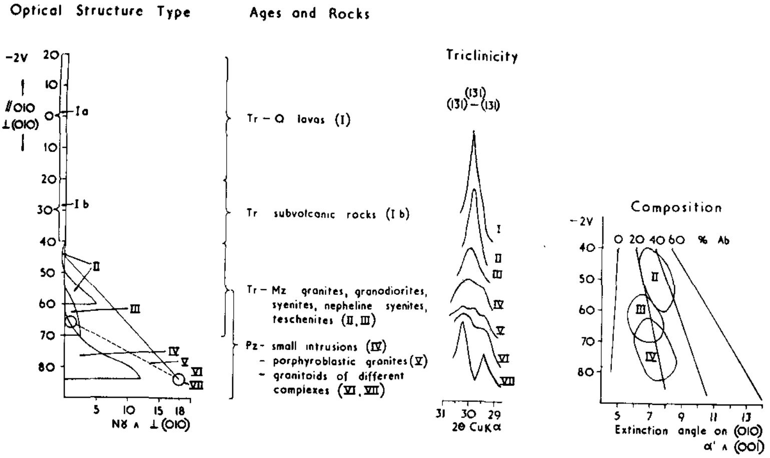

FIG. 4. Evolution of the optical structure types of alkali feldspars in magmatic rocks of the Caucasus geosynclinal province.

The Caucasus petrographic province. The general scheme of the alkali feldspars distribution is given in fig. 4. Some comments are needed for the feldspars of Palaeozoic intrusions. In type V two feldspars coexist: relics of intermediate orthoclase and a host of maximum cross-hatched microcline, without gradual transition between them. These may be called 'hybrid orthoclase–microcline crystals'.

In the fine cross-hatched intermediate to maximum microclines of type VI it was impossible to measure optical triclinicity because of superposition of twins.

The most remarkable feature of this distribution is the dependence on geological age. In Tertiary intrusions the alkali feldspar is a high to intermediate orthoclase; in Palaeozoic intrusions it is maximum to intermediate microcline. But this does not imply that ordering has been occurring all the time from the moment of intrusion and that massifs that have been emplaced for a shorter time contain less ordered feldspars. The existence of one or another type of feldspar in the Caucasus intrusions is a consequence of integral features of the conditions of formation, which include as geological factors the size and shape of intrusions, the depth of emplacement, the tectonic environment, the composition of volatile constituents, and such physico-chemical factors as speed of cooling and catalytic effects as well as, of course, temperature and pressure.

Acknowledgements. The writer is indebted to Dr. I. D. Muir for profitable discussions and to Dr. J. R. Cann for helpful comments on the manuscript.