

# OBSERVATIONS ON THE OCCURRENCE OF PLAGIOCLASE FELDSPARS

JOEL E. AREM © 2011

## OVERVIEW

There exists abundant controversy over the nature and source of enormous volumes (millions of carats) of red and green feldspar gems that have been sold in the gemstone and jewelry marketplace for nearly a decade. Questions regarding the treatment and exact origin of this material have not yet been resolved. It has been conclusively proven that copper (the element that produces the red and green coloration) can easily be diffused into the feldspar structure at high (and possibly also at very low) temperatures. It is generally accepted that diffusion-treated feldspar (labeled “andesine”) is widely sold around the world. The source material for treatment is said to be a pale yellow andesine that occurs in massive quantities in a deposit in ‘Mongolia’ (‘Inner Mongolia’?). However, nobody has yet unequivocally demonstrated the existence of this locality, and none of the supposed production of *untreated* yellow andesine has ever reached the marketplace, even in small quantities. A theorized source of naturally colored red and green andesine in Tibet has likewise never been proven to exist. And even if such proof appeared, the volume of material from this deposit could not possibly account for the huge number of cut red and green “andesine” gems that have been sold.

I have always advocated the (somewhat obvious) premise that every cut gem starts with a piece of rough. This rough is often ‘mineral’ in nature (as opposed to ‘organic’ gems such as amber, pearl, etc.). Any such material that is claimed to be natural in origin therefore should have come from a geological occurrence of some kind. It seems pointless to advocate that the source of a massive amount of gemstone rough is a deposit that is either unlikely or impossible to exist because of the lack of any fundamental geological process that could account for it. Such a claim is risky, challenging and automatically suspect. Whoever makes it should be prepared to offer an abundance of supporting evidence.

The following discussion is a summary of observations that are part of the established foundation of current geological thought. The reader is urged to look at the arguments presented in their most simplistic terms, not unlike the mission of a jury that is charged with the duty of considering only established facts and credible evidence in reaching a verdict. In the words of an often-quoted anonymous observer of the legal system: ‘if it looks like a duck, walks like a duck and quacks like a duck, it is most likely to be a duck’ - unless conclusively proven otherwise.

Faceted transparent plagioclase feldspars are generally uncommon because of the extreme rarity of conditions that allow the growth of large transparent crystals. These conditions are found in environments of slow cooling, but generally with initial magma compositions that produce relatively calcium-rich feldspars, such as labradorite and bytownite. It is therefore not too surprising that localities are known to exist in which significant quantities of transparent labradorite crystals (sometimes as large as 10 cm in length) have been discovered. But, by contrast, magmatic compositions that would yield plagioclase feldspars with high sodium contents are not typical of environments where slow cooling could produce large transparent crystals. More sodium-rich plagioclase, including oligoclase and andesine, is generally encountered in totally different geological settings. Although sometimes yielding andesine phenocrysts, these environments are rich in water, unlike the very high temperature dark basaltic magmas in which water plays no significant role in feldspar crystallization.

The geological conditions that produce granites and similar rocks, because of high atomic mobility and diffusion rates and the likelihood of continued feldspar chemical alteration, are generally inimical to the creation of transparent feldspar crystals. The circumstances that would allow the formation of abundant, large transparent phenocrysts of andesine are therefore exceedingly unlikely, if not impossible. This conclusion is borne out by the lack of any validated report, anywhere in the geological literature, of the prolific occurrence of such large transparent andesine megacrysts. It is *extremely* improbable that dark volcanic rocks, such as lava flows, that have produced so many localities for transparent labradorite, could ever yield equivalent quantities of cuttable andesine.

---

## FELDSPARS

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.

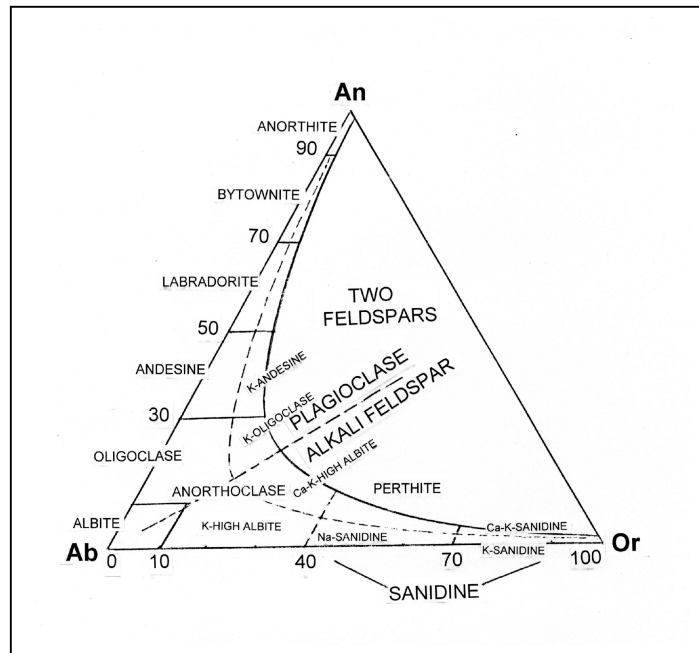
Feldspars make up nearly 60% of the earth’s crust. They are five times as abundant as quartz, and twenty times as abundant as all the carbonates, oxides, sulfides and halides *combined*. The feldspar family is broadly divided into two main groups: **alkali feldspars** (such as orthoclase, with mainly potassium and only a bit of sodium) and **plagioclase feldspars** (with mainly sodium and calcium). There is nearly a complete range of compositions, called a “solid solution series”, between sodium-rich and calcium-rich plagioclases. The plagioclase feldspar names were created many years ago; these names are no longer considered mineral species, but are still in widespread use and therefore are used here for convenience. *Albite* refers to a sodium-rich plagioclase containing up to 10% of the calcium component. The composition range between 10% and 30% calcium is called *oligoclase*; from 30% to 50% calcium we have *andesine*, 50% to 70% calcium is *labradorite*, and 70% to 90% is named *bytownite*. *Anorthite* includes compositions from 90% to 100% calcium component in the structure.

Plagioclase feldspars are found in virtually all igneous rocks (those created by the cooling of the molten material called magma). In fact, igneous rocks themselves are generally classified according to the type of feldspars they contain (as well as grain size and the presence of other minerals). The cooling history of an igneous rock determines the ultimate distribution and size of the minerals that formed as the temperature of the magma decreased. Igneous rocks contain a wide variety of minerals, some of which are light in color and others are dark. Old terminology (amazingly, still in use) referred to darker rocks as “basic” or “mafic”, and lighter ones as “acidic” or “felsic”. The dark rocks typically contain such minerals as high-calcium plagioclase feldspar, olivine, magnetite, pyroxene and many others, typically minerals that are not hydrated. Light colored rocks are generally rich in quartz, amphiboles, micas, sodium-rich plagioclase feldspar and some potassium (alkali) feldspar, and characteristically contain many hydrated mineral species. Water is available and generally plays a role in the cooling history of acidic rocks.

**Figure 1**

Diagram of feldspar names based on their chemical compositions, i.e. relative amounts of Na (sodium), Ca (calcium) and K (potassium). The points of the triangle are so-called "end members" compositions.

An = anorthite all calcium  
Ab = albite all sodium  
Or = orthoclase all potassium



## ROCK TYPES AND GEOLOGY

There seems to be a fundamental relationship between the occurrence of rock types and global geology. The earth is dynamic. The outermost shell is a thin layer (10-15 miles) of solid rock (the earth's crust) that has broken apart into irregularly shaped masses that we call "continents". Under the crust is the "mantle", a thick (about 1,800 miles) layer of molten material under immense pressure. It is now understood that the continents "float" on enormous "plates" of crustal material that move in various directions as a result of convection currents arising in the underlying mantle. The collision of these plates may result in buckling at their edges due to unstoppable compressive forces, in some cases thereby elevating a mountain range (such as the Himalayas). Shear stresses also can result from continental plates sliding past each other; eventually producing cracks (fault lines) that become immobilized due to friction. Earthquakes occur when some of the built-up stress on these fault lines is suddenly released.

A rising convection current in the mantle may force its way under an expanse of crust, causing it to crack apart. The upwelling then continues to squeeze magma into the widening fissure. This process creates a ridge of newly formed rock along the entire length of the crack, and as the magma continues to rise up and flow outward it pushes the cracked pieces of the continental plate apart. The ridge typically is punctuated by a string of active volcanoes. The volcanoes and the crack along the center of the ridge continually pour out massive amounts of magma that cool and solidify into new oceanic crust. This magma, coming directly from the mantle, crystallizes into rocks made up of dark colored minerals, such as we find in lava flows. A process of this kind broke up an ancient landmass millions of years ago and pushed the pieces thousands of miles apart. The space in between, now filled with water, is the Atlantic Ocean, and its mid-oceanic ridge is the longest unbroken mountain chain on earth. Part of it, in the North Atlantic, is the volcanically active region we know as the country of Iceland. Continental plates may also collide in a way that allows the edge of one plate to shove its way underneath another. This process, called "subduction", results in massive amounts of crustal rock being carried deep into the super-hot mantle, and also far in from the edge of the overlying plate. When subducted continental crustal rock melts, it forces its way up into the plate above it, where it may cool and crystallize in the form of gigantic structures known as batholiths.

The continental crust is an average of all the rock types we see at the earth's surface, including large amounts of sedimentary material. When it melts, the result is typically a light colored rock, such as andesite or diorite, or granite, which is the constituent of many batholiths (which, in turn, may eventually be exposed by erosion, giving us such natural wonders as Yosemite Park in California). Magmas that yield granitic rocks also typically contain abundant water, and consequently are characterized by hydrated minerals such as amphiboles and micas. Abundant water also has enormous implications for the occurrence and alteration of feldspars.

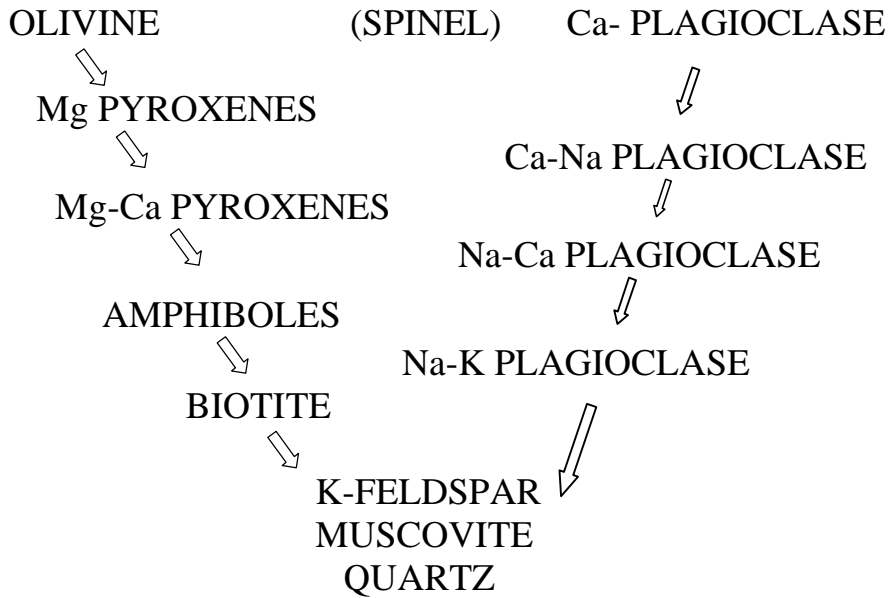
## **MINERALS ARE FOUND WHERE THEY ARE SUPPOSED TO BE**

Although the mantle as a whole may be essentially uniform in its chemical makeup, the composition of magma nonetheless varies greatly from one locality to another. Undersea eruptions along the Mid-Atlantic Ridge may spew out lava with a very different mix of chemical elements than are found in lavas in Japan, Mexico, Hawaii or the Philippines. This variation is reflected in lava temperature and viscosity, and ultimately in the kinds of rocks that are produced.

A century ago, Norman L. Bowen came to Washington, DC to begin his studies of equilibrium in silicate systems. A series of publications starting in 1915 finally led in 1928 to the production of a landmark book, *The Evolution of the Igneous Rocks*. Bowen introduced the concept of a "reaction series", a sequence of mineral precipitation to be expected from a typical cooling magma, based on the melting points of the minerals and supported by innumerable field observations. The first mineral to form is always olivine (the gem variety is known as peridot), followed by plagioclase. The cooling of a typical volcanic magma can be described in terms of two parallel sequences of crystallization. One of these sequences relates to the formation of the rock's primary constituent, plagioclase feldspar. Other minerals form concurrently, also in a definite sequence, as the temperature drops and crystal growth removes chemical components from the melt.

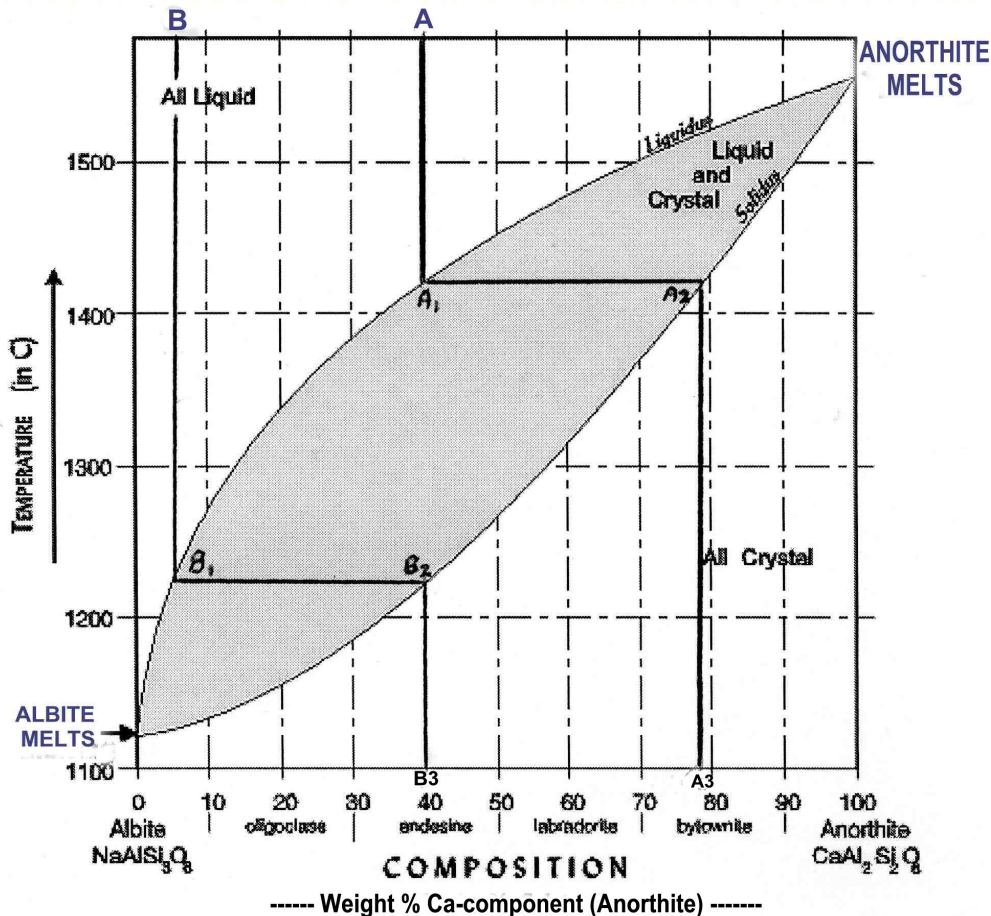
The complete sequences indicated in the diagram are never actualized in a single event. A typical dark magma will be completely solidified at a temperature midway down the series, with all of the initial components tied up in minerals such as olivine, calcic plagioclase and pyroxene. The cooling diagram merely illustrates the *order* of crystallization of various kinds of minerals. What actually forms in a given situation depends on the starting composition of the melt and the geological events in the surrounding environment (rates of cooling, changes in pressure, etc.). The feldspar sequence is called "continuous" because it represents a series of minerals that form in strict sequence with falling temperature. The other series is called "discontinuous" because each mineral that forms reacts with the remaining magma to produce the next mineral down in the sequence. A molten oceanic rock typically has a composition that, if slowly cooled, would produce olivine, pyroxene and plagioclase. Olivine crystallizes first and often sinks through the magma to create a layer at the bottom of the magma chamber. Then plagioclase and pyroxene start to form, gradually using up the elements in the melt that are left over from the formation of the early crystals. All of these early-formed minerals are anhydrous. Any water that is dissolved in the magma would be eventually incorporated into the hydrated minerals that form at lower temperatures. If these minerals do not have a chance to grow, the water is typically squeezed out of the cooling magma. The pyroxene that crystallizes has a composition that is directly related to the composition of the melt. But in the case of the plagioclase, *the solid crystal that forms from the melt has a different composition from that of the liquid* - it is much higher in calcium.

# MAGMATIC REACTION SERIES ACCORDING TO BOWEN 1928



As the melt continues to cool, and *if* the crystals are allowed to react continually with the remaining melt, the composition of the resulting feldspar *continues to change*, until either the ingredients needed for making a feldspar from the melt are used up or the rock solidifies and thermal quenching entirely stops the process. The formation of plagioclase crystals depletes the magma of calcium, and continued crystallization thus produces feldspars with increasingly higher sodium content.

## PLAGIOCLASE FELDSPARS MELTING/COOLING CURVES



In the above diagram, a plagioclase *melt* composition that is 40% sodium and 60% calcium component will, at around 1420° C. (point A<sub>1</sub>), start to produce a *solid* feldspar that is about 78% calcium (point A<sub>2</sub>). If the temperature continues to fall and *if the solid crystals are allowed to continually react with the remaining melt*, the composition of the liquid will fall, for example, to point B<sub>1</sub> (5% calcium) and the crystals will have continually changed composition to point B<sub>2</sub> (about 60% calcium component).

However, in a hot magma that cools *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. The composition of both liquid and solid would remain stable as the crystals grew larger and larger. If rapid cooling then occurred (e.g., the magma was ejected to the surface as a lava flow), the result would be a rock containing large crystals of plagioclase of a single composition embedded in a matrix (called a groundmass) consisting of tiny or microscopic crystals of plagioclase, pyroxene, perhaps olivine, etc. Such a rock is known as a *porphyry*.

Generally, the compositional change during cooling is more rapid, and this typically results in feldspar crystals that are highly *zoned*. Such crystals have cores that are always richer in calcium in succeeding layers of growth. 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 not uncommon in plagioclase. The situation becomes even more complex if there is a bit of potassium in the mix. Crystals of plagioclase that display such oscillatory growth patterns are not transparent enough to produce gemstones.

Moreover, the overwhelming majority of dark magmas have (plagioclase equivalent) calcium contents well over 50%, producing solid crystals of labradorite or bytownite. Andesine is rare in these rocks and, if present, is nearly always part of the groundmass. Water is also not involved in the early stages of crystallization of dark magmas, and water dissolved in the melt is generally squeezed out into “late stage” hot fluids that escape into surrounding rocks and may cause extensive alteration and mineralization.

Andesine is most likely to occur in rocks that began as melts either with a very high sodium content, or under conditions that allowed the feldspar crystals to interact continuously with the surrounding liquid. It is well known that water enormously facilitates chemical reactions in mineral systems, especially in the feldspars. Water is rare in dark magmas, but *is* abundant in magmas that result from the melting of continental crustal material in subduction zones and that cool to form granites and diorites. Granitic rocks are also rich in potassium and sodium. The combination of the right starting chemistry, plus available water to facilitate equilibrium reactions, allows andesine to crystallize in these rocks from total plagioclase (equivalent) compositions as low as 50% calcium. This andesine is never transparent. It formed as a result of continued reaction with a melt, resulting in oscillatory zoning, as well as the influence of water and diffusion of both calcium and sodium in and out of the structure. These factors, combined with pervasive twinning and the formation of submicroscopic domains upon cooling, destroy any hope of transparency in crystals above tiny size. Slow cooling may also occur in large granitic bodies, and andesine porphyrys do exist. But they do not yield facet-grade crystals.

## **ANDESINE AS A PRIMARY PHASE**

Research has been done for decades on mineral assemblages that form under the high pressure conditions typical of the base of the crust or upper mantle. This research suggests that increasing pressure causes the liquidus and solidus curves in the plagioclase phase diagram to move closer together, and therefore at some very high pressure a melt composition with a 50% calcium component will precipitate a solid feldspar of essentially the same composition as the melt. Primary andesine may therefore be a component of rocks that begin to form deep in the crust or upper mantle, possibly as far as 60 km down. Sometimes high-pressure minerals are carried upward by rising magma and mix with other minerals that crystallized at lower temperatures and pressures. These observed high-pressure minerals are called “xenocrysts”, implying that they were not created in the cooling process that gave rise to the rocks that ultimately contain them. Andesine xenocrysts in these rocks often occur with aluminous pyroxenes that are also believed to have formed under high pressure. Xenolithic andesine crystals have been described from various localities. Most of the crystals are under 1 cm in length, and the maximum (rarely) observed size is on the order of 2-3 cm. These crystals are sometimes glassy and transparent, but more often are twinned and opaque. There seems to be no evidence at all in the petrologic literature, either for transparent andesine megacrysts above this size, or for localities in which enormous glassy andesine crystals are abundant.

## **DIFFUSION AND ALTERATION**

The feldspar structure is a “flexible framework” of silicon, aluminum and oxygen atoms, with some intermediate positions occupied by sodium, calcium, potassium, barium, etc. The feldspar group is perhaps the most complex and least understood of all mineral families. The individual structural units are extremely small and tend to grow together in form of submicroscopic (atomic scale) domains that are complexly twinned. On a macroscopic scale the structure presents itself as a uniform, continuous entity. But at the level of unit cells the plagioclase structure is a virtual sieve. The mobility of atoms through it is astounding, even at very low temperature. This accounts for the extreme ease with which feldspars in rocks alter, decompose, and change in composition, especially in the presence of water.

The domain structure can be visualized as follows. Imagine a piece of wallpaper with a two-dimensional repeating pattern that is very small and therefore many images are packed into each square foot. Now carefully slice apart all the individual pattern units (in both directions) and then put adhesive tape on the back to re-connect all the small pieces. From the front the wallpaper would not look any different at all, if the cuts were carefully made. But you would have introduced boundaries between the units that did not previously exist. You might not be able to see them, but there are now very tiny separations between the pattern units. Water might even be able to move through the cuts by capillary action. Now imagine the repeating pattern is in a crystal, is three-dimensional, and the repeating units are sub-microscopic in size. At first glance you would see a contiguous crystal structure, but there would be real boundaries between the individual structure units. It is even possible for the small units to be stuck together in a symmetrical but twinned relationship, where the individual units have lower symmetry, but the repeating macro-pattern displays a higher symmetry that would be revealed by X-ray diffraction. This imagery begins to approximate the complexity of plagioclase feldspar and the actual degree of permeability of the structure. It is easy to see how alteration could occur very quickly and even at low temperature in hydrous environments.

The writer has presented a lengthy discussion on diffusion and feldspar treatment that can be found at this link: <http://www.jewelersethicsassociation.com/docs/GEM%20FELDSPARS.pdf> Minerals tend to be most stable in (or close to) the conditions where they were formed, including pressure, temperature, presence of water, acidity, etc. Volcanic rocks, created under conditions of intense heat and pressure, therefore break down and decompose readily at the earth's surface. The weathering products of such rocks form an amazingly rich and fertile soil, and the process can occur within a matter of a few years. Ever wonder why Hawaii, with its tropical climate, is such a paradise of lush, green forests and plantations?

The plagioclase feldspars all decompose quickly under warm, wet conditions, and the residual products are a group of minerals known as clays. High-calcium plagioclase (formed at the highest temperature) is the most susceptible, with potassium and sodium-rich feldspars being less so. The feldspar structure is so complexly twinned and filled with atomic-scale domains that elements like potassium, sodium and calcium can move in and out with relative ease, even at surface conditions. It has been suggested that sodium and potassium can be *completely and selectively* exchanged in a feldspar without disturbing its structural state. The process of diffusion is accelerated in the presence of hydrothermal fluids (hot watery solutions squeezed out in the very last stages of crystallization of a cooling magma) that can penetrate solid rocks and completely alter the chemistry of pre-existing feldspars. The resulting crystals are usually complexly zoned and show distinct evidence of change in the form of compositional layers. The feldspars in such rocks are therefore never transparent on a macroscopic scale.

## CONCLUSION

Natural environments are never as simple as the ones pictured in neat little diagrams in textbooks. A major complication in observed feldspar mineralogy is the high mobility (by diffusion) of metals within the framework structure, even at fairly low temperatures. This means that calcium can invade a sodium-rich feldspar crystal and change its chemistry, and vice versa (remembering that charge balance must be maintained by concomitant exchange of aluminum and silicon). Alteration of feldspar crystals in low temperature environments is *extremely* common, and can even be accomplished 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. It is extremely unlikely that transparency and homogeneity can be maintained in the face of so much internal chaos.

The basic thermo-chemistry of plagioclase feldspars is well established, and is both derived from and supported by countless field observations and laboratory experiments. Rocks have been studied, analyzed and categorized for centuries. All existing theory and observation suggests that primary igneous rock masses such as lava flows rarely contain macroscopic andesine. If they do, most of the crystals we find were in continuous contact with the magma as it cooled and became chemically zoned (and are therefore not transparent), or else the andesine crystals are high-pressure xenoliths carried up from great depths and, while possibly transparent, they are generally small and scattered. By contrast, equilibrium studies and field evidence definitively support the probability of encountering large, un-zoned labradorite crystals, that under rare (but not impossible) conditions of cooling, could retain a single composition and not react with the surrounding melt, and yet still grow to large size. We do, in fact, know of several such occurrences in Mexico and elsewhere.



Andesine crystals are widely reported in the petrologic literature as xenolithic components of mafic igneous rocks. But andesine is also found in granitic and related rock types, sometimes in the form of porphyritic crystals. These lighter colored “acidic” rocks formed under conditions that would allow a feldspar to continually react and change composition upon cooling, leading to oscillatory zoning. Later alteration of these rocks would further insure the opacity of any contained feldspars. Not surprisingly, the gemstone literature contains virtually no references to faceted andesine. The very few reported occurrences of cuttable material describe only very small transparent fragments.

There appears to be no geological literature that would support a claim of the existence of a rock containing huge amounts of large transparent andesine crystals.

The evidence presented to verify such a deposit would have to be compelling and unequivocal. It would have to consist initially of a large number of random samples taken from an in-situ rock mass (e.g. lava flow), with proof (photographic and anecdotal) that the samples were extracted from within the rock mass; these samples would contain glassy, transparent crystals of andesine feldspar of many different sizes embedded randomly in the rock matrix. The formation itself would have to be pinpointed by GPS and topographic and geological map references, and its origin would have to make sense within its broad geological environment. The rock samples should be petrographically analyzed to yield a plausible geological and geochemical scenario for their formation.

The gemstone marketplace must decide whether millions of carats of red and green feldspar that have been sold in recent years, and which are known to have been treated by diffusion with copper (and other chemicals), were produced from transparent *natural* andesine crystals. The raw material is reportedly mined in a large Asian deposit. Yet none of the ‘untreated raw material’ has been sold anywhere, nor have any credible and comprehensive studies of the ‘deposit’ been offered. A visitor observing a pile of yellow crystals at a locality does not prove the existence of any local rock body that might have produced such material.

It has been demonstrated by laboratory work and abundant examples in nature that sodium can readily diffuse into the plagioclase structure. It might be theoretically possible to treat labradorite by diffusion with sodium, as well as copper and other chemicals, altering its chemistry and optical properties as well as its color. There is no shortage of large transparent labradorite. This material could *potentially* account for *all* the diffusion-treated feldspar that has been produced.

Our world is a truly amazing place and is constantly offering unexpected surprises. It would be hubris to state categorically that transparent megacrysts of andesine could *never* be found. The above discussion is meant only to convey the scientific basis for claiming that the probability of finding such material is vanishingly small.

The sellers of treated feldspar who globally market their stones claim their material was derived from large transparent crystals of *naturally occurring* transparent *andesine*. If the mandate originally given is to rely *only* upon established facts and credible evidence in deciding the truth of this assertion, it is reasonable only to conclude that such material does not (yet), in fact, exist.

---

## REFERENCES

- Abduriyim, A. *The Characteristics of Red Andesine From the Himalaya Highland, Tibet*. Jnl. of Gemmology, 31, 2009, 283-298
- Abduriyim, A. et. al. *Research on Gem Feldspar From The Shigatse Region of Tibet*. Gems & Gemology, 2011, 167-180
- Aoki, Ken-Ichiro, *Andesine Megacrysts in Alkali Basalts From Japan*; Contr. Mineral. Petrol. 25 (1970) 284-288
- Areback, Hans and Stigh, Jimmy, *Polybaric Evolution of the Hakefjorden Complex, Southwestern Sweden, Deduced from Partial Dissolution in Andesine Megacrysts*. GFF 119 (1997) 97-101
- Arem, Joel E. *Color Encyclopedia of Gemstones*. New York, Van Nostrand Reinhold, 1987
- Bacon, C. R. and Carmichael, I. S. E., *Stages in the P-T Path of Ascending Basalt Magma: An Example from San Quintin, Baja California*. Contr. Mineral. Petrol. 41 (1973) 1-22
- Bowen, N. L. *The Evolution of the Igneous Rocks*. Princeton University Press, 1928
- Chapman, Neil A. and Powell, Roger. *Origin of Anorthoclase Megacrysts in Alkali Basalts*. Contr. Mineral. Petrol. 58 (1976) 29-35
- Emmett, J L. & Douthit, T. R. *Copper Diffusion in Plagioclase*. News From Research of GIA, 2009
- Grove, Timothy L., Ferry, John M. and Spear, Frank S., *Phase Transitions and Decomposition Relations in Calcic Plagioclase*. Amer. Min., 68 (1983) 41-59
- Gutmann, James T. *Geologic Studies in the Pinacate Volcanic Field*. Jnl. of the Southwest 49 (2007) 189-243
- Gutmann, James T. *Tubular Voids Within Labradorite Phenocrysts from Sonora, Mexico*. Amer. Min. 59 (1974) 666-672
- Hoffman, A. W., Giletti, B. J., Yoder, H. S. Jr. and Yund, R. A. (ed.), *Geochemical Transport and Kinetics*. Carnegie Institution of Washington, Pub. 634 (1973)
- Laughlin, A. W., Manzer, G. K. Jr. and Garden, J. R. *Feldspar Megacrysts in Alkali Basalts*. Geol. Soc. Amer. Bull. 85 (1974) 413-416
- Ribbe, Paul H., Ed. *Reviews in Mineralogy, V. 2, 2<sup>nd</sup> Ed.: Feldspar Mineralogy*. Min. Soc. Am., 1983
- Righter, Kevin and Carmichael, . E. *Mega-Xenocrysts in Alkali Olivine Basalts: Fragments of Disrupted Mantle Assemblages*. Amer. Min. 78 (1993) 1230-1245
- Rutherford, Malcolm J. *Magma Ascent Rates*. Rev. Mineral. Geochem., 69 (2008) 241-271
- Sinkankas, John. *Gemstones of North America Vol. III*. Tucson, Az., Geoscience Press, 1997
- Sinton, John M, *Ultramafic Inclusions and High-Pressure Xenocrysts in Submarine Basanitoid, Equatorial Mid-Atlantic Ridge*; Contrib. Mineral. Petrol. 70 (1979) 49-57
- Tilley, C. E., Nockolds, S. R. and Black, M. *Harker's Petrology for Students*. Cambridge University Press, 8th ed., 1962
- Williams, H., Turner, F. J. and Gilber, C. M, *Petrography*. San Francisco, W. H. Freeman & Co., 1954