Pyroxene, amphibole, and feldspar

Sometimes, common minerals in igneous and metamorphic rocks are hard to distinguish, unless you know the tricks. Colored mineral such as pyroxene and amphibole can be confusing. Just how do you know whether the green grain under the microscope is hornblende or augite? In this lab we'll develop strategies for determining the identity of that green mineral.

Feldspar is probably the commonest mineral in the Earth's crust. As you remember from the previous lab exercise, plagioclase composition has a great affect on its optical properties. You'll learn how to use them to determine the composition.

Many minerals, including the ones we're concerned with here, have properties that are easy to see under the microscope. A clear one is crystal shape. Some minerals show crystal faces; others have an irregular shape because their growth was constrained by the presence of other minerals or because the grains were weathered and rounded during erosion. The shape of a mineral grain is an important clue to the origin of the rock.

Minerals commonly have cleavage, and the traces of cleavage can be recognized in thin section. The angle between sets of cleavage or the angle between the cleavage and a privileged polarization direction are possible distinguishing characteristics for the mineral.

Other properties of minerals that are useful for identification and for petrogenesis are twinning and exsolution lamellae. Twins are growth patterns in which growth progressed in different crystallographic directions from a common plane in a crystal. The result is a single crystal with a change in crystallographic orientation and shape, almost like a composite crystal.

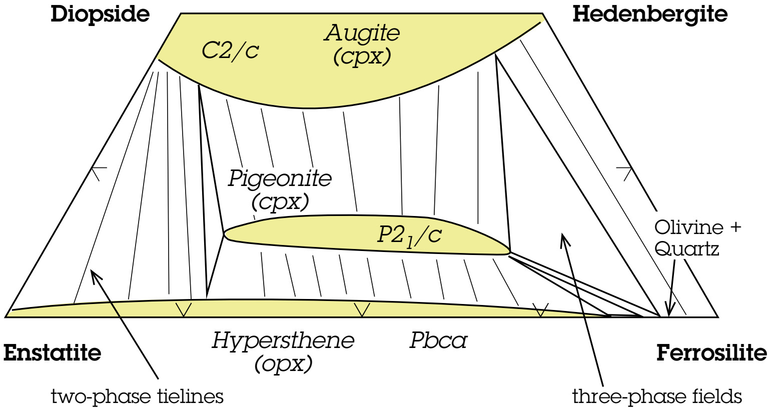
Exsolution lamellae form when a homogeneous crystal forms at high temperature and is cooled to a lower temperature at which the extent of solid solution isn't as great. The crystal unmixes to two minerals as a result. Commonly the minerals share some crystallographic orientation, resulting in a host mineral with a lamella of an exsolved mineral oriented in a particular crystallographic direction of the host. Minerals that have exsolution lamellae are important indicators of the temperature at which the host rock formed. Their presence is also a helpful indicator of their identity.

Let's look at several rocks with example of these minerals to learn how to identify them.

Pyroxene

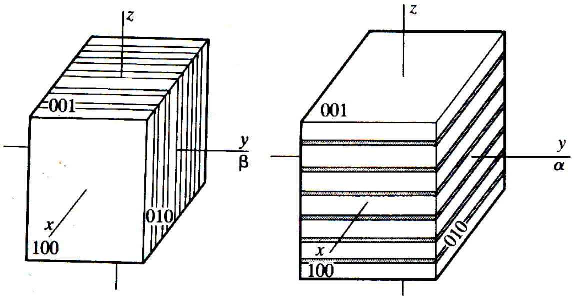
The pyroxene mineral group comprises many minerals with compositions that form solid solutions and those that form mineral pairs with only partial solid solution. We can divide the group into those that consist primarily of Ca, Mg, and Fe and those that contain substantial Al or Fe^{3+}. The first group is called the quadrilateral pyroxenes because the compositions of the endmembers, diopside, hedenbergite, enstatite, and ferrosilite, form a quadrilateral on the lower half of the triangle $CaSiO_3$–$MgSiO_3$–$FeSiO_3$. The endmembers have the pyroxene structure; whereas, $CaSiO_3$, wollastonite, does not because the Ca requires the tetrahedral chain to be kinked in a way that repeats every three instead of every other tetrahedron. See your text for a description of the structure.

Because there are two M sites in pyroxene, Ca prefers only the larger. The result is that the structures and symmetries of the quadrilateral pyroxenes depend on composition. The figure below shows compositional ranges for the structures and the miscibility gaps between them for pyroxenes that crystallize at high temperature.



Note that at low pressure, such as 1 atm., ferrosilite is not stable. Instead, fayalite + quartz are found. Because there are three structures, it is possible under some circumstances to have three pyroxenes in a rock. The compositions of those three are indicated by the corners of the three-phase triangle on the diagram. The bulk composition must fall inside the triangle for al three to be present. It is common for igneous rocks to have two pyroxenes, augite and hypersthene; those compositions are marked by two-phase tielines.

As rocks cool, the range of solid solution becomes more restricted, and it is common to find once-homogeneous pyroxenes with exsolution lamellae. The orientation of the lamellae depends on the structure of the host pyroxene. Augite exsolves opx along (100), and hypersthene exsolves augite, also along (100). The reason for the orientation is because the difference between cpx and opx is the stacking along [100]. The minerals are said to be polytypes of one another; the structural difference between cpx and opx is a difference in the stacking of layers. Pigeonite, though, exsolves augite along (001) because the relation between pigeonite and augite is in the kinking of the tetrahedral chains, which are elongate in the [001] direction. The following diagram illustrate the orientation of the lamellar in an exsolved host pyroxene.

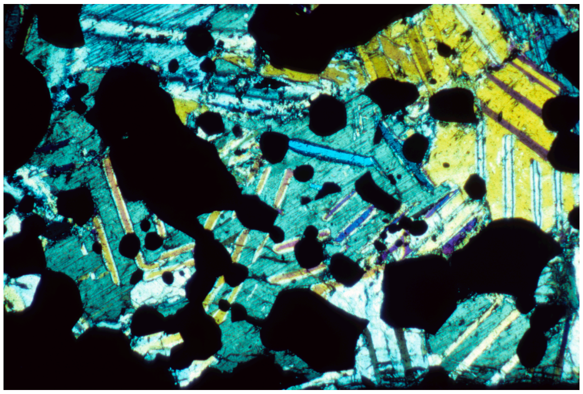


Augite with opx lamellae on (100)

Pigeonite with augite lamellae on (001)

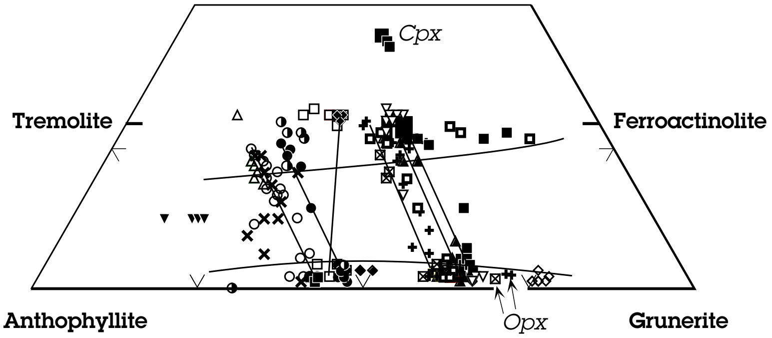
Drawings from Deer, Howie, and Zussman

An example of a pigeonite that exsolved augite on (001), inverted to opx, and exsolved augite on (100) is shown below. This is a thinsection of a metamorphosed iron formation from the Stillwater complex, Montana. The first set of lamellae are large and are easily seen. The second set is very fine and may be hard to see in the image.



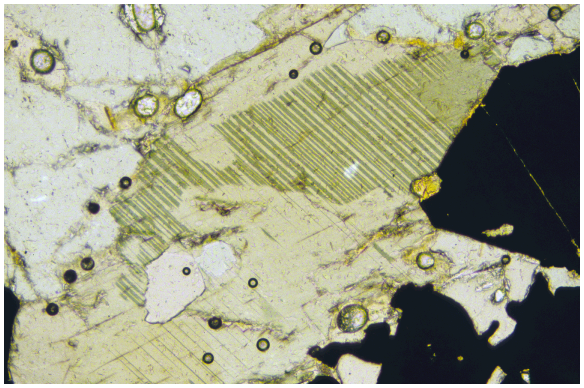
Amphibole

Amphiboles have compositions and structures similar to those of pyroxene. It is common to find amphibole with abundant Al, hornblende, for example; many, though have compositions similar to quadrilateral pyroxene and can be represented on a similar quadrilateral. An example from metamorphosed iron formation from the Ruby Range in Montana is show below.

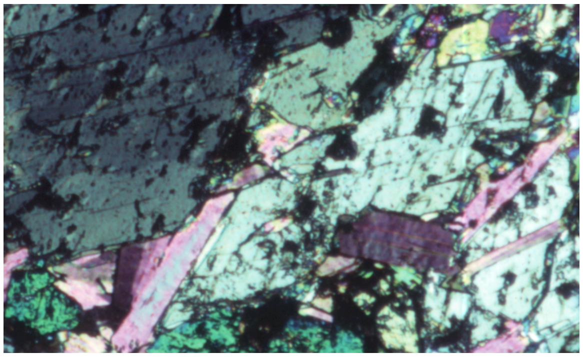


The shape of the quadrilateral is skinnier than the pyroxene quad because of the difference in the Ca:(Mg, Fe) ratio in amphibole. The field for actinolite is analogous to that for augite; actinolite is monoclinic (*C2/m*) also. Cummingtonite is analogous to pigeonite, but cummingtonite typically has very little Ca in it. Cummingtonite is also monoclinic in the same space group as actinolite. The orthorhombic amphibole, anthophyllite, is much more restricted in composition than its analog, enstatite.

Such amphiboles can show exsolution lamellae similar to those in pyroxene. A cummingtonite with exsolution lamellae of green actinolite, from the Ruby Range, is shown.

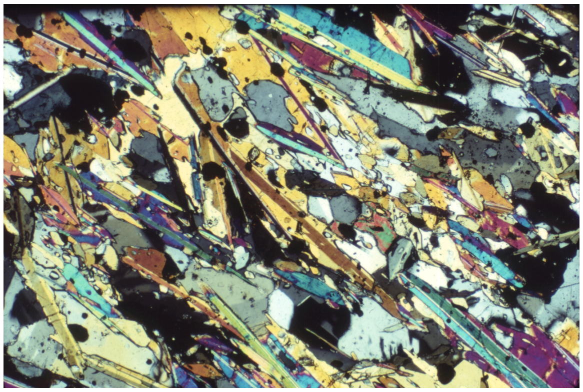


Most common amphibole is the aluminous variety hornblende. Hornblende is much more strongly colored than actinolite and typically shows moderate pleochroism as well. The shape and cleavage of hornblende are diagnostic. An example from the Panamint Mountains, California, is shown below. This is a sample of a metamorphosed basalt, which is called amphibolite because of the abundance of the mineral in the rock.



Note the cleavage and the grain shape. The pinkish grains are biotite.

Twinning in both clinopyroxene and clinoamphibole is common. The twin plane is (100), the stacking direction. It is almost always present in cummingtonite, and an example from the Stillwater complex is shown below.

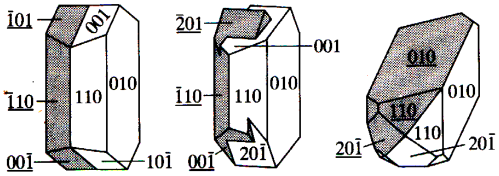


Plagioclase

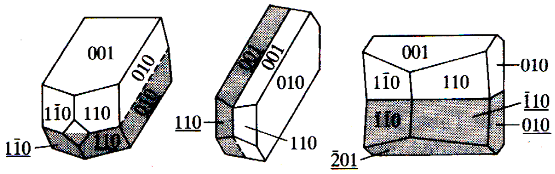
Plagioclase is probably the commonest mineral in the Earth's crust. It makes up a major fraction of all granitic rocks. It is also a major constituent of basaltic rocks. It is without a doubt an important rock-forming mineral.

The composition of plagioclase ranges essentially continuously from albite, $NaAlSi_3O_8$, to anorthite $CaAl_2Si_2O_8$, especially at temperatures near the solidus. At lower temperature, such as that of metamorphism, solid solution is restricted in the intermediate composition range. The result is regions of immiscibility and the formation of host grains with exsolution lamellae. Feldspars such as the peristerites and labrodorite have an opalescence caused by the existence of microscopic exsolution lamellae. But volcanic plagioclase is generally free of lamellae.

Plagioclase is almost always twinned, though, and there are several twin laws. The most common is the albite twin. The albite twin forms along the (010) plane with an axis of rotation along [010], as shown below. In most cases, the twinning is multiply repeated along [010]; this gives the "polysynthetic" twinning visible in hand samples of plagioclase. Another common twin is the carlsbad twin. This twin is generally a simple twin, occurring only once in a grain. The carlsbad twin also forms along (010), but the twin axis is along *c*.



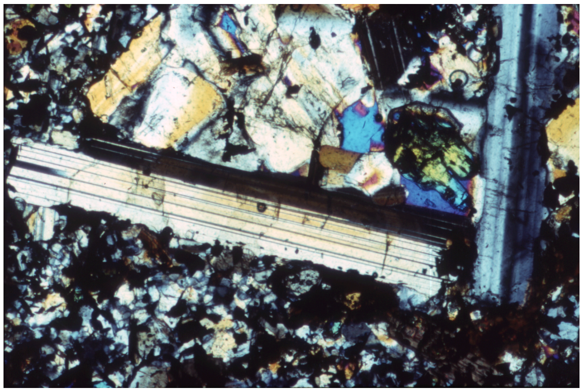
(a) Carlsbad contact twin (b) Carlsbad interpenetrant twin (c) Baveno twin



(d) Manebach twin (e) Albite twin (f) Pericline twin

Some common feldspar twins

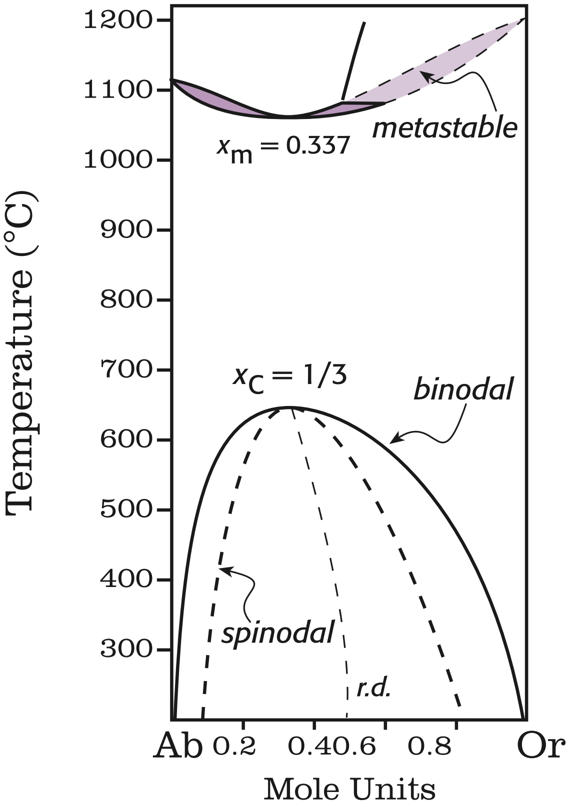
In thin section, the twinning is obvious. An example from the Duluth Gabbro, Minnesota, is shown below.



Because the optical properties depend strongly on composition, it is possible to determine the composition of plagioclase from the extinction angles against the lamellae. I've attached a few pages from Deer, Howie, and Zussman that describe the optical and physical properties of plagioclase.

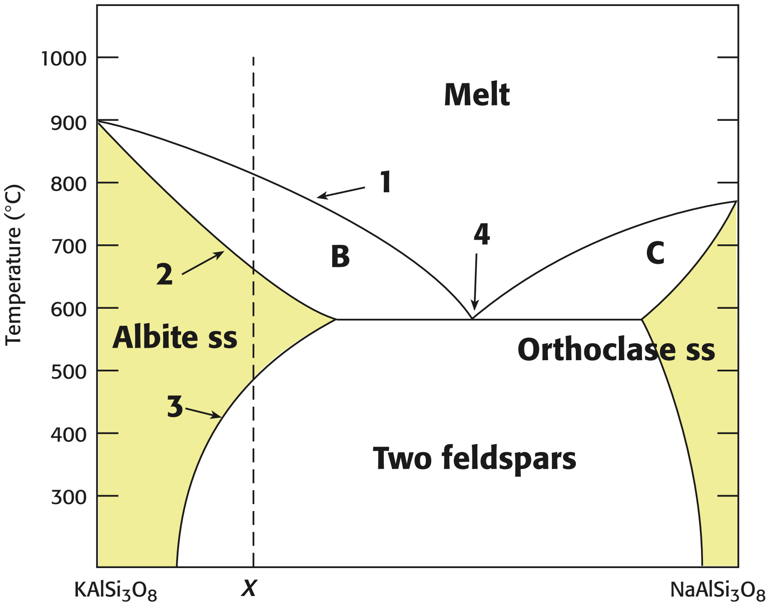
Alkali feldspar

Alkali feldspar, $KalSi_3O_8$–$NaAlSi_3O_8$, shows partial solid solution at low temperature but much more extensive solution near the solidus. In fact, at low pressure, there is complete solid solution below the solidus. Any feldspar that crystallizes from a low-pressure alkali-rich melt will form a solid solution between orthoclase and albite. As the rock cools, though, the feldspar unmixes to form an intergrowth of albite and orthoclase. If orthoclase is the host, the intergrowth is called perthite; if albite is the host (less common), it is called antiperthite. A simple phase diagram shows the crystallization behavior at low pressure.



Feldspar at temperatures greater than 650 °C have complete solid solution. At lower temperature, the feldspar exsolves two feldspars with compositions on the binodal (also called the solvus).

At high pressure, though, feldspar melts before the crest of the solvus is reached. Two feldspars are always stable, and there is only limited exsolution.



Now, in the middle of the compositional range, liquids crystallize to form two feldspars instead of one.

Exercises

1. Make a table showing properties of augite and hornblende that help you distinguish them. Consider color, pleochroism, cleavage, extinction angle, $2V$, optic sign, birefringence, and anything else that might help you. To do this you need to look at thin sections containing just amphibole, just pyroxene, and both pyroxene and amphibole. Example samples: 5-4-338, NG36B, 25277.

2. Look at thin sections of rocks containing plagioclase, alkali feldspar, and both alkali feldspar and plagioclase. Use the optical properties to learn to distinguish them. Example samples: 22500, 16200, 16151, 44-5078.

3. Look at the provided thin sections containing plagioclase. Use the Michel–Levy method to determine the composition. Also use the maximum extinction angle method. If you can find them, use the combination of carlsbad and albite twins and their extinction angles to determine the composition. Samples: 22500, 13500.

4. The following thin sections contain most or all of these minerals. Identify the minerals in the thin sections and determine the plagioclase compositions.

84LGM133	garnet amphibolite	FR2	Franciscan blueschist
21300	diorite	2230	andesite
22000	vitrophyre	LL6	garnet–biotite–pyroxene

from Deer, Howie, and Zussman p. 443–450

Optical and Physical Properties

The optical properties of the plagioclases are directly related to their anorthite content. The relief and birefringence are both low and similar to those of quartz. The refractive indices increase steadily with increase in An content; the birefringence, however, does not vary regularly.

The perfect {001} and good {010} cleavages, together with a systematic variation in the optic orientation within the series, allow the extinction angles to be used to determine the composition.

The optic axial angle for natural low-temperature plagioclase varies from approximately $2V_\gamma$ 75° to $2V_\alpha$ 75° but changes sign three times in the series, and is of less diagnostic value. Other properties varying with the composition and used for determining the plagioclases include the specific gravity, and the birefringence in sections of known orientation.

The refractive indices of the plagioclase feldspars are closely related to the chemical composition. A determinative chart is given in Fig. 159: it is important to note that the measurement of the refractive indices must be accurate to ± 0.001 to obtain an accuracy of ± 2 per cent An. The refractive indices of high-temperature plagioclases vary slightly from those of the low-temperature series: the difference in the α indices is very small but that for γ is more noticeable, e.g. natural low-temperature albite has α 1.5273, γ 1.5379, whereas synthetic high-temperature albite has α 1.527,γ 1.534. Thus measurements of α will give a reliable estimate of the composition of a plagioclase regardless of its structural state.

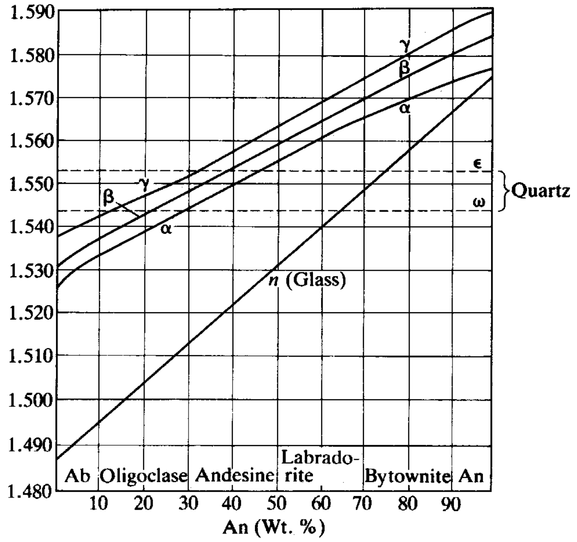


Fig. 159 Refractive indices of the albite–anorthite feldspars. The variation refers to highly ordered plagioclase. Curves for highly disordered plagioclases show small differences at the albite- and anorthite-rich ends of the series. The refractive indices of glasses of plagioclase compositions are also shown.

Approximate refractive indices of the more sodic plagioclases may be estimated in thin section by observing the Becke line on boundaries with quartz (ω 1.544, ϵ 1.553), or with the mounting medium where its refractive index is reliably known. In this way it may lie possible to place a plagioclase more sodic than about An_{48} into one of five compositional subdivisions.

The normal immersion method using sodium light is relatively rapid and is capable of giving sufficient accuracy of refractive indices of the plagioclase series for normal purposes. When working with cleavage fragments two varieties may be recognized: those lying on the perfect basal cleavage {001} and those on the slightly less perfect cleavage parallel to {010}. The somewhat rectangular fragments lying on the {001} cleavage have the {010} cleavage almost vertical and show the multiple albite twin lamellae parallel to {010} under crossed moralizers. Fragments lying on the {010} cleavage have a more angular outline due to the intersection of the expect {001} cleavage with the poor {100} parting at about 64° and no albite twins are visible. The lower refractive indices obtainable from either of these cleavage fragments do not normally differ appreciably, and are also close to the true α refractive index, so that it is usually sufficiently accurate to determine the lower refractive index on an {001} or {010 } cleavage flake and to plot this on the α curve to determine the plagioclase composition. The single variation method uses the dispersion of the refractive indices of plagioclase in cleavage flakes parallel to {001} or {010} in conjunction with an immersion medium the dispersion of which is known: the refractive indices are compared, using a monochromator, until matching is obtained between the feldspar and the immersion medium.

The composition of a plagioclase may also be determined by melting a small amount of material, quenching it to a glass and determining the refractive index of the glass. The refractive index of an isotropic glass is more easily determined than the refractive index for a known orientation in a triclinic mineral, and for the plagioclase feldspars the rate of change in refractive index of the glass with composition is approximately twice as great as in the indices for crystals of plagioclase (Fig. 159); the method can also give the average composition for material with strong zoning or with exsolution intergrowths. The refractive indices of K-feldspar and albite glasses are rather similar (1.487 and 1.489 respectively); thus the presence of even substantial amounts of the orthoclase molecule has little elect on the determination of the anorthite content: the original structural state of the plagioclase is of no consequence. The refractive index is particularly useful for obtaining the composition of calcic plagioclase, for which the use of extinction argles is less reliable. The Becke line effect, because feldspars have appreciable dispersion, is enhanced by using a yellow filter.

The optic axial angle of plagioclase of the plutonic low-temperature series is always large ($> 75°$), the optic sign is (+) for albite, changes to (–) in the more calcic oligoclase range, becomes (+) again for most andesines, and reverts to (–) in bytownite and anorthite. High-temperature plagioclases have different optics; thus volcanic albites have $2V_\alpha \sim 50°$. The variation of the optic axial angles for both series together with values for specimens heated at near-solidus temperatures is shown in Fig. 160.

The optic axial plane varies considerably with composition. In low albite it is approximately perpendicular to z but in the more calcic plagioclases it tilts over until in anorthite it is nearly parallel to z (Fig. 161). The elect of the changing orientation results in systematic variations in extinction angles.

Although the universal stage was once the major tool for determining optical orientations of feldspars, the results were less precise (and less accurate) than those that can be obtained using spindle-stage techniques. The latter are now capable of locating an optical direction to within a few tenths of a degree and can be used in conjunction with the X-ray precession method capable of locating crystallographic axes to within 0.1°.

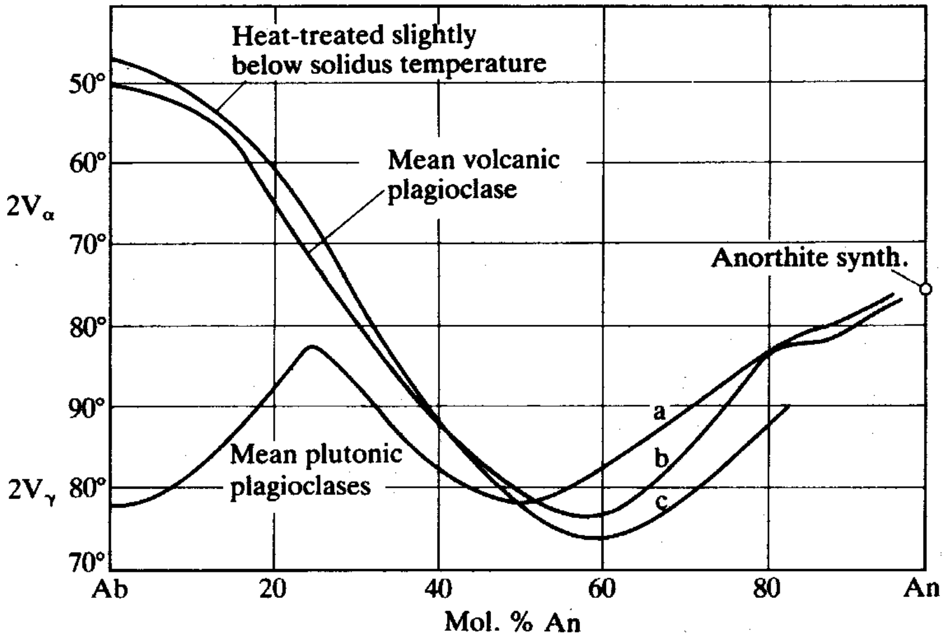


Fig.160 Optic axial angle as a function of plagioclase composition. Curves a, mean of plutonic plagioclases (low temperature); b, mean of volcanic plagioclases (high temperature); c, plagioclases heat-treated slightly below solidus temperature.

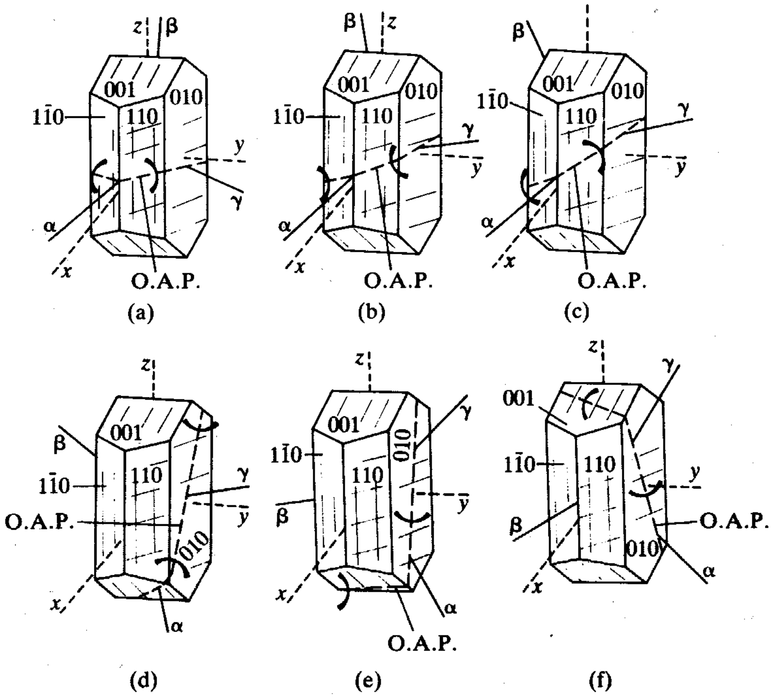


Fig. 161 Optic orientation of the low plagioclases: (a) albite; (b) oligoclase; (c) andesine; (d) labradorite; (e) bytownite; (f) anorthite.

In the majority of twinned plagioclase crystals the composition plane is parallel to the crystal length. In plutonic and hypabyssal rocks the plagioclase are elongated parallel to [001] and fattened on (010) with multiple twinning predominantly on the albite law. In many volcanic rocks plagioclase occurs as microlites, is not twinned, and is elongated parallel to [100]. In metamorphic rocks twinning is usually simple and commonly is not present at all; combined albite–carlsbad twinning does not occur.

The maximum extinction argles of albite twins in sections normal to {010} or in the so-called symmetrical zone are diagnostic (Fig. 162). In thin section the alternate twin lamellae give symmetrical extinction angles on either side of the twin plane (Plate 4a,b). Such sections may be recognized by the sharpness of the composition plane between albite twin lamellae, which should show no lateral movement when the microscope focus is raised or lowered; by the equal interference colours of the twin lamellae when the twin plane is parallel to the vibration directions of the polarizers; and by adjacent lamellae giving equal extinction angles on either side of the twin plane. Values which show more than a 5 per cent divergence in the extinction angles for the adjacent twin lamellae should be discarded, but lesser variations may be averaged: it is essential to take measurements from several (6–12) suitable grains, and the highest symmetrical extinction angle must then be used. In all plagioclase determinative methods using extinction observations, the position of extinction may sometimes be more easily recognized with the aid of a 'sensitive tint plate.'

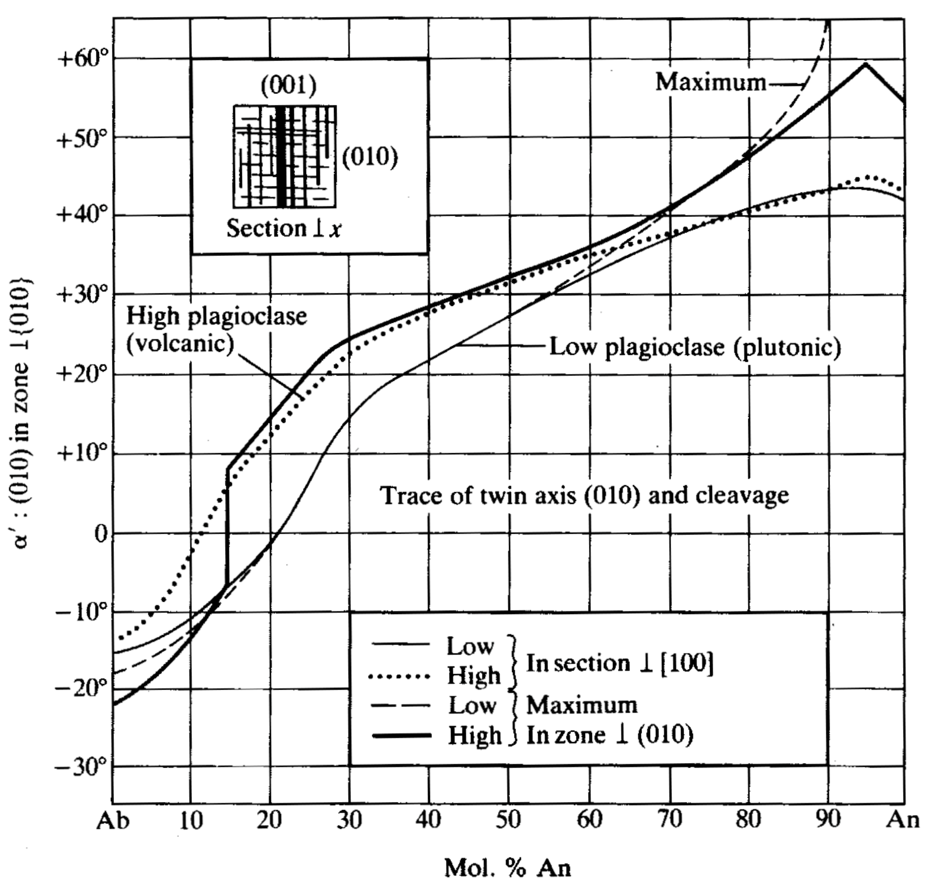


Fig. 162 Extinction angles, α':(010) in the zone $\perp$ (010) for bigh- and low-temperature plagioclase.

Extinction argles are measured from tile fast vibration direction (α') to the cleavage trace, but depending upon composition extinction can occur on one side or the other, lying in the obtuse or acute angle made by the cleavage trace with the y axis. The y direction is not always well defined and in any case there is some confusion in the literature as to which side is termed positive and which negative. In practice the ambiguity which occurs with 1ow extinction antes (about 20° either side of zero) for compositions An_0 to An_{35} (Fig. 162) can best be resolved by observation of refractive indices (Fig. 159). Alternatively a combined twin method may be used.

Conjugate extinction angles The typical appearance of a Carlsbad twin in which each individual contains albite twin lamellae is illustrated in Fig. 163. The measured values of the angles will vary according to the orientation of the crystal but the relationship between them is constant and a single measurement of a set of conjugate extinction angles is sufficient to determine the composition using the curves of Fig. 164. In practice the mean of the two extinction angles 1 and 1′ on the portions related by the albite law is plotted in conjunction with either the extinction angle α' to (010) for the second half of the Carlsbad twin, or the mean of 2 and 2′ of the albite twins if present in the other half of the Carlsbad twin. Suitable sections may be recognized by the fact that when the trace of the twin plane is oriented in the 45° position, the albite twinning disappears and the crystal appears to be a single Carlsbad twin.

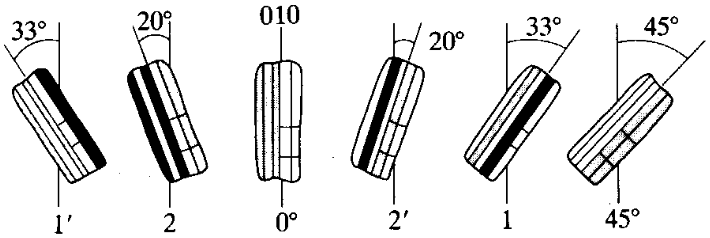
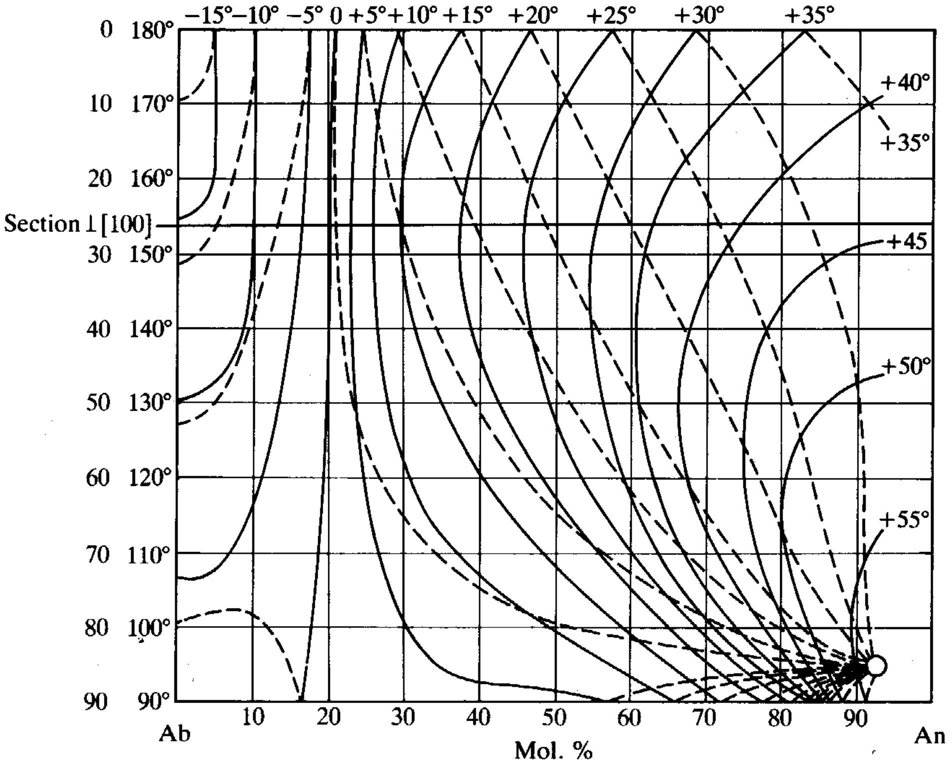


Fig. 163 Appearance of a Carlsbad twin in which each individual displays albite twin lamellae as the microscope stage is rotated with crossed polarizers. 1,1′, extinction positions of albite lamellae in Carlsbad individual at the right; 2,2′, extinction positions of albite lamellae in Carlsbad individual at the left. The albite lamellae become virtually invisible in the 0° and 45° positions of the stage; the Carlsbad twin is visible in one or both positions by a difference in the brightness of the two individuals. The twins in this illustration are also indicated by the (001) cleavage.



Solid curves for individual 1, broken curves for individual 2

Fig. 164 Variation of extinction angles of combined Carlsbad–albite twins for low plagioclases as a function of An content and orientation in zone normal to (010), including the section normal to x. The extinction positions are on opposite sides of the (010) trace at around An$_{20}$. Those for An$_{0-20}$ are taken as negative (after Tobi, A. C. & Kroll, H., 1975, Amer. J. Sci., 275, 731–6).

The extinction angle in sections normal to x is also diagnostic, and varies approximately 1° for each 1 per cent An from An$_0$ to An$_{70}$ and then by about $\frac{1}{2}^\circ$ for each 1 per cent of An to An$_{100}$. The composition of the plagioclase can thus be obtained from a single suitable section, i.e. it is not necessary to measure the maximum extinction angle for a large number of sections. Such a section is normal to both the {001} and {010} cleavages, shows the albite twin lamellae on {010}, the {001} cleavage forms an angle of 86° with the {010} cleavage and albite twin lamellae, and the cross-section tends to show an almost square outline (Fig. 162).

Iridescence and colour Plagioclases in the albite–oligoclase range of composition, which are resolved on a very fine scale into sodium-rich and less sodium-rich regions, often yield crystals which are iridescent, particularly when viewed on the (010) face. These are known as peristerites, an allusion to the play of colours on a pigeon's neck. The white to bluish iridescence (or 'chatoyance') is similar to that exhibited by the perthite intergrowths of alkali feldspars; the term 'moonstone' has been applied to both, but is perhaps better restricted to alkali feldspars. These effects are the result of multiple reflection (or diffraction) at the boundary between perthite or peristerite lamellae, the thickness of which are of the order of the wavelength of light. Feldspars with composition in the andesine–labradorite range often show a multicoloured iridescence ('labradorescence'), also best seen on (010). Aventurine feldspar has plate-like inclusions, commonly of an iron oxide, which give the mineral a spangled appearance.

Plagioclase is usually colorless when entirely fresh but typically has a white appearance due to incipient alteration. Other colorations sometimes found are generally due to inclusions: for example, anorthite crystals in xenoliths may be pink or blue from enclosed sillimanite or corundum (sapphire), while the bytownite of a contaminated euchre from Carlingford, Ireland, is so full of iron ore as to be almost black in hand specimen.