

# GEM FELDSPARS and FELDSPAR TREATMENTS

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As a group, feldspars are the most abundant minerals on planet Earth. Yet despite mineralogical superabundance and gargantuan crystal size, transparent feldspar gems (with a few *notable* exceptions) are usually tiny and extremely rare. The vast majority of ornamental feldspars are opaque or translucent, white, gray or a very pale hue, and often display a “phenomenon”, such as iridescence or some other type of color effect. These materials, including moonstone and sunstone, have been prized as gems for centuries. Several, including labradorite and amazonite, are widely used in jewelry.

**Question:** what has prevented the gemstone world from paying as much attention to feldspars as they deserve?

**Answer:** *Extreme rarity, small size, and lack of bright coloration has prevented the gemstone world from paying as much attention to feldspars as the group deserves.*

The following article is an attempt to correct this mistake and reveal the amazing story of a group of gems that may turn out to be major players in the future of the jewelry trade.

Feldspars make up nearly 60% of the earth’s crust. They are five times as abundant as quartz, and twenty times as abundant as all the carbonates, oxides, sulfides and halides *combined*. Feldspars are present in almost every type of igneous rock (those formed by cooling of a molten substance called *magma*). They also can be deposited by hot watery solutions in cracks and veins. Slow cooling of such liquids can result in crystals of enormous size, especially in very coarse-grained igneous rocks called *pegmatites*. Pegmatite minerals include many gem materials, such as beryl, tourmaline, spodumene and garnet. The typical feldspar in such rocks is a pinkish mineral called *microcline*. There are reports in the mineralogical literature of microcline crystals of almost mythic size. One such crystal, in a quarry north of Kristiansand, Norway, reportedly had dimensions of 30 x 12 x 7 *feet*. A quarry in the Russian Urals measuring 30 x 30 feet (and unknown depth) was opened *within* a *single* feldspar crystal. The Devil’s Hole beryl pegmatite in Fremont County, Colorado, was described in a 1950 U.S. Geological Survey report. The main open-cut in this mine revealed a flat 2,000 square foot surface of microcline up to 40 feet thick. Individual unbroken cleavage planes across this surface indicate that the *entire mass* was a *single crystal*. Another western pegmatite was reputed to have produced a single feldspar crystal that, when extracted, filled two railroad boxcars.

## CHEMISTRY and CLASSIFICATIONS

Understanding feldspars requires at least a minimal awareness of chemical terminology and conventions. It never hurts to review the basics! Most scientists accept the idea that atoms are the fundamental building blocks of all matter, and for the last century (more or less) the accepted “model” of the atom is visualized as a VERY small particle in the center called the *nucleus*, surrounded by a “cloud” of rapidly spinning negative charges called electrons. (We are all familiar with electrons; when they are moving in a wire they do a great job of heating up things they pass through, such as the filament in an electric light bulb, which then glows and gives off heat and light.)

The atomic nucleus consists of neutral particles called *neutrons*, and positively charged particles called *protons*. In a “neutral” atom there are equal numbers of electrons and protons, so the positive and negative charges balance out. If an atom loses one or more electrons, it is left with more positive charges in the nucleus than there are negative charges to balance them, and the result is an entity called an “ion” (eye’-on), which therefore has a net positive charge and is called a *cation* (cat’-eye-on). The process of losing electrons is called “oxidation”.

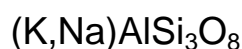
If an atom accepts electrons, it acquires a net negative charge (the process is called “reduction”) and the result is a negatively charged ion, called an *anion* (an’-eye-on). Ions are *charged particles* – atoms with either more or less electrons than there are protons in the nucleus to balance their charges. The exchange or sharing of electrons between atoms is called *chemical bonding*, and is the force that makes atoms stick together. The “oxidation state” of a cation is basically the amount of positive charge it has. A cation that has a charge of +3, for example, is in a “higher oxidation state” than a cation with a +1 charge.

## THE FELDSPAR GROUP

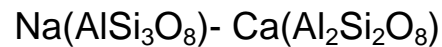
The name *feldspar* refers, not to a single mineral, but to a group of minerals with related structures and compositions. All are framework silicates made of oxygen plus silicon and aluminum and various other metals including calcium, sodium, potassium and barium. The feldspar structure is a three-dimensional network of oxygen, silicon and aluminum atoms, linked at specific points by atoms of three metals: potassium, sodium and calcium. The silicon and aluminum atoms share a structural position (call this “A”), and the other metals occupy a different structural site (call this “B”). All feldspars display either monoclinic or triclinic symmetry. All display cleavage, and most can occur in well-formed crystals in specific geologic environments. Feldspars are called “rock forming minerals”, because they are found in nearly every kind of igneous and metamorphic rock on the planet. Most of these rocks contain feldspar mixed with other minerals, but some rocks are made entirely of feldspar crystals.

The feldspar family is broadly divided into two main groups: **alkali feldspars** (with mainly potassium and only a bit of sodium in the B position) and **plagioclase feldspars** (with mainly sodium and calcium on the B site). There is nearly a complete range of compositions between sodium-rich and calcium-rich plagioclases. The more detailed feldspar classification scheme involves both chemistry and structure, and the observed structure depends both on the original temperature of formation and on subsequent thermal changes. It has been found that, at high temperature, there is complete mixing and distribution of the “B” site metals. So-called *high temperature feldspars* retain their structural state (and symmetry) as they cool; but for certain compositions, as the feldspar cools to lower temperatures the structural symmetry drops to triclinic. Thermal changes may also cause metals in the structure to be re-distributed in specific “ordered” ways, causing changes in symmetry. Feldspar structures, especially at high temperatures, offer very high diffusion rates for metals, allowing a redistribution and ordering of the silicon and aluminum atoms that make up the basic structural framework.

The two main feldspar groups differ chiefly in the metal occupying the B position. Ions of sodium and calcium are very similar in size, but the potassium ion is much larger. Potassium and sodium ions have a charge of 1+; the charge of the aluminum ion is 3+, calcium is 2+, and silicon is 4+ The formula for alkali feldspar is:



If a calcium substitutes for either a sodium or potassium atom in the structure there would be a surplus of positive charge. The electrical balance is achieved by reducing the amount of aluminum. Thus we have the plagioclase formula:



indicating that every calcium atom present is balanced by an aluminum atom replacing one of silicon in the structure.

There are a few additional members of the feldspar chemical family. If the element barium substitutes for calcium in amounts greater than 90% the mineral is called *celsian*. Another mineral called *hyalophane* has barium replacing sodium or potassium, with an accompanying increase of aluminum replacing silicon.

The underlying structure of potassium feldspar is triclinic, but complex twinning and chemical ordering results in crystals that appear to have monoclinic symmetry. Monoclinic crystals have two crystallographic directions (axes) at 90-degrees (right angles) and a third direction that is not perpendicular to the other two. This yields crystals that sometimes resemble a box with a top that slopes downward instead of being flat. Good mineral examples are crystals of microcline (see figure 7). The name monoclinic itself means “one inclined axis”.

Sodium and calcium feldspars are triclinic. As you might guess, in triclinic crystals all three crystallographic axes are inclined to each other. In some cases, however, the angles are very small, and such feldspars may strongly resemble their monoclinic cousins.

## CRYSTALS AND CRYSTAL GROWTH

Crystals are *solids*, which means that (a) they melt at a *very specific* and well-defined temperature, and (b) the atoms in them are arranged in *very specific* ways, with long-term “periodicity”. This means that the atoms in a solid are bonded together by electronic forces into specific, repetitive patterns. If you heat up a solid, the atoms start to vibrate. At a certain point the vibration is so energetic that the electronic bonds holding the atoms together in a fixed pattern actually break, and the atoms can move freely around each other, creating a liquid. The solid has melted. If you cool this liquid, the atoms start to move back together and, when the melt is sufficiently cooled, the bonding energy overcomes the heat-induced vibrations and the atoms arrange themselves into the same ordered (crystalline) structure as before. This so-called melting point is *very specific* and *very precise*, and is a basic property of any given solid material.

Glass is not a solid. This sounds very strange, because if you hit glass with a rock it shatters, and it certainly seems solid enough. However, if you heat glass it slowly gets hotter and hotter, turns red, and then flows. There is *no specific temperature* at which the glass can be considered “melted”. Glass is amorphous – its atoms are not arranged in a periodic, extended geometric structure, but rather they are piled and jumbled together at random. There is *no one specific temperature* at which all the bonds between the atoms are broken, and certainly they are not broken all at the same time, which is why heated glass softens rather than melts. Glass is therefore called a “supercooled liquid”, and is *rigid*, but not *solid*.

When a crystal grows, atoms that are moving around in a molten liquid or a hot solution stick together because of electronic bonding forces between them. If the temperature is too high, they un-stick almost immediately, and wander around again in search of other atoms to bond to. But as the temperature drops, the atoms do not move around as energetically. Eventually, atoms that stick together *remain* stuck together.

These tiny clusters then start arranging themselves into a configuration that ‘minimizes the total energy of the system’, i.e., a crystalline structure that is characteristic of the atoms involved and the conditions of their surroundings.

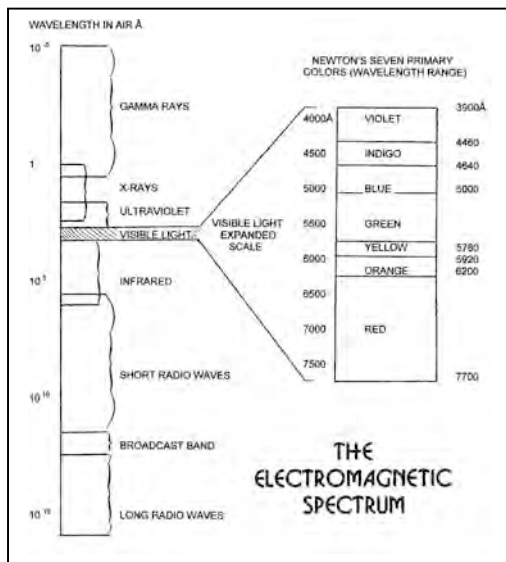
If you have ever played “Tetris”, you know that the object of the game is to twist and turn strings of blocks in order for them to lock into place without any spaces between them. This is exactly what happens in a growing crystal. The perfection of the final product depends on how quickly the crystal grows and many other factors. Think of the game of musical chairs. People wander in a circle around a string of open spaces and suddenly are asked to sit down when the music stops playing. Alas – in the game there is always one more person than there are chairs, and the one left standing must leave the game. In crystals, falling temperature forces atoms to “sit” into positions determined by the growing structure (called a “lattice”). But what happens if an atom cannot find a “seat” in the lattice ‘when the music stops’? In this case, it might wind up stuck between adjacent atoms (an *interstitial*), distorting the lattice, and leaving a hole (*vacancy*) in the structure where an atom should be.

The atoms in a crystalline lattice form an array, like a playground ‘jungle gym’, a scaffolding with a specific shape, and with specific distances between the junctions. There are many shapes of jungle gyms, and there are also many crystal geometries. The basic shapes of lattices are described in terms of crystal “systems”, and any given crystalline material is characterized by its lattice geometry and the specific atoms that form the periodic array. A mineral (or gemstone material) is defined, in fact, by its crystal geometry and constituent atoms. No two combinations are exactly alike.

## **A QUICK CRASH COURSE ON COLOR**

The universe is filled with radiation. Energy travels, in a vacuum, in the form of little particles called “photons”. But when traveling through anything else (gases, liquids, solids) energy seems to behave as ripples that we call waves. These waves look much like the ocean waves that strike a beach – there are high points called “crests”, and low points called “troughs” that move to shore in an alternating sequence. The height of a wave (“amplitude”) indicates its strength. Compare the gentle waves you find on New Jersey beaches to the giants that wipe out surfers in Hawaii! The distance between successive crests is called the wavelength. You can easily imagine that if large waves hit a beach every 10 seconds they will cause a lot more damage than if they strike the shore every minute or two. The energy carried by a wave depends on both its amplitude and frequency. If the waves hitting a beach have shorter wavelengths, it means that more waves will hit the beach per minute, carrying more energy. So short wavelengths have waves with more energy, long wavelengths have waves with less energy.

The energy that fills the universe ranges from the almost unimaginably energetic short wavelength entities known as cosmic rays and gamma rays, to the long lazy waves that carry radio signals that bounce around our planet. The whole range of energies is called the “electromagnetic spectrum”. Our human eyes have evolved to “see” only a tiny portion of this spectrum, a range of wavelengths, more or less in the middle, that we call “visible light”. Each “color” that we can see is an even smaller piece of this tiny sequence of wavelengths or energy levels. Red light has the longest waves (lower energy) we can see, and violet (higher energy) the shortest. The whole series is called the “visible spectrum” and is dramatically revealed when a rainbow forms, with colors appearing in the sequence red-orange-yellow-green-blue-violet. Wavelengths just beyond our ability to see at opposite ends of this spectrum are called *infra-red* (=heat energies) and *ultra-violet* (= sunburn energies).



THE ELECTROMAGNETIC SPECTRUM

Light is energy, and the electrons surrounding the atoms in a crystalline lattice have a specific kind of energy “profile”. Light passing through a solid may interact with the electrons in the structure. Sometimes nothing happens, and the light passes through unchanged. These ‘intrinsically colorless’ substances allow white light (which is a mixture of all the spectral colors, e.g. sunlight) to pass unaltered. Other solids are colored because the electrons around the atoms in the structure interact with the light passing through, absorbing some of the wavelengths (energy levels) in the light. The rest of the wavelengths from the original (white) light emerge. The color we see in such a material is *subtractive* – i.e., it consists of the wavelengths that *remain* after some others are absorbed. A ruby appears red because the green and blue wavelengths are mostly absorbed by the material, and only the red (and a bit of yellow and violet) get through. This also explains why larger gemstones appear darker than smaller ones; the light path in a large stone is longer and this allows more light to be absorbed.

What happens if a normally colorless crystal structure is invaded by an atom that doesn't belong there? This is like a fat person playing musical chairs, and trying to share a seat with another person when the music stops. It is a *very* uncomfortable situation. The presence of this foreign atom distorts the lattice, and therefore the electronic field around its atoms. This distorted field no longer allows white light to pass through unchanged. Some wavelengths are absorbed, and the escaping light now has a visible color. This mechanism of lattice distortion creates what is termed a “*color center*”. Solids that are normally colored even when pure, such as malachite and azurite, are called *idiochromatic* (“self-colored”). Materials that can *become* colored due to the presence of impurities are called *allochromatic* (“other-colored”).

Many gem materials are colorless when pure (beryl, some tourmalines, corundum, etc.) and can acquire an enormous range of hues when impurity (foreign) atoms become trapped in their crystal structures. The actual color produced by an impurity is a function of BOTH the nature of the impurity AND the type of structure it invades. A perfect example is chromium, an element that can exist in crystals in several different oxidation states (i.e., different levels of positive charge). When chromium enters the structure of beryl, the result is an intense green hue (emerald); but chromium in corundum turns it bright red (ruby). Sometimes two different kinds of impurities in a structure interact, via a mechanism called *charge compensation*. The new electron configuration thus produced may give rise to a new type of color center. A good example is the interaction of iron and titanium in corundum, giving us the lovely blue color that inspired the name sapphire. The same element in a structure can even exist in different oxidation states in different structural positions, and create several colors in the same material.

Anything that distorts the crystal structure of a (normally) colorless material can potentially create a color center. Perhaps the best example is diamond. Clusters of nitrogen atoms will produce a yellow color in diamond. Boron impurities cause a blue color. But certain hues do not result from impurities. Rather, defects (misalignments) in the diamond crystal structure distort the electron fields and cause certain wavelengths to be absorbed, resulting in shades of red, pink and brown. Intense radiation can also be used to knock electrons out of their normal positions, and the resulting damage to the structure produces a color. This same process also gives us an endless supply of (treated) blue topaz.

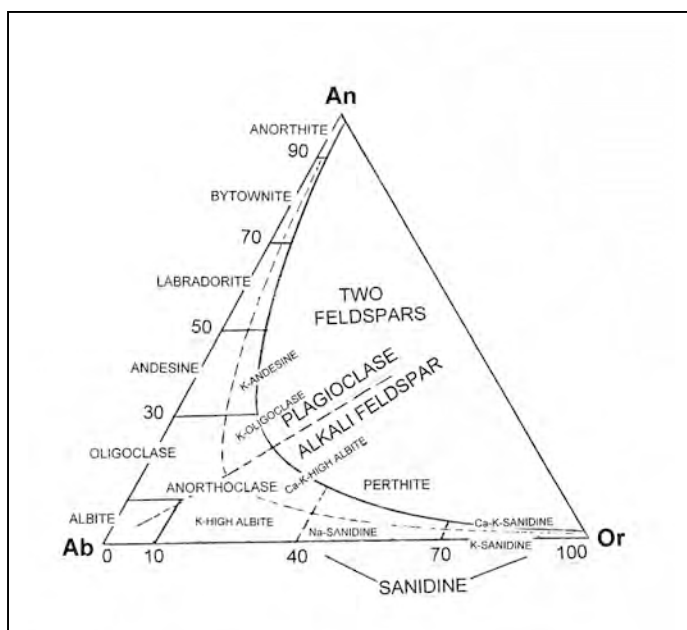
## COLOR IN FELDSPARS

Feldspar without inclusions, exsolution features and chemical impurities is colorless. A trace of ferric (3+) iron will create a yellow hue, which is usually pale in labradorite and can be very strong in orthoclase. Yellow sanidine from Wyoming contains up to 18% iron. Malagasay yellow orthoclase owes its color to ferric iron (3+), but also contains a trace of ferrous iron (2+).

Triclinic potassium feldspar (e.g. microcline) with a blue-green color is generally known as **amazonite** (Fig. 6). The cause of this coloration is lead (the more lead, the greener the hue) combined with structural water in proximity to the lead, and a dose of radiation to create a Pb+ color center. Green orthoclase has been discovered in Viet Nam in recent years. The material contains an unusually high content (up to 0.5%) of lead, and is strongly pleochroic. Blue-green microcline crystals from Colorado (see Fig. 7) are spectacular and well known to mineral collectors. These are associated with smoky quartz, which is known to acquire its brownish hue as a result of irradiation. Blue cleavelandite from California is also believed to contain lead, and a number of cut gems of a lovely blue oligoclase from Kenya (Fig. 27) have been seen in the marketplace in recent years. Reddish feldspars (such as the ones found in a typical granite) owe their red/pink hue to a trace of ferric iron (Fe3+) that is likely present as oxide inclusions.

## FELDSPAR FORMATION

Figure 1 shows a composition diagram of feldspars. The corners represent feldspar species that have only one kind of metal in the B structural position: sodium, potassium or calcium. The diagram also gives a hint as to why the feldspar group is so incredibly complex.



**Fig. 1** The feldspar group, with end-members anorthite (An) = all calcium, albite (Ab) = all sodium, and orthoclase (Or) = all potassium, in the B position.

Different minerals melt and cool in different ways. If you have a container of molten corundum, for example, and let it cool very slowly, it will solidify into a crystal that has the *same* composition as the melt. The same thing would happen with spinel, olivine (peridot) and other minerals. However, this is *not* the case with feldspars.

A molten plagioclase feldspar, cooling within a magma (melted rock) chamber, typically has a composition that reflects the chemical mix left over after other minerals (olivine, pyroxene, etc.) have already crystallized. But with feldspar, the solid crystal that forms from the melt has a *different composition* from that of the liquid. As the melt continues to cool, the composition of the resulting feldspar *continues to change* until the ingredients needed for making a feldspar from the melt are used up. Typically, the solid crystal that forms is higher in calcium than the composition of the melt. Continued cooling depletes the magma of calcium, and so continued crystallization results in feldspars with increasingly higher sodium content. That is why sodium feldspars are prevalent in rocks that form at relatively low temperatures.

In magmas that cool very slowly it is possible for a single temperature, and therefore a single feldspar composition, to be maintained for a long time, allowing relatively pure crystals to grow to large size. But generally the compositional change on cooling is more rapid, and this typically results in feldspar crystals that are highly *zoned*. Such crystals are always richer in calcium in their core than in succeeding layers of growth. But magma chambers may have convection currents, allowing crystals that are forming within them to rise and fall repeatedly. The effect of this is to change the crystallization temperature around the floating crystals, and succeeding layers alternate between being richer and poorer in calcium. This “*oscillatory growth*” is relatively common in plagioclase. The situation becomes even more complex if there is a bit of potassium in the mix.

Natural environments are never as simple as the ones pictured in neat little diagrams in textbooks! A complication in observed feldspar mineralogy is the high mobility (by diffusion) of “B” position metals within the framework structure, even at low temperatures. This means that calcium can invade a sodium-rich feldspar crystal and change its chemistry, and vice versa. Alteration of feldspar crystals is extremely common, and can be accomplished within magmas, during metamorphism by high temperature solutions, and even by groundwater! Atomic mobility can allow a feldspar containing potassium and sodium to segregate, over time, into alternating sodium-rich and potassium-rich layers, although the continuity of the underlying structural framework itself may not change during this process. This atomic mobility has enormous implications for the treatment of feldspars.

## **TWINNING**

Twins are crystal intergrowths, in which alternating units are usually related by symmetry elements of the crystal host. As far as a growing crystal is concerned, a shift in growth direction is NOT a structural defect if the shift is along a path that obeys the internal symmetry of the structure. Macroscopically, however, twins may *appear* to be ‘different crystals that have grown together’. Mineral intergrowths themselves are extremely common; but they are not “twins” unless the participants are joined along an element of symmetry or a type of plane surface known as a “*composition plane*”.

Triclinic feldspars have lower symmetry than monoclinic ones, but in feldspars the difference is very small. The difference is small enough, in fact, to allow sodium-rich and potassium-rich feldspars to inter-grow along certain crystallographic layers, ones that are virtually identical in their respective structural dimensions at the growth interface.

Twinning, in essence, creates a crystalline entity that has a “built-in” symmetry element (e.g. a twin plane – Fig. 2), and so the end result may be a form that appears to be more symmetrical than the un-twinned material. “*Pseudosymmetry*” is extremely common in feldspars.

There is a whole catalog of named feldspar twins that refer to specific symmetry elements. These twins are very characteristic of certain feldspars and have external manifestations that are well known and familiar to mineralogists. These named twins include Carlsbad, Baveno, albite, Manebach, esterel, Ala and pericline. Many feldspars display several different types of twinning, even within the same crystal.



Fig. 2 Twin planes evident on a feldspar cleavage surface.



Fig. 3 Carlsbad twins in orthoclase (Brazil, Spain).

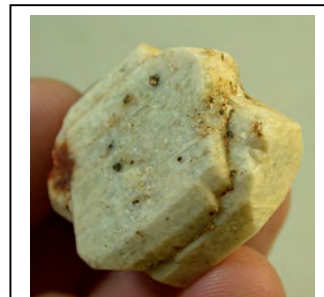


Fig. 4 Carlsbad twin in orthoclase from Spain.

## THE FELDSPAR FAMILY

There is a huge list of names associated with feldspar mineralogy. Why didn't I start this discussion by providing a list of these names, such as we do with garnets and other groups? The reason is that most of the names are related, not just to the chemistry of the material, but also to symmetry, temperature of formation, intergrowths and other characteristics. None of the distinctions would have made sense unless the preceding information had been provided first.

## PLAGIOCLASE

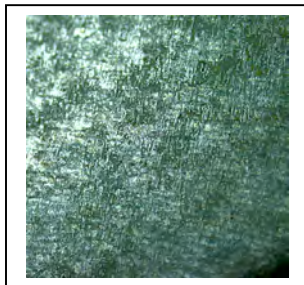
Pure sodium plagioclase feldspar is called **albite**. A platy variety that is sometimes transparent is known as *cleavelandite*. Pure calcium plagioclase is called **anorthite**. Many years ago mineralogists created a series of names for intermediate compositions. These mixed Na-Ca feldspars are no longer considered “species”. But the names are so useful, and have been around so long, that getting rid of them seems to be a chore that is scarcely worth the effort.

**Albite** includes the range from pure Na (sodium) to a composition that has 10% Ca (calcium). From 10% to 30% Ca the name given is **oligoclase**. From 30% to 50%, **andesine**. Next in the sequence is **labradorite** (50% Ca to 70%), then **bytownite** (70% to 90% Ca). **Anorthite** refers to a plagioclase that has 0 to 10% sodium, i.e. a pure calcium “end member” of the series.

## ALKALI FELDSPAR

**Orthoclase** is the potassium “end member” and is characterized by two cleavage directions at right angles to each other. Although crystals of orthoclase appear monoclinic, the underlying structure has only recently been found to be triclinic and very finely twinned. Another alkali feldspar with a formula consistently greater than 80% potassium is called **adularia**. This is a relatively rare species with distinctive morphology and unique mode of formation.

The potassium feldspar that is most stable at low temperatures is a triclinic mineral known as **microcline**. Microcline displays a range of structural variations with differing levels of symmetry deviation between triclinic and monoclinic, and is usually twinned, often in two directions. This texture is clearly visible in thin rock sections and is known as “cross-hatching” (see Fig. 5)



**Fig. 5** Cross-hatch twinning is easily seen in thin sections, but is sometimes even visible on the surface of a crystal – in this case, microcline from Colorado.



**Fig. 6** Amazonite (microcline) from Brazil showing typical green coloration



**Fig. 7** Amazonite (microcline) from Colorado, with smoky quartz.

If we add sodium to the formula, we have a range of intermediate compositions known as **sanidine**. At high temperature there is complete solid solution, and a large range of feldspars with compositions between the pure sodium and pure potassium end members.

At lower temperatures, however, the intermediate compositions *segregate* into two different minerals with more restricted ranges in chemistry. This “*unmixing*” or “*exsolution*” results in a material called **perthite**, characterized by intergrowths of sodium-rich and potassium-rich feldspar. Perthites have distinctive textures and patterns of twinning that can be macroscopic (perthite), very small (*microperthite*) or submicroscopic (*cryptoperthite*). Feldspars along the Na-K line that are sodium-rich are sometimes called “potassium-high albite”, or **anorthoclase**.

## FELDSPAR GEMS

### FELDSPAR GEM CATEGORIES

I will categorize gem feldspars into three categories:

1. Feldspars that are transparent enough to yield faceted gemstones;
2. Feldspars that display optical effects;
3. Feldspars that are translucent or opaque but have ornamental value because of distinctive textures or admixtures with other minerals (i.e., rocks)

### FACET MATERIAL

***The combination of complex chemistry and intergrowths, changes in structure upon cooling, and pervasive twinning are reasons why feldspars are seldom transparent. Despite ubiquity, abundance and huge crystal size, feldspars have so many light-blocking features (twin planes, lamellar structure, regions of differing structure, etc.) that it is all but impossible to find material transparent enough to cut into faceted gemstones.*** There are, of course, notable exceptions.

All the plagioclases have been faceted, and they exist in collections as small, colorless or pale colored gems, typically under 5 carats in weight. Some of these may well be twinned or unmixed, but on a scale so small that the material is *visually* transparent. Other plagioclases may form as single large transparent crystals if cooling is slow enough that the crystal precipitating from the melt may continue to interact with the surrounding material, changing slowly in composition while cooling. The transparency is preserved if the resulting crystal is suddenly chilled so quickly that un-mixing cannot occur (e.g., extruded in a lava flow). The latter circumstances appear to be much more likely for plagioclases of intermediate composition, corresponding to andesine/labradorite/bytownite. This category of gem feldspars includes the familiar sunstones from Oregon, and plagioclases found in lava flows in New Mexico, Australia, Mexico, and many other localities. These cuttable feldspars occur as *phenocrysts* - crystals grown to macroscopic size by slow cooling at depth, followed by sudden quenching. The phenocrysts are embedded in a fine grained igneous rock, typically basalt.

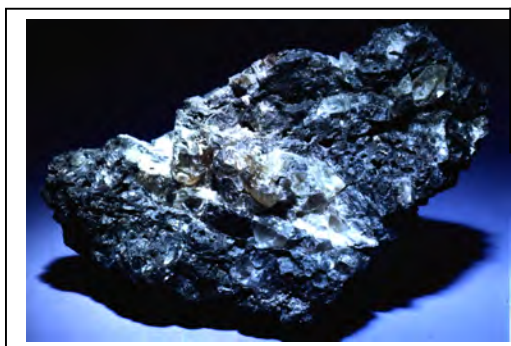


Fig. 8 Labradorite - yellow phenocrysts in basalt (Casas Grande, Mexico)



Fig. 9 Labradorite - phenocryst extracted from weathered basalt, Casas Grande, Mexico

Another striking, and unique occurrence of transparent feldspar is the orthoclase from the Malagasy Republic (Madagascar). This occurrence relates to special extremely coarse-grained rocks (*pegmatites*) in which potassium feldspars are common. Pegmatites are generally believed to form in veins, deposited from watery fluids that represent the end stage of cooling of a granitic magma. Slow cooling and high mobility of atoms in the fluid allows for the growth of enormous crystals - not only the familiar pegmatite gemstones (beryl, tourmaline, spodumene, etc.) but also the feldspar behemoths referred to at the beginning of this article. In the Malagasy occurrence, potassium feldspar crystals (orthoclase), colored bright yellow by a trace of ferric iron, have grown as transparent crystals up to the size of small shoe boxes. The largest known feldspar gems have been cut from these crystals, some of them exceeding 1,000 carats in weight, and there are many stones in the hundreds of carats.

## OREGON SUNSTONE

Undoubtedly the transparent feldspars that are best known to the gemological community are the labradorite phenocrysts found in basalt flows in south-central Oregon, and which have come to be known as **Oregon sunstone**.

Oregon sunstone is, commercially, perhaps the best known of all transparent feldspars. The material occurs chiefly as irregular pale yellow masses, but other observed colors include orange, red and green. The red and green material is intensely pleochroic. A large percentage of the production consists of a yellow host containing numerous oriented tiny (and very thin) flakes of metallic copper. These reflect light as schiller with an orangy-pink hue. Clouds of microscopic copper inclusions can even impart a pinkish color to a pale yellow host crystal.

The potential availability of sunstone from Oregon is enormous because of the large size and extensive distribution of the host lava flows.



Fig. 10 Red Oregon sunstone with a "cloud" of included copper platelets.



Fig. 11 Cut Oregon sunstone gems, displaying color zoning and pink schiller (in the cabochon).

### PHENOMENAL STONES

Gems displaying "phenomenae" include familiar stars and catseyes, in which oriented inclusions reflect light, and making a domed cabochon concentrates these reflections into straight lines. There are also many gems that have iridescent and reflective features. In general, *iridescence* is caused by light "*interference*", i.e. the separation of white light into colors by reflection from thin parallel layers of an inhomogeneous medium. We all have seen oil slicks on rainy-day puddles. When light enters the oil surface, part is reflected and part is refracted (bent in a direction towards a line perpendicular to the surface). The refracted ray then strikes the surface of the underlying water layer, and part is again reflected. The rays reflected from both surfaces combine and head towards your eye, but the ray that hit the water traveled a longer path and was also slowed down a bit by its journey through the oil. The reflected light rays then *interfere* with each other. The intensity of certain wavelengths is enhanced, and of others is reduced or extinguished, and we see the result as separate colors. The layers must have a thickness on the order of light wavelengths for this phenomenon to occur. Thicker layers cause the observed color to be shifted from the blue towards the red end of the visible spectrum.

Feldspars, as we have seen, almost always consist of layered structures with alternating sheets of minerals with different compositions, or with alternating layers having a twinned relationship. Although the "layers" in most feldspars are on the scale of 30-1,000 Å thick (visible light is around 4,500 to 6,500 Å) there are many examples where the layers are the right thickness to cause light interference. It turns out that a certain range of plagioclase compositions (roughly in the albite region between 2-3% and 15-16% calcium), while homogeneous at high temperature, un-mixes as it cools into layers of distinctly different composition (more or less equal to a combination of albite and oligoclase).

The layers are extremely thin, causing bright iridescence with a pearly grey-white or bluish tint. More than 150 years ago these feldspars were dubbed "**peristerites**" because the colors resembled a pigeon's neck feathers (Greek for pigeon: *peristera*). Peristerite makes wonderful cabochons that have a unique and distinctive appearance.



Fig. 12 Peristerite, displaying bright white reflections under the surface of the cabochon.



Fig. 13 Blue sheen labradorescence, in labradorite from the Malagasy Republic.

Plagioclase feldspars of intermediate composition (anorthite = 40-60%) almost always show an iridescence of some kind. This came to be called “**schiller**” (German for iridescence), and also “**labradorescence**” because it was typical of the rocks found on the Isle of Paul, Labrador. The effect is caused by interference reflection from parallel layers (*lamellae*) of different composition, and it has been determined that reddish colors seem to be more prevalent in crystal regions with higher An (calcium) content.

Twinned labradorites may display bright schiller crossed by stripes without iridescence (see Fig. 14), because the “stripes” are actually twins, and within them the orientation of the exsolution layers is different from that of the matrix. These alternating stripes will show the color effect, but in a different orientation. The actual observed iridescent color in a labradorite is determined by the thickness of the reflective lamellae, and a given fragment of crystal may vary in color in different areas that have slight variations in calcium content. The labradorite from Finland displays an amazing range of very intense colors, and has been named **spectrolite** (see Fig. 15) Labradorite from the Malagasy Republic is well known for its intense blue schiller, most strikingly displayed in well oriented cabochons (see Fig. 13). Iridescent labradorite occurs worldwide, and sometimes is the single component of certain types of rocks, as on the Isle of Paul, Labrador.



Fig. 14 Labradorescence (schiller) in spectrolite, crosscut by twinned areas with different orientation.



Fig. 15 Spectrolite from Finland, showing intense schiller coloration

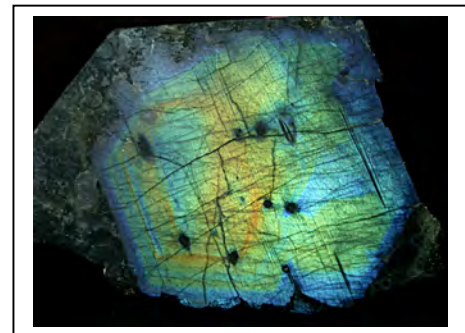


Fig. 16 Large phenocryst of labradorite (4 cm) with schiller and zoning evident.

**Moonstone** is an ancient gemstone and continues to be popular throughout the world. Some authors have mistakenly labeled, as moonstone, certain peristerites. In an un-mixed plagioclase the reflecting lamellae may be irregular or broken into small bits that individually are smaller than light wavelengths. The optical effect seen in this material (Fig. 17) is due to so-called *Tyndall scattering*, with a diffuse milky sheen similar to that observed in milky opals. A white or blue iridescence (*adularescence*) is more properly termed *moonstone* when seen in some cryptoperthitic alkali feldspars.

These perthitic intergrowths have lamellae of varying composition, periodically twinned lamellar intergrowths, or both. The sheen in these feldspars is typically white but can also be bluish, and rarely colored (as in labradorite). A sodium-rich plagioclase from Tanzania with an intense blue sheen was described in 2005, and an oligoclase from Mexico occurs in a gabbroic mass in the form of superb sharp crystals with intense blue reflections at their terminations; these crystals have also yielded lovely faceted gems with a blue adularescence. Similar appearing material, identified as sanidine, was found in New Mexico in 1988.

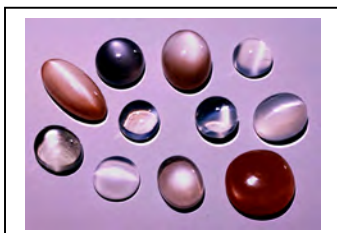


Fig. 17 Moonstone from India, an ancient and highly prized gemstone.

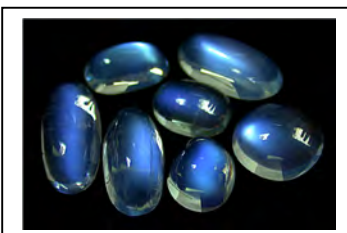


Fig. 18 Moonstone from Sri Lanka, displaying the rarest and most valuable hue, a strong blue coloration.



Fig. 19 Sunstone from India, with orange aventurescence due to included hematite.

**Sunstone**, a name widely used in relation to Oregon labradorite, is historically better known in the form of an oligoclase feldspar containing tiny platelets of hematite that give the material an orange color, and also produce a broad lustrous surface made up of myriad individual reflections. This phenomenon is generally referred to as *aventurescence*. India (Fig. 19) is a classic source of this material, in which the individual spangles that cause reflections are extremely small. An oligoclase from Tanzania described in 2002 is light gray-green and contains much larger individual hematite plates than is observed in the Indian material. Yet another Tanzanian sunstone, reported in 2003, was identified as orthoclase containing deep orangy-red elongated platelets of hematite. Cabochons cut from this material display a star as well as aventurescence. An orthoclase from Australia has been described that contains oriented exsolution inclusions of ilmenite and hematite; these inclusions are visible as a kind of diagonal latticework pattern, and the material also displays both adularescence and aventurescence. *Golden Sunstone* is a trademarked name for yellow labradorite that has been faceted in specific styles to enhance brilliancy and saturation.

## **FELDSPAR ROCKS**

Feldspars are so common and ubiquitous that early petrographers devised a classification system for igneous rocks based primarily on the amount and type of plagioclase feldspar in them (petrology is the study of rock origins, and petrography is the descriptive study of rocks and rock textures). This classification is still widely adopted. A primary distinction is made between rocks in which plagioclase feldspars dominate over alkali ones, and vice versa. Further sub-classifications involve the amount of free silica present, grain size and the nature of any accessory minerals. The descriptive nomenclature of petrography is so huge as to be mind boggling, practically another language in itself, and is further complicated by the persistence of names that originated more than a century ago.

As we have seen, most feldspars are opaque (translucent at best) because of the presence of twinning and intergrowths, as well as further complications due to un-mixing, diffusion and alteration. Feldspars can be white, green, pink, orangy, reddish, bluish and brown, and can display a wide variety of optical effects. Remember also that rocks are mixtures of minerals, and the cooling history of rocks may vary widely.

**The combination of feldspar mineralogy, grain size and texture therefore produces, in combination with other minerals, geological materials with almost endless variety, that are hard and durable enough to be used as ornaments.**

If you have ever “shopped granite”, e.g. if you were remodeling your kitchen and wanted new counter-tops, you might have visited a showroom where hundreds of enormous polished slabs of rock stood like sentinels, awaiting your approval. They are not all granites. You would be amazed at the range of colors, patterns and other subtleties to be found in the petrological world.

A rock type known as **anorthosite** is composed entirely of plagioclase feldspar, with a composition usually in the middle of the Na-Ca series. These feldspars frequently display schiller, and a polished rock slab can display large, randomly oriented feldspar crystals that “wink” on and off with a silvery or bluish iridescence in different parts of the slab (see Figure 22). Such rocks are commonly used as facing materials on large buildings.

**Granite** is a common rock made up (usually) of potassium feldspar, quartz and mica, with a huge potential list of other (accessory) minerals depending on locality of origin. Typical granites are shown in figures 20-21. One type of granite is made up of pinkish/orangy orthoclase mixed with green epidote (and a bit of quartz), and the texture is approximately *equigranular* (all the mineral grains are about the same size). This rock was found in the Unaka Mountains of the southeastern U.S. and acquired the name **unakite**. It is widely used for cabochons, beads, carvings and other ornamental applications (Figure 23).

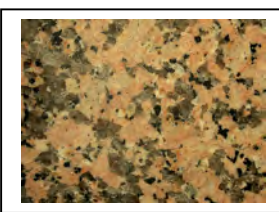
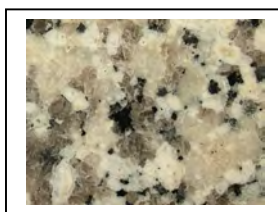


Fig. 20, 21 Granites from various localities, containing feldspar, quartz and mica.

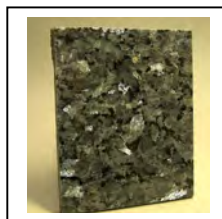


Fig. 22 Anorthosite, a rock made up entirely of feldspar.



Fig. 23 Unakite, an unusual granite from Virginia containing quartz, pink orthoclase and green epidote.

Worldwide, there may be thousands of different rocks available for construction and decoration. Only an insignificant percentage of these has been considered or used for personal adornment. This wealth of patterned rocks may therefore be one of the largest and most diverse potential resources available to the gemstone community. The supply of these materials is effectively endless.

## **FELDSPAR TREATMENT**

The open framework of the feldspar structure appears to allow a significant amount of ionic mobility, not only of component metals (Na, Ca, K, etc.) but even the basic structural components, i.e. Si and Al. This mobility allows the random distribution of Si and Al on structural sites at high temperature (producing higher symmetry) to be replaced by an “ordered” distribution (and lower symmetry) at lower temperatures. Ordering and un-mixing produce compositional lamellae and complex twinning, complicated by other compositional changes due to subsequent alteration and reactions in a melt or solution.

All of these structural disruptions provide conduits for the movement of atoms. It has been suggested that diffusion along twin planes, grain boundaries, etc. increases atomic movement in a feldspar (versus “intracrystalline” diffusion, i.e. through the structure) by a factor of one *million* or more. This kind of information is critical for scientists who study rock formation and the interpretation of rock histories by observing minerals and textures. It is also tempting to creative people who might wonder what else can be forced to move through a feldspar at elevated temperatures. Since copper is present in Oregon sunstone, creating pretty colors, it is not improbable that someone might have tried to recreate the effect in a laboratory. The results of such experimenting can be seen in the current gemstone marketplace, in the form of plagioclase feldspars that have been saturated with copper via diffusion, thereby artificially producing intense red and green pleochroic colors. This scenario may be the tip of an iceberg. Color change by diffusion of beryllium in corundum is an established fact. Gemologists must be ever vigilant in their efforts to maintain awareness and improve detection. But this critical awareness has been stymied by the complexities of nomenclature and the rapid development of sophisticated methods of altering and creating colors in various gemstones. The following is an attempt to simplify and clarify this bewildering mass of information

## **CREATING AND CHANGING COLOR, AND THE MECHANICS OF DIFFUSION**

Gemstone treatment is centuries old, and has long been an accepted aspect of the trade. Heating, in fact, is entirely responsible for the lovely blue color of zircon, and the intense saturated violet-blue that has made tanzanite so popular. But the “dark side” of technology is rapidly gaining ascendance. The production of chemically and physically altered gemstone materials is starting to reach epidemic proportions, and the health of the gemstone industry is now in jeopardy. The first step in dealing with this problem is to understand what is being done to alter gemstones, and the second is discovering ways to detect these treatments.

Heating, as a process, is “low-tech” and relatively easy to understand. The same is true for gemstone “coatings” (thin layers deposited on gem surfaces), and even the physics of irradiation has been thoroughly investigated. But some new treatments that have arisen in the past few years are creating some concern, and perhaps even alarm. One of the most disturbing, and also one of the hardest to diagnose, involves the actual forced high-temperature penetration of chemical impurities directly into the crystalline structure of a gemstone. This process is generally labeled “diffusion”, but the terminology used to describe it is complex and has been hopelessly confused when verbalized outside of scientific circles. It is critical to get this vernacular on firm ground, or the gemstone trade will never be able to properly discuss it.

### **DIFFUSION DEFINED**

The mechanism that has been suggested for the creation of both red “andesine” feldspar and the colors in treated topaz and some tourmalines and garnets is *diffusion*. The term “grain boundary diffusion” has been suggested as the correct descriptive terminology for what has been observed in some gem tourmalines, versus “bulk diffusion” to describe the process used for “andesine”. These terms can be confusing and are often incorrectly used. This can result in preoccupation with semantics rather than observations. The simplest way to resolve this problem is to rely on internationally accepted definitions. A decade ago, the International Union of Pure and Applied Chemistry (IUPAC) organized a task force to create a lexicon of terms for solid state diffusion. The resulting recommendations were published in *Pure and Applied Chemistry* in 1999. We may also rely on established reference works that provide widely accepted nomenclature standards. Here are the *internationally accepted definitions* for diffusion-related terms:

**Diffusion** is defined (*Glossary of Chemical Terms, Van Nostrand Reinhold, 1976*) as: *The mutual permeation of two or more substances due to the kinetic energy of their molecules, so that a uniform mixture or solution results.*

**Lattice Diffusion** (= bulk diffusion): *A diffusion process which takes place through the bulk lattice of the crystal and excludes such mechanisms as short circuit diffusion along dislocations, grain boundary diffusion and surface diffusion.*

**Short Circuit Diffusion** (= grain boundary diffusion): *Any diffusion process occurring via grain boundaries, surfaces or dislocations.*

**Pipe Diffusion** (= Short Circuit Diffusion): *Diffusion along a dislocation.*

And finally, a **grain boundary** is defined (*Glossary of Chemical Terms, Van Nostrand Reinhold, 1976*) as: *The surface separating two regions of a solid in which the crystal axes are differently oriented.*

The mathematical descriptions of diffusion contain several terms which are constants for specific materials, leaving the only significant variable as temperature. For all practical purposes, diffusion is a process that is dramatically enhanced as the temperature of the system rises. This, of course, makes perfect sense. Kinetic energy is the energy of motion, and in all substances (gases, liquids, solids) the movement of component atoms and molecules increases with rising temperature. Mixing of two substances is tremendously accelerated if the particles involved are buzzing around, rather than sluggishly crawling over and around each other. In the case of gases and liquids, molecular movement is already facilitated by their physical state, in which the molecules are free to move about. Solids are a different story. Solids *by definition* are crystalline, and so we must have a proper visual concept of what a crystal looks like on an atomic scale.

It might be easier to do this if you can visualize the molecules (groups of atoms) in a liquid, such as water (a good visual reference might be a bucket of marbles). The molecules do attract each other because of electronic bonding forces, but kinetic energy allows them to slip and slide around each other. The molecules are still basically touching and packed together, without any open spaces. If a space did open up, the dynamic movement of the molecules would immediately close it. If the temperature of the system drops, the movement of the molecules slows down. Eventually (think: 'molasses') motion within the liquid is really sluggish, and the attraction of the molecules starts to overcome the kinetic energy that keeps them moving.

At a *very specific temperature* (called the *freezing point*) the bonding forces overcome kinetic movement, and suddenly ALL the molecules instantly lock into a fixed pattern. This pattern extends *identically* through the *entire mass* of material, and the way the molecules arrange themselves depends on what kind of molecules they are, and certain rules having to do with pure geometry. We can describe these patterns in terms of boxes and lines, little diagrams that illustrate the shape of the pattern (like a single repeating element of a wallpaper design) and how the pattern is extended (with consecutive repeats, rotations, mirror images, etc.). But we cannot confuse the diagram with the reality – inside the crystal there is no wallpaper – just lots of atoms, stuck tightly together in a fixed array, with certain symmetrical clusters that repeat themselves in all directions.

This symmetry can be described mathematically. It turns out that geometric objects can only pack together in a limited number of arrangements, all of which were worked out centuries ago. Eventually, these arrangements were simplified into little diagrams, with boxes and lines *representing* the symmetry elements of the repeating patterns... and crystallography was born.

The description of freezing obviously applies to a crystal that solidifies from a melted substance. Let's go back to water. Water is molten ice. Ice is a crystalline solid and the geometry of its structure is wonderfully illustrated by the incredible hexagonal (6-sided) entities that we call snowflakes. If you could make an ice cube with total perfection, the pattern of water molecules in it would be unbroken in all directions, and the cube would display characteristic optical and physical properties, just like a crystal of beryl or spinel. If you poured maple syrup over this ice cube, the syrup would flow down the outside and not penetrate the ice at all, any more than it would penetrate a quartz crystal.

But if you crush the ice in a blender, making thousands of tiny particles, each tiny bit would be randomly oriented – the *long range* crystalline structure of the original ice crystal would be destroyed. In this aggregate, the ice fragments would have crystallographic symmetry elements that are no longer perfectly aligned. Instead of a tightly packed periodic array, we now have a mass of tiny misaligned grains, with spaces between them. If you pour syrup over the crushed ice, the syrup can now penetrate along the grain boundaries, and we have..... a snow cone!

Artificial diffusion-coloring has been observed in corundum and now, apparently, also in feldspars. How should gemologists classify the type of diffusion they are seeing? Some gemological journals have used the term “grain boundary diffusion”, but this term is only appropriate for describing color enhancement in certain specific gemstone materials.

## GRAIN BOUNDARY DIFFUSION

A well formed crystal is not made up of grains – it is a tightly packed array of atoms and molecules. Crystals seldom grow with complete perfection (outside of a laboratory) and most have internal irregularities. But these irregularities (dislocations, stacking faults, point defects, etc. etc.) are NOT the boundaries between “chunks” of material that have somehow stacked up unevenly, like crates piled up in a warehouse (Fig. D-4). Rather, they are parts of the crystal where some atoms have slipped out of their normal positions, creating tiny irregularities but not huge open spaces. The long-range order is not affected, and adjacent parts of the crystal remain symmetrically aligned. Since, by definition, grains are “*regions of a solid in which the crystal axes are differently oriented*”, a **single crystal** is *not* made up of grains, and is *not* filled with *grain boundaries*.

The concept of “grain boundary diffusion” is not relevant in the case of most gemstone materials. Only a few gemstones grow from a melt. Most are created by the slow deposition of atoms and molecules in a hot, watery solution as it cools. But slow growth in solution creates the same internal long-range perfection as slow cooling from a melt. The fact that gems are transparent indicates that their long-range internal crystalline structure has been maintained. If not, and the material was made up of small crystals jumbled together with NO long-range periodicity, light would *not* pass through unaffected, and the stone would be translucent or opaque (e.g., jade, chalcedony). In such cases there *could* well be grain boundaries, and the movement of fluids along them would be relatively easy (which is why jade and chalcedony can be dyed).

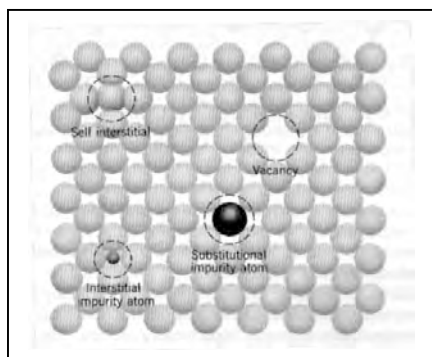
## LATTICE, OR BULK DIFFUSION

“Lattice diffusion” or “bulk diffusion” is the actual movement of atoms *within* a crystal lattice (i.e., a solid). But if crystals are made up of tightly packed atoms and molecules, how can anything move through them? The answer has two parts: temperature and defects.

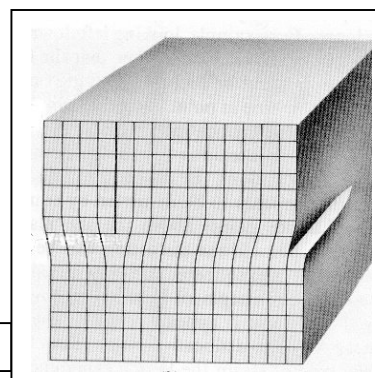
Remember the illustration of freezing water? Above the freezing point the water molecules may be sluggish, but they do have relatively complete mobility. It’s like a packed crowd in Times Square on New Year’s Eve. You can jostle and squeeze through with a bit of effort, made easier if someone moves out of the way and creates a small open space that closes right behind you when you pass. Once the New Year ball begins to drop, and people stop talking and moving around and stand still so they can watch it, getting through would be a much bigger chore.

What if you could take a crystal and heat it up *almost* to the melting point (the same as the freezing point, but coming up-temperature rather than down). The atoms in the structure have not yet *broken* the electronic bonds that have locked them together into a repeating pattern. But they are still moving around *much* more energetically than when the crystal is cool. In our metaphor, the New Year ball has now reached bottom, the crowd has cheered, and the people in Times Square, though still standing in place, are *getting ready* to move. If you see an opening between two people, you can push your way through the crowd, and keep moving through as long as there is a small space you can work your way into as you go.

Crystals generally grow quickly enough that small irregularities do occur along the way. One of these is called a *point defect* – a place in the crystal structure where an atom is missing from where it should be (a *vacancy*), or merely a misalignment of adjacent atoms. At high temperature, but *below* the melting point, an atom can push its way into the lattice and into the defect; it can then continue to move through the structure by changing positions with atoms and finding additional point defects along the way. Point defects within a crystal also move around at high temperature, and are considered to be the primary mechanism of solid state diffusion (Fig. D-1)

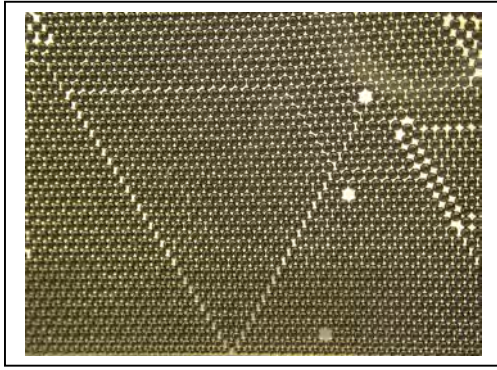


D-1 Point defects

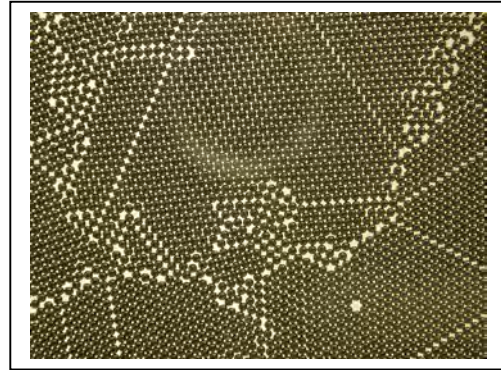


D-2 Dislocation

Since diffusion is almost completely dependent on temperature, you would have to get a crystal *very, very* hot into order to move atoms through any significant thickness of it. Ideally, maximum diffusion would take place *just* below the melting point, where the crystal structure remains intact but the atoms are moving very energetically and an impurity can work its way through. The problem is that only a handful of gem materials can melt when heated and then re-crystallize upon cooling (the best known being corundum and olivine) or withstand near-melting point temperatures without decomposing. For these materials, “lattice diffusion” is a correct term to describe the mechanism of coloration. But what about other materials, such as some tourmalines, that simply shatter or decompose when heated to a stage long before a temperature was reached where diffusion to introduce a color was practical.



D-3 Line defects



D-4 Grain boundaries

## PIPE DIFFUSION (ALONG A DISLOCATION)

Crystals are seldom perfect. They contain a wide variety of defects that affect both their physical and optical properties. In addition to point defects, there are *line defects* (Fig. D-3,4) where adjacent layers of atoms have shifted slightly 'out of register'. The misalignment can involve an entire plane of atoms as well. One type of plane separating misaligned units of structure is called a *dislocation* (Fig. D-2).

What if an atom was trying to work its way into a crystal structure, and suddenly found a clear path for movement? Let's go back to Times Square.

Imagine that there are several large tour groups visiting New York and are filling up most of the space at 42<sup>nd</sup> Street and Broadway. You are trying to move through the crowd but the tour groups are blocking your way. You notice that there is a lot of chatter and interaction between members within a group, but not so much along the boundary between the groups. It turns out to be not as difficult to move forward if you take advantage of the lower level of interaction along this boundary. If you looked down from a tall building you could probably make out the faint line separating the two groups, because the people would be interacting more frequently with others within their group than across the boundary.

Now let's imagine that the tour group leaders are all trying to do head counts. They ask all their tour members to line up in rows to make the count easier. In one group all the people turn facing uptown, and in the adjacent group all the people turn facing downtown. From your vantage point way up in the tall building, you would now *easily* see the line separating the groups, because at the boundary, even though the people were still packed together, they would have their backs to each other.

In growing crystals there are often zones where adjacent layers of atoms suddenly switch orientation. These adjacent layers still fit nicely together, but the atoms may suddenly align themselves in a different direction. It is important to note that, in all such cases, the new alignment is *symmetrically related* to the old one, and as far as the crystal is concerned this is no big deal. It is as if a geometric wallpaper pattern had areas within it where piece of the pattern were turned upside down. The pieces of the overall pattern still fit nicely together because the pattern at the edges lines up properly. But if you look at the wall from a distance you can see that a portion of the wallpaper 'doesn't look quite right' because it now consists of blocks that *internally* are each pattern-perfect, but when stuck together don't continue the original unbroken pattern arrangement.

A layer within a crystal where a shift in the symmetry of the atoms has changed the direction of growth is called a *twin plane*. Twinning is very common in minerals, as we have previously seen in feldspars, and is even visible macroscopically in other materials such as ruby, sapphire and spinel. Twins are crystallographic regions within a crystal that are not aligned exactly the same way, but fit perfectly together because they are *symmetrically related* by the same geometric laws that define its internal arrangement. From our point of view, a twin plane is just a zone within the material. From an atom's point of view, it is a superhighway.

In the Times Square analogy, even though the adjacent tour groups might still be packed tightly together, the line where people stood back-to-back would offer a trivially easy path for you to push through the crowd, with no significant interference. You could also move all the way through the crowd as far as the line separating the groups persisted.

Twin planes provide an opportunity for impurity atoms to migrate through a crystal MUCH more readily than via the slow, laborious process of playing "musical chairs" with lattice atoms, one at a time. Dislocations also provide a much easier path for diffusion, especially at high temperatures.

### **IN SUMMARY:**

- (a) bulk (lattice) diffusion to introduce color into a gemstone is ONLY practical for materials that melt without decomposing, and can re-crystallize from the molten state, because sufficient mobility for impurity atoms could only be maintained at very high temperatures; However, new research may have somewhat changed this restriction (see below).
- (b) grain boundary diffusion is only applicable to materials made up of grains, i.e. what we may term "polycrystalline aggregates";
- (c) heating increases chemical mobility, and allows greater penetration of dyes and impurities into small cracks and along grain boundaries;
- (d) well formed single crystals do not contain grain boundaries and therefore can realistically be colored only by introducing colored substances into cracks and defects, or through bulk (lattice) diffusion. Dislocations and twin planes, however, are frequent characteristics of single crystals, and provide paths of greatly enhanced atomic mobility. These features therefore play a major role in enhancing the migration of chemicals and impurity atoms deep within a crystal.

It appears likely, based on a variety of published reports, laboratory investigations and locality visits, that the "red andesine" that has flooded the marketplace in recent years is *all* copper-diffused. The starting material appears to be yellow labradorite, and the only *provably* established source capable of yielding the enormous volume of faceted red and green stones appearing in the trade is Mexico. Consequently, the only widely accepted and proven locality for *naturally occurring* red and green plagioclase is Oregon.

Many gemstones cannot withstand the high temperatures used for the diffusion treatment of feldspar. However, recent information circulating within the gem trade suggests that a process has been developed for the diffusion of many gem materials at fairly low temperatures, using specific chemical additives to enhance the mobility of chromophores into their structure. Such a process would enormously complicate the lives of practicing gemologists, who are already struggling to keep up with new technologies. It would also challenge the gemstone trade to become aware of, and properly label, any new treatments that alter the natural colors of gemstones being sold in the marketplace. Such developments make it ever more important for gemologists to understand the mechanics of these new treatment processes, and be able to apply the proper terminology when reporting and describing them.

## CONCLUSION

The world may soon be 'running out' of gemstones. China and India now have an enormous (and expanding) middle class, and in these countries gems are intrinsic to their cultural history. There is also a large new group of successful (and rich) entrepreneurs in Russia. The pressure this new demand creates on gemstone supplies is already being felt, and cannot be relieved by existing mines and production. The internet and rapid communication have forever changed the development of markets, compressing into decades what previously took centuries. The jewelry industry would be well advised to broaden its awareness and acceptance of other kinds of geological materials, and perhaps even create public awareness (and demand) through active promotion.

The feldspar family is amazing. In terms of variety, including colors, optical effects and textures, it is unrivaled in the gemstone world. Lack of transparency may be considered by some to be a failing, and a limitation on gemstone use. But in feldspars this is more than compensated by a wealth of attractive optical and physical attributes.

The marketplace has gotten used to the introduction and proliferation of "new" gemstones. Tanzanite, for example, now considered an "alternate birthstone", did not even *exist* as a marketable gem material about 40 years ago. Other materials (e.g. sphene, apatite, etc.) are gradually infiltrating the jewelry trade. But the production of these gems is too small to make a serious dent in the supply/demand shortfall.

**A gemstone is properly defined as "a mineral that is cut and polished for ornamental purposes".** The category of "ornamental materials" also includes a wide variety of inorganic (and organic) products that can easily be adapted for use in jewelry. Feldspars, either as distinct species or as components of attractive and colorful rocks, are abundant enough to satisfy the needs of a large portion of any possible future demand

We therefore only need look around (and down at the ground!) to see where the future of the gemstone trade might lie

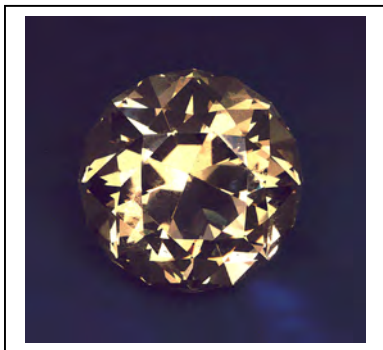


Fig. 24 Orthoclase from the Malagasay Republic.



Fig. 25 Labradorite (Golden Sunstone ®) from Chihuahua, Mexico.



Fig. 26 Labradorite (sunstone) from Plush, Oregon deposits.

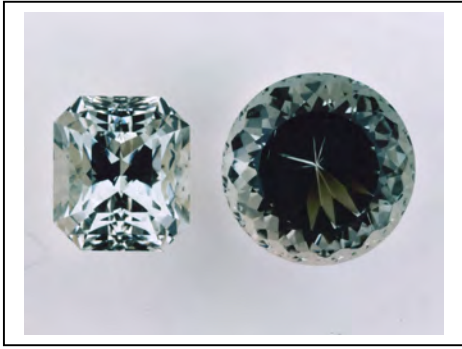


Fig. 27 Oligoclase  
(blue) from Kenya.



Fig. 28 Labradorite  
(sunstone) from Oregon  
showing range of colors.



Fig. 29 Moonstone  
(oligoclase) from  
northern Mexico.

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