FELDSPARS, A REVIEW

By

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INTRODUCTION

Feldspar is the dominant mineral in the rocks which make up the upper 10 miles of the earth's crust. The feldspars constitute almost 65 percent of the volume of the average igneous rock and thereby occupy a unique position in igneous petrology. Petrographic classifications of igneous rocks are based upon the composition of the plagioclase feldspar and the ratio between the alkali feldspars and plagioclase feldspars. Furthermore, the composition of the feldspar in metamorphic rocks has attained an important position in the interpretation of petrogenesis since the advent of the modern view of the facies concept. The textural relationships of the feldspars provide one criterion to distinguish between magmatic and metamorphic rocks. In addition the structural modification and textural relations of feldspars in a given rock permits one to determine the thermal history of the rock in question. Thus it is easy to understand why the feldspars are the most intensively studied group of rock-forming minerals. There is a tremendous volume of literature pretaining to the feldspars scattered through numerous journals. The purpose of this paper is to review the literature and compile the most significant facts relating to composition, internal structure, physical-chemical relations, optical data, and petrogenetic considerations.

COMPOSITION

The general formula for the feldspars is given as WZ_4O_8; in which W may be Na, K, and Ca as well as minor amounts of Ba, Sr, and Pb; and Z is Si and Al. The Si:Al content varies from 3:1 to 1:1 and therefore the general formula is often stated as $WAl(Al, Si)Si_2O_8$, with the variable (Al, Si) balanced by variations in the proportions of univalent and bivalent cations. The Ba, Sr, or Pb feldspars are rare and not significant rock-forming minerals and therefore will be neglected in later discussions. Thus we will consider the feldspars only in terms of the $KAlSi_3O_8$ (Or), $NaAlSi_3O_8$ (Ab), and $CaAl_2Si_2O_8$ (An) components. For the purpose of this paper the feldspars will be grouped into two systems Or-Ab (Alkalic feldspars) and Ab-An (Plagioclase feldspars) inasmuch as Or is virtually immiscible in An.

INTERNAL STRUCTURE

The structure of the feldspars consists of a continuous three-dimensional network of SiO_4 and AlO_4 tetrahedra with the positively charged cations located in the interstices of the negatively charged network. The tetrahedral network is somewhat elastic and is thus able to adjust itself to the size of the cations. When the cation is large (K) the symmetry is monoclinic or

psuedomonoclinic; in the case of smaller cations (Na, Ca) the structure becomes somewhat distorted and the symmetry is triclinic.

The oxygen ions of the SiO_4 and AlO_4 tetrahedra are shared at the common corner of two adjacent tetrahedra. Each group of four tetrahedra thus form a ring at any given level in the structure. The tetrahedra of one level are linked with those of adjacent levels to form a chain. Two such chains in a mirror image relationship across a plane parallel to (010) occupy the unit cell.

Alkali Feldspars

The alkali feldspars occur as several distinct forms which have different but intergradational optical and physical properties. Sanidine, the monoclinic high-temperature form, occurs in volcanic rocks. Orthoclase, another monoclinic form, and microcline (triclinic) occur in a wide variety of igneous and metamorphic rocks formed at intermediate to low temperatures. Adularia is the name given to the form, either monoclinic or triclinic, which is found in low-temperature hydrothermal veins, replacement deposits, and in some low-grade metamorphic rocks.

Within the past decade research has somewhat clarified the relationships between the various forms. Barth (1934) was the first to propose the modern viewpoints of structural conversion to the phenomena observed in the feldspars. Barth proposed that monoclinic sanidine might represent the more disordered form, which is stable only at high temperatures, while microcline represents a less symmetrical but more ordered form. Barth concentrated his efforts on the statistical distribution of the SiO_4 and AlO_4 tetrahedra. Buerger (1948) worked along the same lines, but also considered the role of K in controlling the ease of the Al and Si exchanges. Laves (1952), after careful optical and X-ray diffraction work, concluded that there are two stable modifications of $KAlSi_3O_8$—sanidine which is the stable modification above 700^oC, and microcline which is the stable modification below 700^oC. The two forms were related to each other by structural conversions; sanidine the disordered form and microcline the ordered polymorph based upon exchange of Si and Al. The degree of disorder is a function of temperature. Laves considers orthoclase as an intermediate metastable crystal modification.

J. V. Smith (1954) pointed out that order-disorder relations in the feldspars could best be discussed in terms of accurate measurements of the Al-O and Si-O distances. Furthermore, he demonstrated how a statistical method based upon observed fluctuation of electron densities in a Fourier analysis could detect possible errors in the precise determination of the above distances. Bailey and Taylor (1955) applied the technique to triclinic K feldspars and their results combined with work on sanidine definitely established the order-disorder conversion phenomena between microcline and sanidine.

Laves and Hafner (1956) adapted the techniques of infrared absorption to the study of feldspars, and were able to determine the order-disorder relationships with an even greater sensitivity than previous workers. These authors found in the various feldspars (sanidine, orthoclase, microcline, and adularia) a systematic reduction of absorption with increasing degrees of disorder produced by long term heat treatment.

Our understanding of the system Or-Ab has been greatly extended by structural studies. Bowen and Tuttle (1950) found that the $d_{(\bar{2}01)}$ spacings plot as a straight line as a function of the chemical composition which supports the idea of complete solid solution at high temperature. The transition from monoclinic to triclinic symmetry was determined by Gabrielle Donnay and J. D. H. Donnay (1952) based upon discontinuities for the alpha and gamma crystallographic angles and also the splitting of the $d_{(111)mon}$ lines into the $d_{(111)tricl}$ and $d_{(1\bar{1}1)tricl}$ lines. The difference of both spacings is a good measure of the departure from monoclinic symmetry. At lower temperatures the solid solutions are metastable and under conditions of slow cooling breakdown into oriented intergrowths of subparallel lamellae of alternate sodic and potassic composition.

Plagioclase Feldspars

The system Ab-An has long been quoted as a classic example of perfect solid solution series. The solid solution is of the coupled substitution type where $Ca + Al \rightleftharpoons Na + Si$ maintains electrical neutrality within the framework. Complications in the plagioclase structures arise from the fact that exchange of Al and Si cations in the tetrahedral positions occurs to a greater or lesser extent in all members of the series.

The structure of albite and orthite were originally thought to be the same. Taylor, et al. (1934) investigated the structures in detail and reported weak interference lines which indicated that anorthite had a c_o value twice that of albite, thus suggesting a superstructure. Laves and Goldsmith (1954) confirmed the superstructure of anorthite when they found the diffraction pattern for the main cell (class a) were always sharp, whereas those for the additional superstructure (class b and c) were weak and diffuse. The subsidiary spots were explained as structural conversion phenomena, namely Al and Si for the class b spots and in the positions of the Ca for class c.

The structural differences between natural and artificial high-temperature plagioclase and natural low-temperature plagioclase have been discussed in detail by Tuttle and Bowen (1950). They concluded that low-temperature plagioclase in the range An_{35} to An_{70} consists of two intimately intergrown feldspars (Fig. 7), whose compositions are a function of temperature. Plagioclase feldspar within the range An_0 to An_{35} consists of a single homogeneous low-temperature phase. Laves (1954) describes the sodic end of the plagioclase series somewhat differently. He found that all low-temperature plagioclases within the compositional range of An_5 to An_{17} are composed of two distinct crystal phases, one with the characteristics of albite and the second with lattice angles of andesine An_{30} (Fig. 12). According to Laves the plagioclases in the range An_{17} to An_{30} exhibit less tendency to unmix.

Infrared absorption analysis of plagioclase may become an important tool in distinguishing the degree of order in the various phases as indicated by preliminary work by Laves and Hafner (1956) and Thompson and Wadsworth (1957).
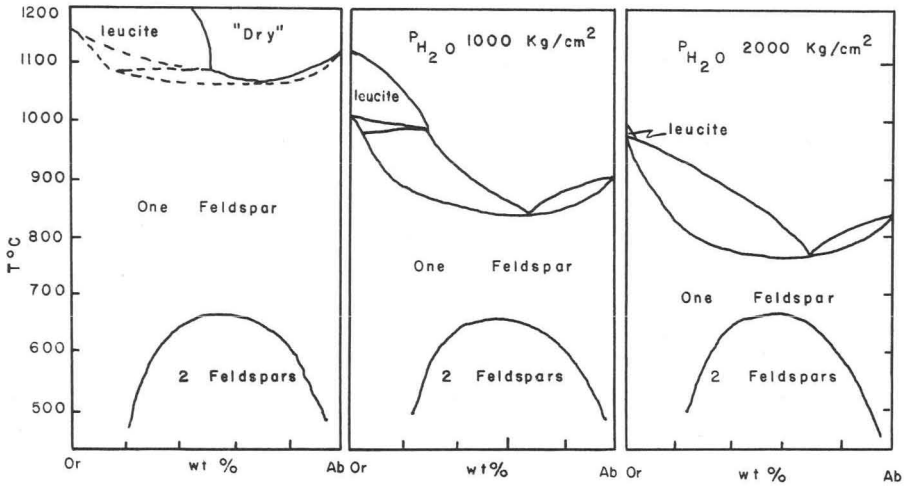
Figure 1. -- Equilibrium diagrams for the system Or-Ab for dry melts and at 1,000 and 2,000 Kg/cm^2 water pressure. After Bowen and Tuttle, 1950.
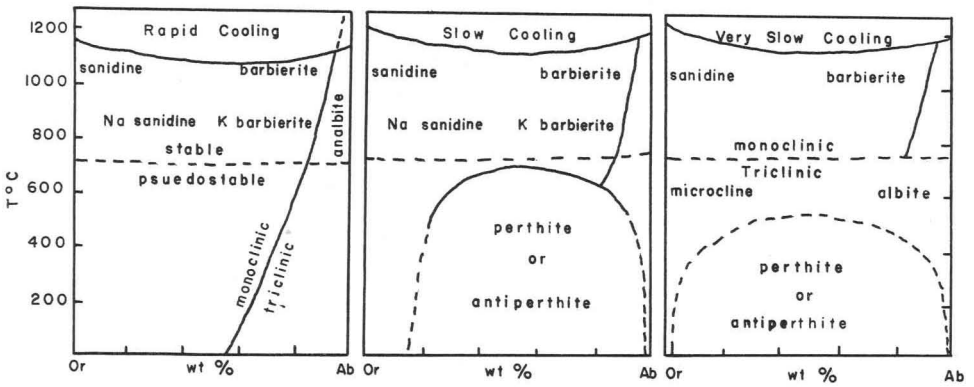

Figure 2. --Phase relationships in the system Or-Ab with rapid cooling to suppress exsolution and Si-Al ordering, with slow cooling which permits ordering of Na and K but too fast for Si-Al ordering, and very slow cooling to permit exsolution as well as ordering of Si-Al. After Laves, 1952.
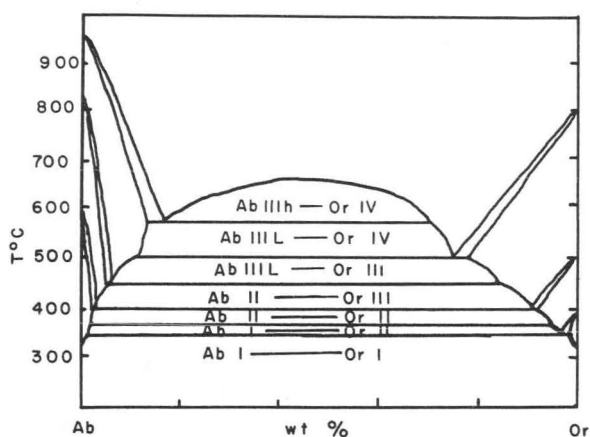
Figure 3. --Schematic equilibrium diagram for the system Or-Ab with various
modifications. Ab I—low albite, Ab II—high albite, Ab IIIL—high albite
which becomes monoclinic at 920°C, Ab IIIh—high albite monoclinic. Or I—
microcline, Or II—orthoclase, Or III—low sanidine, Or IV—high sanidine.
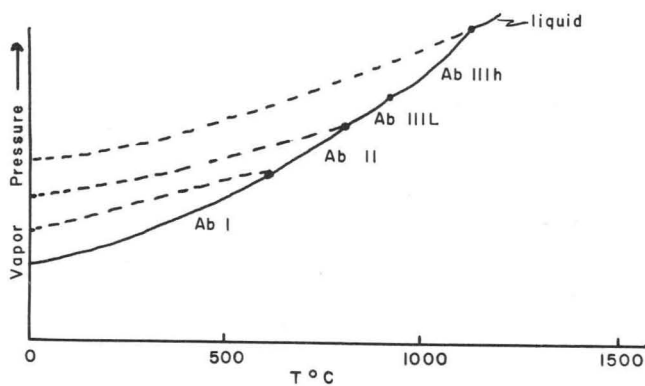After Tuttle and Bowen, 1958.

Figure 4. --Schematic pressure-temperature diagram for albite. Symbols same
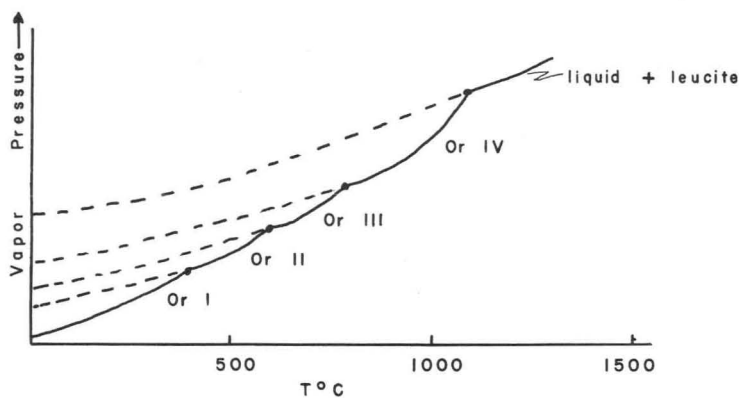as in Figure 3. After Tuttle and Bowen, 1958.

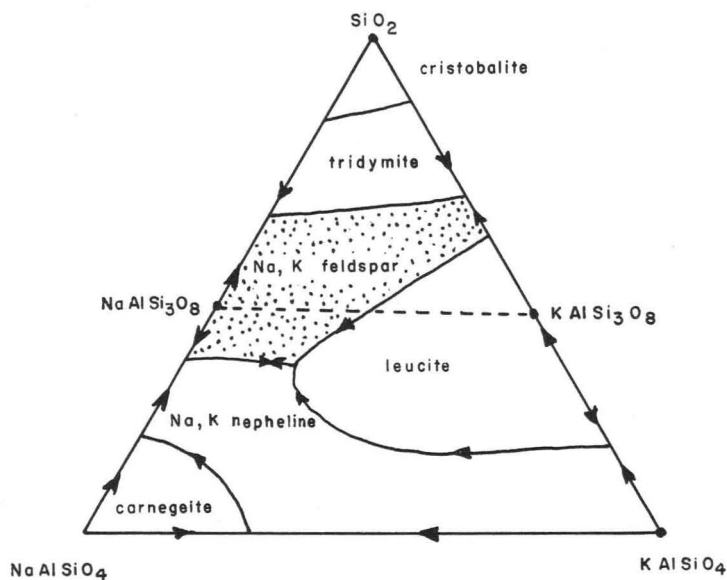Figure 5. --Schematic pressure-temperature diagram for potash feldspars. Symbols same as for Figure 3.

Figure 6. --Phase diagram for the system nepheline-kaliophilite-silica. After Schairer and Bowen, 1935.
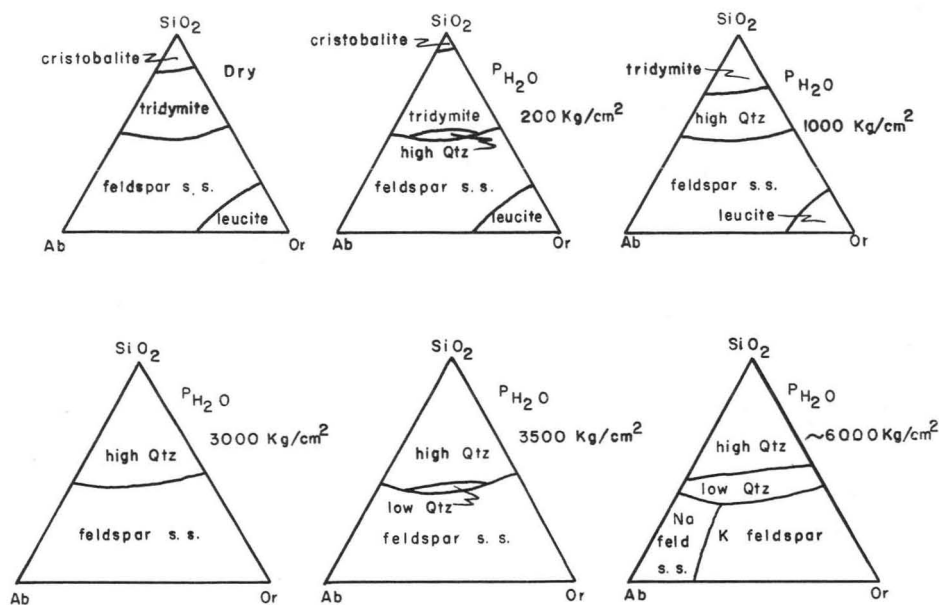
Figure 7. --Stability fields at the liquidus in the system $NaAlSi_3O_8-KAlSi_3O_8-SiO_2-H_2O$ for various pressures of water vapor. After Tuttle and Bowen, 1958.

PHYSICAL CHEMICAL RELATIONS

The physical-chemical approach to the study of feldspars has yielded a great deal of information concerning the phase-equilibrium conditions within the feldspar group. Petrologists have long speculated about the role of volatiles and pressure in phase equilibria, but it was not until the past decade that experimental studies confirmed much of the earlier speculation. Water and other volatiles tend to decrease viscosity and lower temperatures of crystallization. A great many of the classical phase siagrams must be modified to fit the new data based upon recent "wet" experimental studies and also the results of the detailed structural studies of the feldspar group.

Alkali Feldspars

At high temperatures there is a complete solid solution series between Or and Ab, and all members with more than 49 percent Or melt incongruently to leucite and liquid. The system Or-Ab has been studied in detail by Bowen and Tuttle (1950) especially with regard to the influence of water (Fig. 1). The diagram also shows the sub-solvus curve for the separation into two feldspars at lower temperatures, i. e., the unmixing of feldspars in the solid state to form perthites. Note that boundary curve position is uneffected by the presence or absence of water inasmuch as it deals with solid state equilibria only. However, the results of laboratory investigations indicate that the rate of unmixing is a function of the water content. The preservation of perthite in rocks indicates either a condition of rapid cooling or the absence of water vapor, since unmixing occurs in the laboratory within a matter of hours or days in the presence of water.

The phase relationships are further complicated by the existence of both high- and low-temperature modifications. Laves (1952) discussed the problem of the alkali feldspars in great detail and proposed the following diagrams (Fig. 2). Tuttle and Bowen (1958) present a somewhat different diagram for the phase relations in the system Or-Ab (Fig. 3). They point out the sluggishness of the structural conversions and the fact that two to four phases may coexist in cryptoperthites which appear optically homogeneous. For example, the following phases have been reported from single crystals: High sanidine--low sanidine, low sanidine--microcline, low sanidine--orthoclase, orthoclase--microcline, high albite--low sanidine, high albite--orthoclase, high albite--microcline, low albite--orthoclase, low albite--microcline, high albite--low albite--orthoclase--microcline, and low albite--orthoclase--microcline.

The stability relations of the soda feldspars are shown in Figure 4. The Ab I, Ab II, and Ab IIIL forms are triclinic, whereas Ab IIIh is monoclinic. The various forms reflect differences in the degree of order of the Al-Si distribution within the tetrahedral positions as discussed previously.

The stability relations of the various modifications of potash feldspars are not as well known as those of albite. Tuttle and Bowen (1958) give the following diagram as a possible interpretation of the polymorphic forms (Fig. 5).

The behavior of alkali feldspar melts can be illustrated by the phase relationships in the system nepheline-kaliophilite-silica by Schairer and

Bowen (1935). Bowen (1937) referred to this system as "petrogeny's residua system" (Fig. 6). The stippled portion of the diagram represents a thermal valley occupied by the alkali feldspars. Liquids of any composition will upon cooling change in composition toward this valley. The residual liquids thus will have a composition lying in the thermal valley.

The phase relationships illustrated in Figure 6 were based upon studies of a "dry" system, and many of the boundary lines were hypothetical since crystallization in the dry method was impossible. When hydrothermal quenching apparatus was perfected it was only natural that first efforts were directed at petrogeny's residua system. Tuttle and Bowen (1958) published the results of their experimental investigations of the system $NaAlSi_3O_8$--$KAlSi_3O_8$--SiO_2--H_2O, which provide quantitative data on melting character-istics as well as information on fractional and equilibrium crystallization. Crystallization in hydrous systems can be promoted by either a decrease in temperature and/or pressure or by the increase of pressure in a system undersaturated with respect to the volatile component. The stability fields on the liquidus surface, for the above system, at various water vapor pres-sures emphasize the role of water in equilibrium relationships (Fig. 7).

Plagioclase Feldspars

The classical diagram by Bowen (1913) for the system Ab-An con-firmed Tschermak's theory and established what was considered as an ideal series of crystalline solutions. The diagram was revised by M. J. Buerger (1948) when he discussed the structural conversions in the plagioclase series. The discrepensies between the optics of plagioclase from plutonic and volcanic rocks lead Buerger to attack the problem from a thermodynamic sense and as a result he proposed the following diagram (Fig. 8). He concluded that the phase relationships established by Bowen were valid for the high-temperature plagioclase, but proposed an unmixing phenomena in the sub-solidus regions.

Tuttle and Bowen (1950) studied the structural differences between artificial plagioclases, natural high-temperature plagioclase from effusive rocks, and the plagioclase from plutonic rocks. Their results, as mentioned previously, indicate that at low temperatures plagioclases of compositions An_0 to An_{35} exist as homogeneous phases structurally different from the correspond-ing feldspar formed at high temperatures. In the region An_{35} to An_{70} the feld-spar exists as submicroscopic intergrowth of two feldspars (Fig. 9).

The effects of pressure on the equilibrium conditions in the plagioclase series have not been investigated extensively. However, one comment is worthy of mention. In general the slope of the liquidus curve for most substances is positive. In the presence of dissolved volatile material the slope flattens, and if a sufficient amount of volatiles are present it may even become a negative slope.

PHYSICAL PROPERTIES

The crystallography of the feldspars is very similar with the angles of the monoclinic and triclinic forms differing by only three to four degrees. Feldspar crystals are often prismatic in habit and somewhat flattened parallel
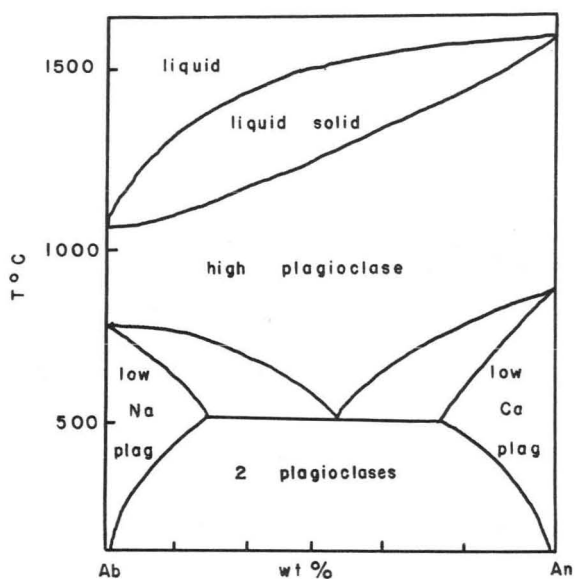
Figure 8. -- Equilibrium relations of the plagioclase feldspars.   The liquidus-solidus portion after Bowen, 1913, and the subsolidus after Buerger, 1948.
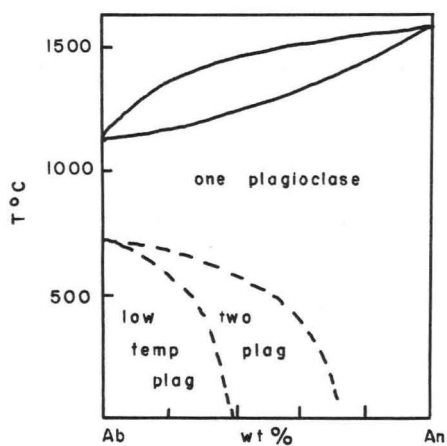

Figure 9. -- Hypothetical equilibrium diagram for the subsolidus relations of plagioclase feldspars.   After Tuttle and Bowen, 1950.
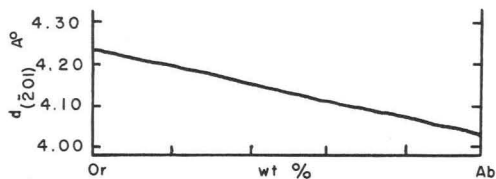
Figure 10. --Spacing of (201) in a series of alkali feldspars prepared at $900^{\circ}C$ and 300 Kg/cm^2 water pressure. After Bowen and Tuttle, 1950.
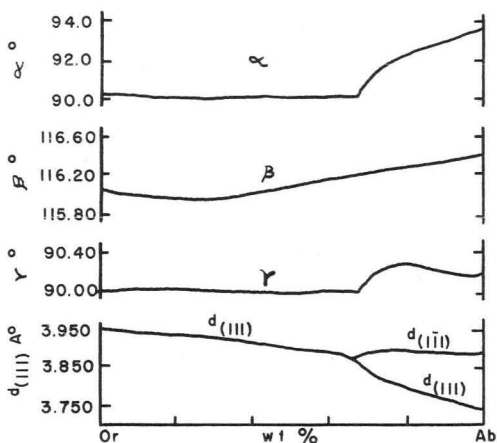

Figure 11. --Crystallographic angles and $d_{(111)}$ spacing in high-temperature artificial alkali feldspars, Donnay and Donnay, 1952.
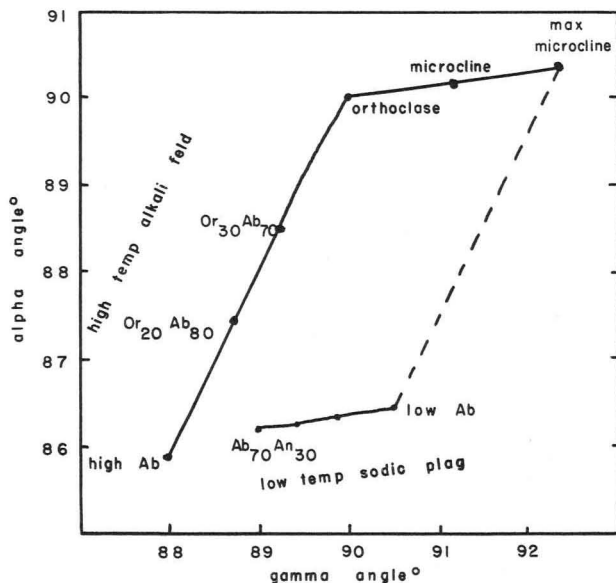

Figure 12. --Alpha* and gamma* parameters of the reciprocal lattice of alkali feldspars and some low-temperature sodic plagioclase, MacKenzie and Smith, 1956.
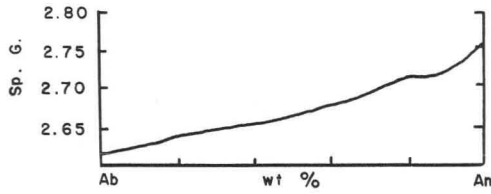
Figure 13. --Variation in specific gravity in the plagioclase group.

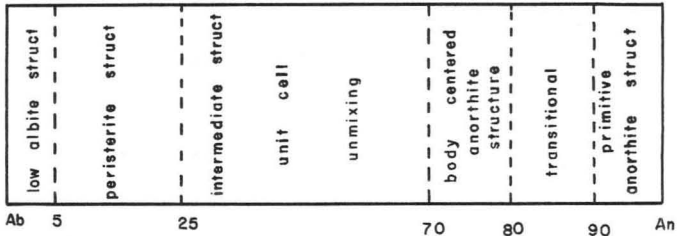Figure 14. --Structural divisions of the plagioclase group after Laves, 1954, and Gay, 1956.

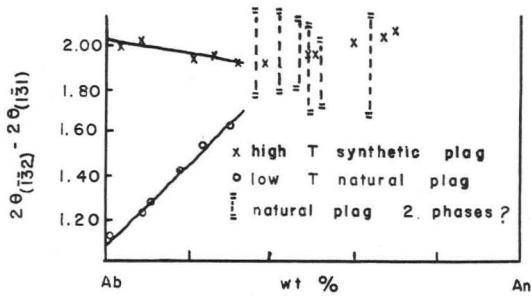

Figure 15. --Variation of the angle between the $(1\bar{3}2)$ and $(1\bar{3}1)$ with composition of the plagioclase feldspar (Tuttle and Bowen, 1950).
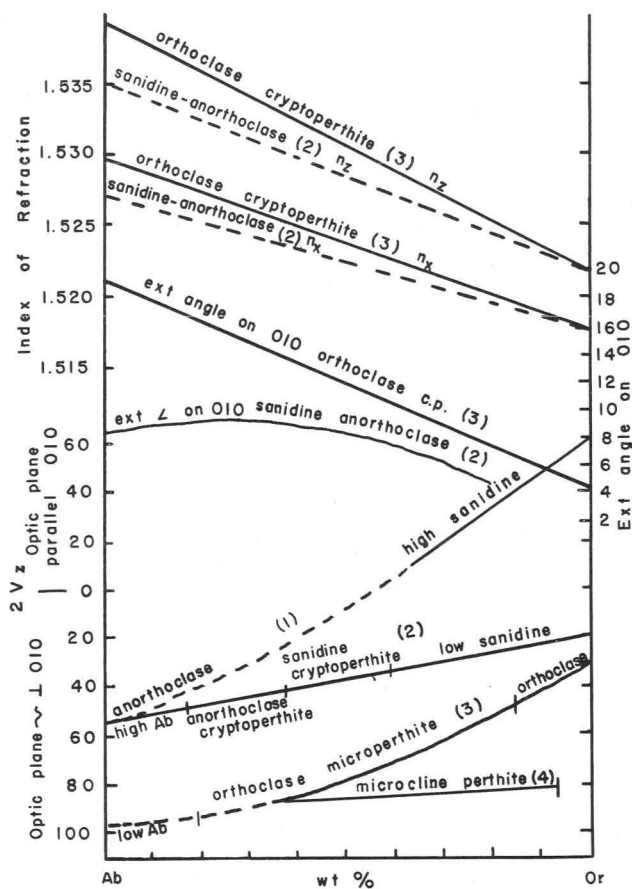
Figure 16. --Optical properties of the alkali feldspars as a function of composi-
tion and structure. After Tuttle, 1952, and MacKenzie and Smith, 1956.

to 010, or they may be elongated parallel to "a" in which case they appear prismatic due to the development of the 001 and 010. Anorthoclase is commonly elongated parallel to the vertical axis. Plagioclase may be elongated parallel to "b." All feldspars have perfect 001 cleavage and good 010 cleavage, which make an angle of 90° in the monoclinic feldspars, 89° 43' in microcline, and 93° 34' to 94° 12' in the plagioclase series.

The common types of twinning found in the feldspars include the Carlsbad, Manebach, Baveno, pericline, and albite laws. Carlsbad twins are simple parallel twins in which the composition plane is 010 and the twin axis is "c." Manebach twins are simple normal twins with 001 as the composition and twin plane and the twin axis is normal to 001. In Baveno twins the twin axis is normal to 021 which is the composition plane and twin plane. Pericline twins are repeated parallel twins in which the twin axis is "b" and the composition plane is a rhombic section parallel to the "b" axis. Albite twins are repeated normal twins with 010 as the composition and twin plane and the twin axis normal to 010.

The monoclinic feldspars are commonly twinned according to the Carlsbad law, but may also be twinned according to the Manebach or Baveno laws. Repeated twins of the albite or pericline types are impossible in the monoclinic feldspars. In the triclinic feldspars the albite type of twinning is nearly always present and other types such as pericline and Carlsbad are common.

Alkali Feldspars

The specific gravity of the alkali feldspars ranges from 2.54 to 2.61. The variation in specific gravity is a function of solid solution in the series Or-Ab. The density ranges from 2.54 in microcline to 2.57 for the monoclinic members with continued increase as the Ab content increases until it reaches 2.61 for the albite end of the series. The hardness varies from 6.0 to 6.5.

The cell size and "d" spacings reflect changes in composition and the degree of order-disorder within the alkali feldspars. Bowen and Tuttle (1950) plotted the "d" spacings of a series of synthetic alkali feldspars and their results are shown in Figure 10. The most surprising feature of the diagram is the smooth, continuous transition of "d" spacings from high-temperature monoclinic Or phase to the triclinic high-temperature Ab phase.

Gabrielle Donnay and J. D. H. Donnay (1952) extended the studies of Bowen and Tuttle. They found a continuous change in the unit cell dimensions as a function of composition for the $d_{(\bar{2}01)}$, but found a marked break in the crystallographic angles alpha and gamma when the ratio of K:Na was 1:2. Furthermore, the $d_{(111)}$ spacings of the monoclinic crystals split into $d_{(111)}$ and $d_{(1\bar{1}1)}$ when the crystals became triclinic (Fig. 11). The break in curve of the crystallographic angles and that for the $d_{(111)}$ spacings appears at a composition which coincides with the minimum on the phase diagram in Figure 1.

Recently J. V. Smith and W. S. MacKenzie developed a technique for the rapid determination of basic angle constants of the reciprocal lattice, alpha* and gamma*, as indicators of the crystal phase and composition of alkali feldspars (Fig. 12). This method employs an oscillation diagram with 010 as the oscillation axis and is extremely useful in determining the exact nature of the

unmixed phases in microperthites. The X-ray oscillation method gives infor-
mation on the nature of twinning in the unmixed phases. For example, they
have been able to demonstrate that the potassium component is often forced to
be triclinic as indicated by the doubled spots on the oscillation photograph.
Diffusiveness of the spots has been attributed to nonequilibria in the thermal
history of the feldspars.

Plagioclase Feldspars

The density of the plagioclase feldspars varies with the progressive
change in chemical composition from 2.61 in albite to 2.76 in anorthite (Fig.
13). Similarly there is a progressive increase in the melting temperature
from 1100° to $1550^{\circ}C$. Hardness ranges from 5.0 to 6.5.

The analogy of the albite and anorthite structures has been discussed
previously with regard to the superstructure of anorthite. The following dia-
gram illustrates one interpretation of the structural divisions within the plagio-
clase group (Fig. 14). Tuttle and Bowen (1950) studied the structural details
of plagioclase by comparing the spacing shifts for the ($1\bar{3}2$) and ($1\bar{3}1$) reflections
on powder diagrams. They established the range for structural heterogeneity
shown in Figure 15.

OPTICAL PROPERTIES

All feldspars are biaxial and colorless in thin section. Most of the
feldspars have large 2V angles, except sanidine, and the optic sign may be
positive or negative. The birefringence is weak and refringence is low. The
optic orientation is different in the various kinds of feldspars and is extreme-
ly important in distinguishing between them microscopically.

Alkali Feldspars

Tuttle (1952) has attempted to reconcile the structural and optical
classifications of the alkali feldspars. He recognizes four series based upon
the accurate measurement of 2V and orientation of the optic plane (Fig. 16):
(1) The high sanidine--anorthoclase cryptoperthite, (2) sanidine--anorthoclase
cryptoperthites, (3) orthoclase cryptoperthites, and (4) microcline crypto-
perthites. The first series is distinguished by the orientation of the optic
plane parallel to 010 and a 2V of $20-60^{\circ}$. The sodic end of the series is char-
acterized by an abnormal 2V angle, 60° for high Ab, and the indices of refrac-
tion. The second series is characterized by having the optic plane nearly
normal to 010, small extinction angles on 010 (4 to 8°), and by indices of re-
fraction which are slightly less than those for the third series. Anorthoclase
contains over 63 percent Ab and is gradational with sanidine in its optical
properties. Most if not all sanidines which contain over 40 percent Ab show
some unmixing of high-temperature albite. Anorthoclase is distinguished from
orthoclase and microcline by the extinction on 010 and smaller 2V angle. The
third and fourth series have low-temperature albite as a common sodic end
member characterized by an optic angle about Z of 100° and the highest indices
of refraction of all alkali feldspars. The orthoclase of series three is

distinguished from untwinned microcline of series four by the extinction angles on the 001, 0° for orthoclase and $10\text{-}15^{\circ}$ for microcline, and by the differences in 2V angles.

Plagioclase Feldspars

In the previous discussion it was noted that the plagioclase feldspars exist in both high- and low-temperature modifications. The accurate identification of the plagioclase becomes one of the most important determinations the petrographer makes. The degree of accuracy required will dictate the method of identification employed.

The most rapid and reliable method of plagioclase determination is by means of the index of refraction of cleavage fragments. For routine work the use of crushed fragments and standard oil immersion techniques will be sufficiently precise. The results from such measurements can then be used to determine composition from curves such as those in Figure 17.

For routine examination of thin sections the extinction angle methods are commonly employed. Two general methods are used: (1) the statistical method in which only the maximum extinction angle is significant, and (2) methods which give the composition from a single measurement, i. e., the combined Carlsbad-albite twin method. For either method suitable crystals will be those which are cut normal to 010. Such crystals can be recognized by the sharpness of the composition planes with slight changes in focus, uniformity of illumination of all lamellae when parallel to the vibration directions of the nicols, and symmetrical extinction when rotated to right and left. A characteristic of the extinction angle methods which should be noted is that the angles are commonly given as positive and negative extinction angles (Fig. 18). The angle is negative for compositions in the range of An_0 to An_{21} and positive for those above An_{21}. In order to distinguish between positive and negative extinction angles one must use a crystal in which the 001-100 edge is present, and such crystals are rarely found. Therefore, the distinction between these compositions must be made on the basis of indices of refraction or optical sign. Plagioclase in the range An_0 to An_{21} will have indices of refraction less than balsam (negative relief) and will be optically positive. For all plagioclases greater than An_{21} the indices of refraction will be greater than balsam (positive relief) and the optic sign may be either positive or negative.

The statistical method (Michel-Levy Method) is the most widely used method, although it is not always reliable. The method can be used only for plagioclase twinned according to the albite law. In some plagioclases only pericline twins are found and, unfortunately, they cannot always be distinguished from albite twins. In all but the most calcic plagioclase (anorthite) the albite twins are length-fast; pericline twins may be either length-fast or length-slow. Therefore, the extinction angle used must be from the direction of the fast ray to the trace of the albite twin (010) and hence angles of greater than 45° are possible. The method is applicable only when feldspars of one composition are present since by its very nature it determines only the most calcic plagioclase present.

Whenever a rock contains plagioclase with combined Carlsbad-albite twins the second method is to be preferred, since measurement of one grain is sufficient to determine the composition of the plagioclase. The grains which
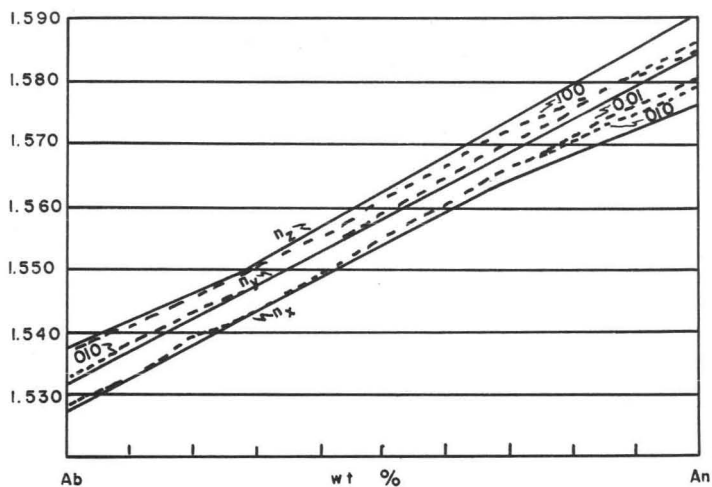
Figure 17. --Indices of refraction of plagioclase feldspars, after Chayes, 1952 (solid lines) and of cleavage flakes, after Tsuboi, 1923 (dashed lines).
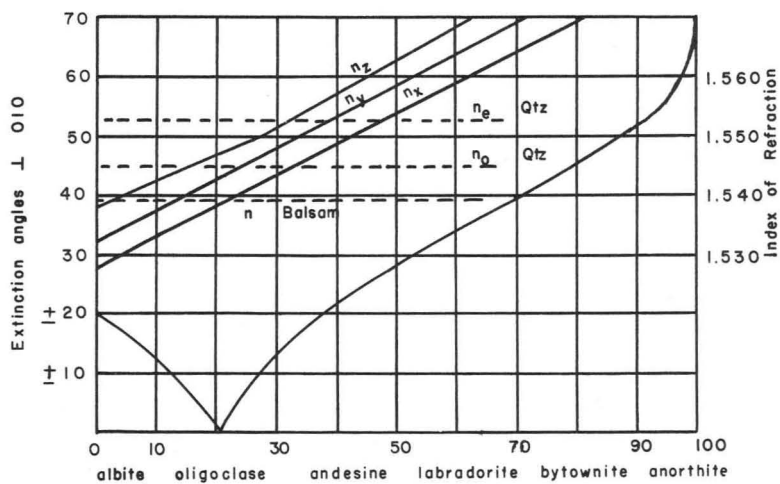

Figure 18. --Curve showing maximum extinction angle of albite twins cut normal to (010) for plagioclase feldspars (Michel-Levy Method). The relationship of the indices of refraction of plagioclase, quartz, and balsam are shown as well. Modified after Kerr, 1959, and Wahlstrom, 1955.
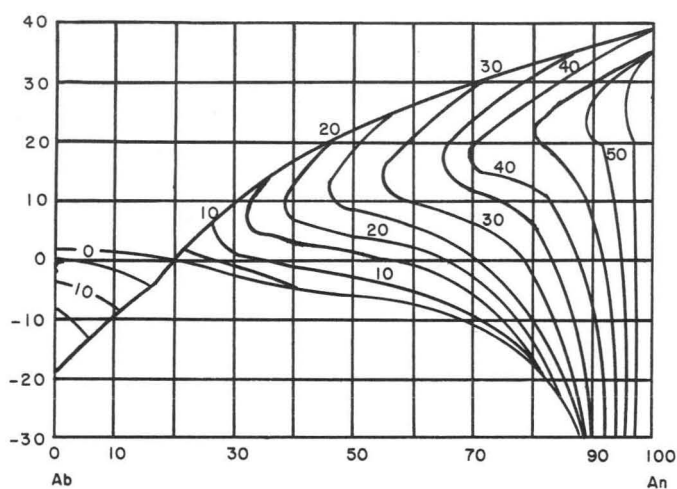
Figure 19. --Curves showing extinction angles of combined Carlsbad-albite twins normal to (010) for the plagioclase feldspars. From Kerr, 1959, after Wright, 1911.

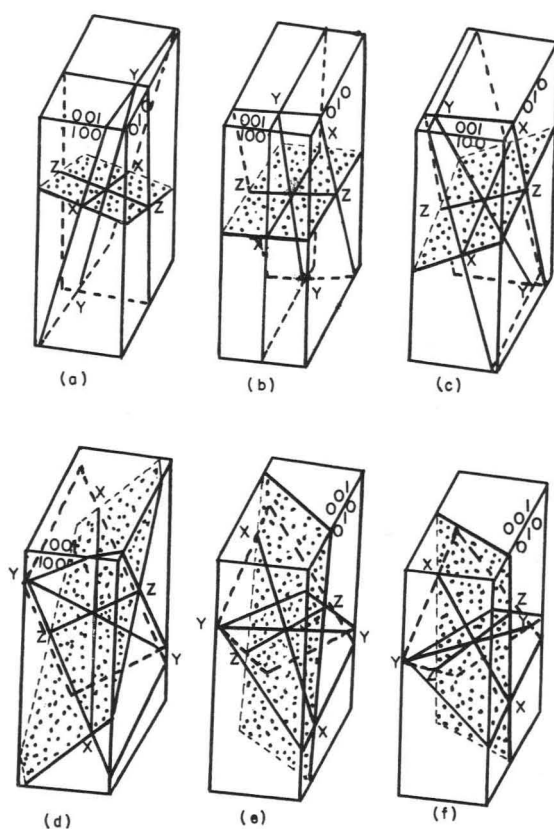(a)   (b)   (c)

(d)   (e)   (f)

Figure 20. --Optic orientation of the plagioclase feldspars: (a) albite, (b) oligoclase, (c) andesine, (d) labradorite, (e) bytownite, and (f) anorthite. Optic plane stippled. After Winchell and Winchell, 1951.
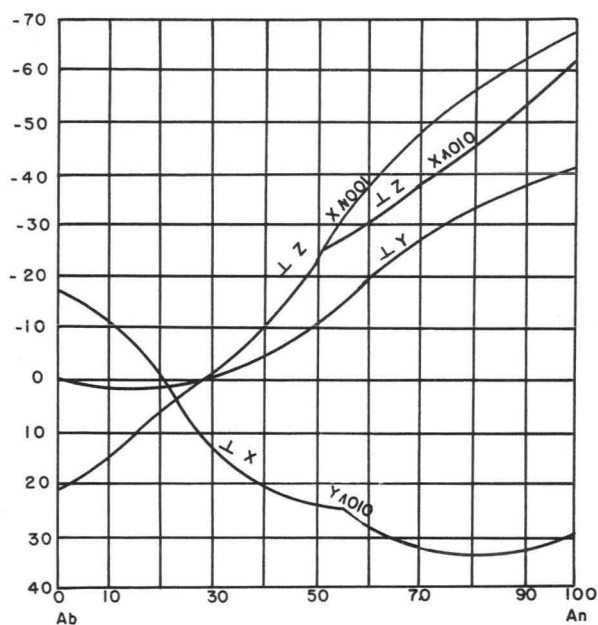
Figure 21. -- Extinction angles of plagioclase from grains oriented in certain optical directions. After Wright, 1913.
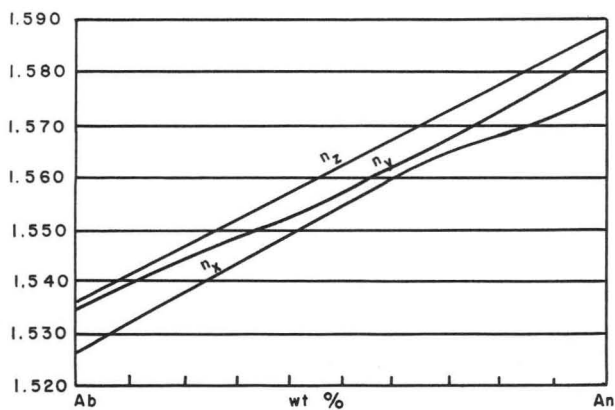
Figure 22. --Indices of refraction of plagioclase inverted to the high-temperature modifications by heat treatment. After J. V. Smith, 1957.
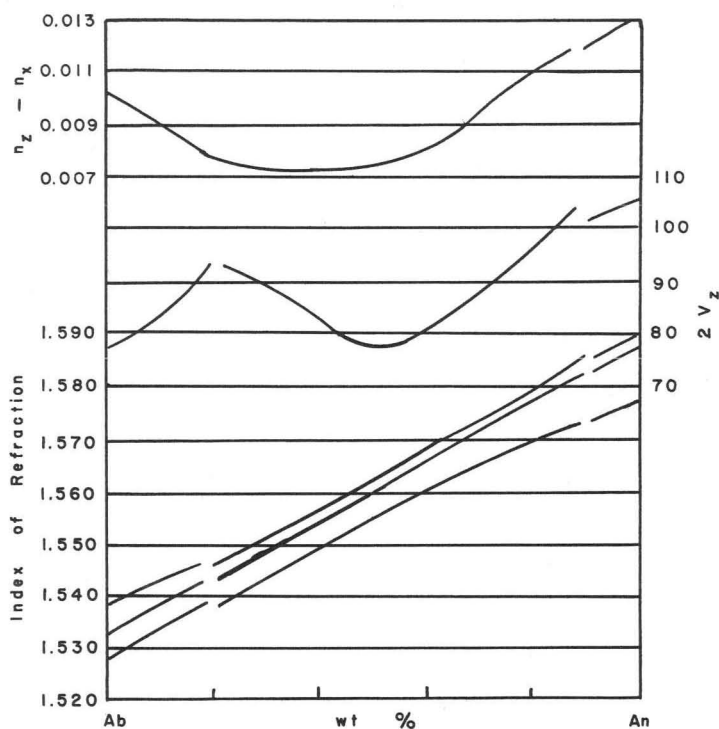
Figure 23. --Optical properties of low-temperature plagioclase, after J. R. Smith, 1960.

Figure 24. --Relation between 2V and composition of some plagioclase feldspars. The solid line represents 2V of natural high-temperature feldspars, heated natural feldspars, and synthetic high feldspars. The dashed line is for natural low-temperature feldspars. After Tuttle and Bowen, 1950.

are suitable for measurement will have the same properties as those given above. Also, when the twin planes are in the 45° position the albite twins disappear and only the Carlsbad twins will be evid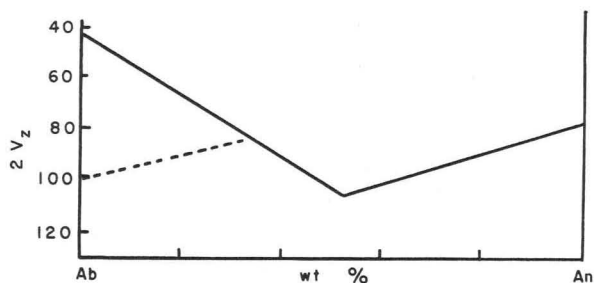ent; while when the twins are in the 0° or 90° position all of the twin elements will be equally illuminated. The procedure is the same as for the statistical method except that two sets of angles are measured, the extinction angles for the albite twins in each of the Carlsbad twins being measured. In general one set of angles will be larger than the other, and the two values applied to Figure 19 will give the anorthite content of the plagioclase.

Although the previous methods are ones most commonly used, they are limited to twinned plagioclase which are free from zonal complications. Sections normal to the optic directions X, Y, and Z are very useful, since they are applicable to twinned or untwinned crystals and because the accuracy of orientation may be checked optically. The changes in optical orientation within the plagioclase group are shown in Figure 20. The sections normal to Z are most useful. Such sections show no albite twinning, except in calcic plagioclase where they will broad and diffuse, and will show the best defined and sharpest zones in zoned crystals. These sections permit the study of variations in composition in zoned crystals. The grains will exhibit an intermediate interference color and will give a centered bisectrix figure in which the optic plane is fast (X) and the optic normal (Y) is slow. Sections normal to X also have an intermediate interference color, but will show sharply defined albite twins if present. The grains will yield a centered bisectrix figure in which the optic plane is slow (Z) and the optic normal fast. Sections normal to Y will show the maximum interference color and give a flash figure (optic normal interference figure). Measurement of the extinction angles permits the determination of plagioclase with a high degree of accuracy (Fig. 21).

More precise plagioclase determinations can be obtained from optical properties but the techniques are considerably more exacting. Many comprehensive studies of the plagioclase group have revealed a small but distinctive difference between the optical properties of the high- and low-temperature types. Smith (1957) converted natural plagioclases to high-temperature forms and determined the indices (Fig. 22). Compare these with the values for low plagioclase given in Figure 17, and the main difference which becomes apparent is in the sodic end of the series from about An_0 to An_{35}. The precision index determination of plagioclase involves the standard universal stage procedure described by Emmons (1943) or a method devised by J. R. Smith (1960). On the basis of his detailed work on low-temperature plagioclase Smith drew a new set of curves for such feldspars (Fig. 23).

The measurement of 2V angles provides additional distinction between high- and low-temperature plagioclase as shown by Tuttle and Bowen (1950). The results of their work are shown in Figure 24. Compositions were determined by refractive index determinations. Compare values with those determined by Smith (1960). Note that within both curves certain decided breaks occur in the optical properties. These breaks coincide with the structural changes previously discussed.

PETROGENIC CONSIDERATIONS

The almost universal occurrence of feldspars in igneous and metamorphic rocks gives them an important role in petrogenesis. Our knowledge

of the feldspars has advanced to the point where they can be used to decipher
the mode of origin of many of the rocks in which they are found. As pointed
out previously the petrographer must make rather detailed studies and use all
the tools available in order to obtain the information necessary for petrological
interpretations.

The feldspars provide a clue to the thermal history of the rocks in
which they are found. Thus it becomes imperative that one distinguishes be-
tween the high- and low-temperature forms (Figs. 16, 23, and 24). In general
the high-temperature forms are found in volcanics and basic igneous rocks,
while the low-temperature modifications are characteristic of plutonic rocks
of granitic composition and also of most metamorphic rocks. The composition
of the plagioclase feldspars found in metamorphic rocks is a guide to the facies
environment. Thus, in rocks of the lowest metamorphic grade, albite is the
stable form, and the excess Ca will be held in some anorthite substitute min-
eral such as epidote. As the intensity of the environment increases the plagio-
clases become progressively more calcic and the quantity of anorthite substitute
mineral, epidote, scapolite, etc., decreases. In the highest grades of meta-
morphism, the upper part of the almandine amphibolite facies and the granulite
facies, calcic plagioclases are stable (bytownite or anorthite) and the anorthite
substitute minerals are absent. At the present time, the alkali feldspars are
not as useful for facies indicators of metamorphic rocks. However, microcline
appears to be the stable polymorph until the environment becomes such that
calcic plagioclases are stable, at which time the stable alkali feldspar is ortho-
clase. The high-temperature polymorph, sanidine, forms only under conditions
of pyrometamorphism.

The zonal nature of many of the plagioclase feldspars has been used
by many as a criterion for petrogenic interpretations. Various types of zoning
are recognized: (1) Normal or progressive zoning, (2) reversed zoning, and
(3) oscillatory zoning.

The normal or progressive zoning is characterized by the gradual
advancement of extinction from the center of the grain outward or vice versa.
The zones may be either continuous or discontinuous (Fig. 25). The individual
zones are usually broad and may or may not exhibit sharp boundaries (Fig. 25).
Normal continuous zoning would be expected to develop in the plagioclase crys-
tals of a magma if the cooling were nearly continuous and equilibrium almost
maintained. Similarly, such zoning could form in a metamorphic rock sub-
jected to nearly continuous retrogressive metamorphism. Discontinuous nor-
mal zoning in feldspars is found in both igneous and metamorphic rocks. Such
zoning results from a sudden departure from equilibrium conditions. Factors
which might be responsible for change equilibrium include pressure changes,
change in volatile content, side reactions (such as assimilation), and meta-
somatic introduction of material. Thus in igneous rocks discontinuous normal
zoning may result from any one or a combination of the above factors, or it
may be the result of overgrowths of sodic plagioclase on early formed crystals
in the late magmatic or deuteric stage. In metamorphic rocks discontinuous
normal zoning could originate in the following ways: (1) as the result of sudden
departures from equilibrium conditions during retrogressive metamorphism,
(2) in response to incomplete equilibrium attainment by progressive metamor-
phism, and (3) metasomatic introduction of Na.

Reversed zoning is found in both igneous and metamorphic rocks. In
either rock type the presence of reversed zoning indicates a condition of non-
equilibrium. In igneous rocks the reversed zoning is often of the type shown
in Figure 26A, that is it has a fairly uniform core and a more calcic border.
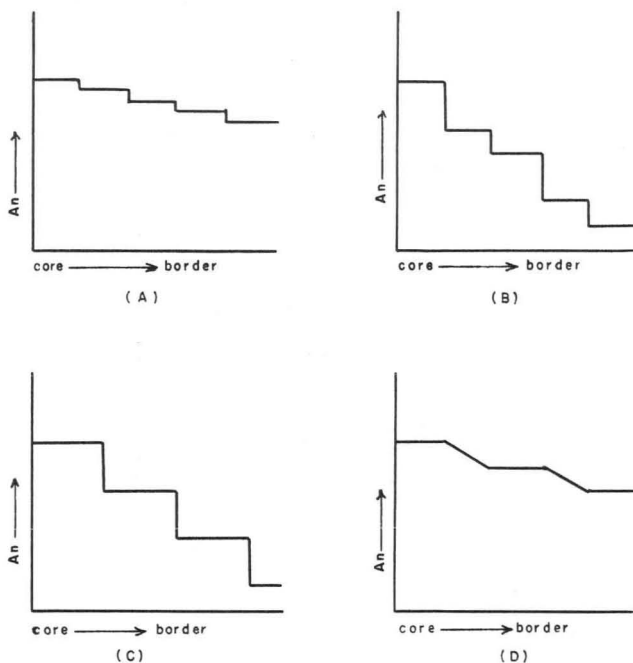
Figure 25.--Schematic diagrams to illustrate variations in An content of zoned plagioclase from core to border. (A) normal continuous zoning (essentially a smooth curve variation), (B) normal discontinuous zoning, (C) normal zoning with broad sharply defined bands, and (D) normal zoning which shows gradational contacts between zones.
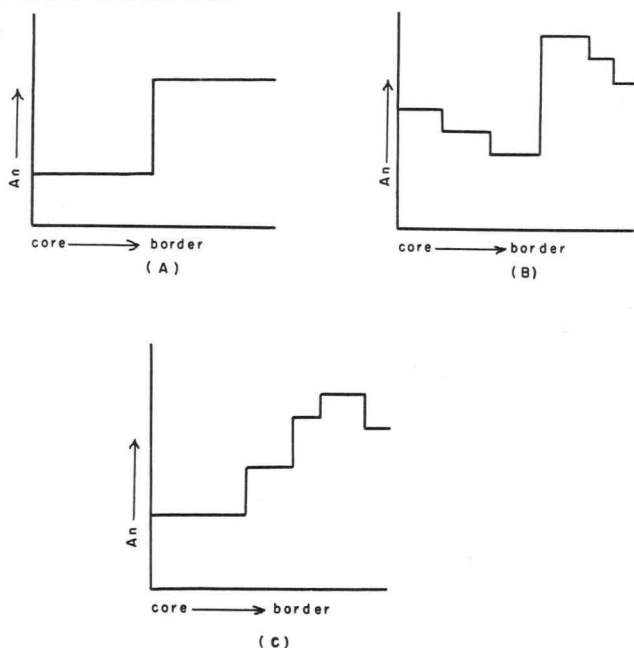
Figure 26.--Schematic diagrams to illustrate the variation in An content of reverse zoned plagioclase. (A) simple reverse zoning, (B) combination of normal zoning and simple reverse zoning, (C) combination of discontinuous reverse zoning and normal zoning.
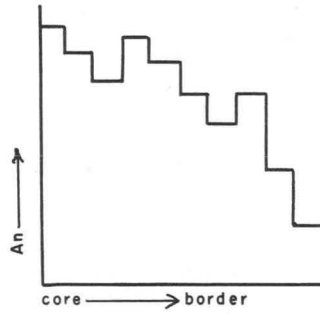
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Figure 27. --Schematic diagram of variation in An content within an oscillatory zoned plagioclase crystal.
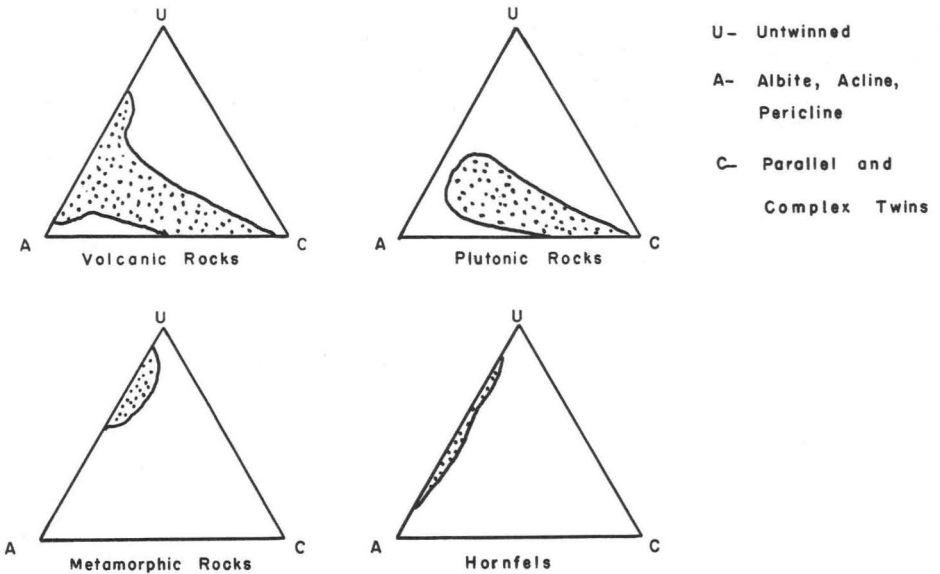

Figure 28. --Distribution of twin types in selected rock types, after Gorai, 1950.

Such zoning may be the result of a shift in equilibrium as a result of assimilation, or it may reflect a change in the volatile content of the magma. The plagioclases in many igneous rocks are typified by combined normal and reversed zoning as shown in Figure 26B. This type of zoning is best explained by the equilibrium shifts associated with changes in pressure and/or volatile content of the magma. Reversed zoning within the plagioclases of metamorphic rocks is a common feature. The most common types observed are illustrated in Figure 26A and C. The zonal development reflects incomplete equilibrium conditions in response to progressive metamorphism. The simple reverse zoned crystals are common in rocks of low grade metamorphism in which the core represents the stable plagioclase during the initial stages of metamorphism and the rim the phase which was stable at the peak of metamorphism. The presence of the relict core indicates that complete mineralogical equilibrium was not attained. Zoned crystals of type (c) are characteristic of medium to high grade metamorphics. Each successive step represents the mineralogical phase developed on a thermal plateau during progressive metamorphism. Very often these plagioclase crystals will show some evidence of normal zoning in response to the retrogressive conditions.

According to Emmons (1953) oscillatory zoning is characteristic of plagioclase crystals formed from a true igneous liquid. Such zoning is made up of a large number of thin shells with sharp contacts between successive shells (Fig. 27). The overall trend is toward normal zoning, although reversals are often observed. Some borders between shells are irregular and appear to have undergone partial resorption prior to growth of succeeding shells. The common suggestion for growth of such crystals has been to expose the crystals to liquids of different compositions. Such an explanation is difficult to accept because of the amount of movement of liquids and/or crystals required to develop the observed zoning. Fenner (1950) and Tuttle and Bowen (1958) have discussed the role of volatiles during crystallization and conclude that pressure changes and loss of volatiles can account for the oscillatory zoning.

The nature of twinning has been used by a number of workers as a guide to the origin of rocks. Gorai (1950) made a statistical study of the twins in various rock types (Fig. 28). He concluded that the albite, acline, and pericline twins are commonly present in both igneous and metamorphic rocks; and that the remaining parallel twins and complex twins are characteristic of plutonic or volcanic rocks. Emmons (1953) stresses that the plagioclase of metamorphic and metasomatic rocks are untwinned or only slightly twinned. Furthermore, Emmons believes that the plagioclase from the borders and roof portions of intrusions are either untwinned or slightly twinned. Twinning post-dates zoning and often destroys all evidence of earlier zoning. Emmons postulates that zoning is a prerequisite for twinning. The nature of the twinning is also useful as a rapid clue to the nature of the plagioclase. For example, albite is characterized by broad poorly defined twins, oligoclase (especially the calcic end) and andesine exhibit sharply defined and very closely spaced twin lamellae, and the calcic plagioclases have well-defined twins in a random distribution of broad and narrow bands.

The perthitic feldspars offer an excellent key to petrogenic interpretation. The amount of solid solution between Or and Ab is a measure of the minimum temperature at which the feldspar could have formed under equilibrium conditions. The above equilibrium could be obtained in either a magmatic or metamorphic environment. The detailed study of feldspars will indicate the nature of the perthite. That is, whether they consist of sanidine--high-albite, anorthoclase--high-albite, orthoclase--high-albite, orthoclase--low-albite, or

microcline--low-albite (see Fig. 16). The high-temperature phases are characteristic of rocks with a magmatic history or of a high-temperature pyrometamorphism. Those of the low-temperature modifications, orthoclase or microcline perthites, either crystallized or recrystallized at moderate to low temperatures.

The distribution, arrangement, and kind of inclusions within the feldspars serve as an additional petrogenetic criterion. The plagioclase feldspars of volcanic and hypabyssal rocks such as basalt, diabases, andesites, or dacites often contain inclusions of glass or small blebs of matrix materials. In gabbro, norite, and related igneous rocks the plagioclase crystals may be clear and free from inclusions, but very often will be filled with dusty inclusions or contain oriented plates of ilmenite, hematite, etc. The more alkaline varieties often contain orthoclase as antiperthitic blebs within the plagioclase. A great deal of variation is found in the inclusions contained by the plagioclase of diorites and quartz diorites. The plagioclases show all gradations from grains devoid of inclusions to those with a few poikilitic inclusions of mafic minerals, iron ores, or apatite to plagioclase crystals with abundant poikioblastic inclusions of mafic minerals, opaques, quartz, etc. Such textural variation with the rocks of the diorite family suggests they originate in more than one way. The plagioclase grains of the granodiorite-granite family are in general free from inclusions other than alteration products, but may contain poikilitic inclusions of earlier minerals and rounded blebs or quartz, albite, etc., which may be related to late magmatic effects or to post-consolidational reactions.

The feldspars of metamorphic rocks may be free from inclusions, but typically contain rather abundant inclusions. The feldspars of schists and gneisses incorporate grains of the matrix during growth and thus will contain abundant poikioblastic inclusions of quartz, mica, or amphibole. The growth of the feldspar may have been pretectonic as evidenced by granulation and bending of cleavages, syntectonic as indicated by the presence of helicitic inclusions in feldspar porphyroblasts, or post-tectonic as shown by the secondary overgrowths with abundant inclusions aligned parallel to schistosity or foliation. The feldspars themselves often occur as poikioblastic inclusions in micas and amphiboles of schists and gneisses. The alkali feldspars of high grade rocks are typically perthitic and often contain inclusions of quartz as well. The presence of plagioclase crystals with strong reversed zoning and containing abundant poikioblastic inclusions of quartz, mica, and amphibole in many of the diorites and quartz diorites of the large composite plutons suggests that they may be of metamorphic origin.

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