

DOUBLE TROUBLE: NAVIGATING BIREFRINGENCE



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Front cover: The view along the optic axis/c-axis of a nearly equilateral calcite cleavage rhomb.

Back cover: Prismatic calcite crystals from Dalnegorsk, Primorskiy Kray, Far-Eastern Region, Russia.

Below: Left to right: Various specimens of quartz and Iceland spar studied for this paper: the nearly equilateral calcite cleavage rhomb shown on the cover; a 40 mm optical calcite sphere; a 60 mm optical quartz sphere; a polished rhomb with mark for navigational use, a faceted calcite with rhomb “rough & cut” set; Leif Karlsen’s large cleavage rhomb from Iceland, subject of his 2003 book *Secrets of the Viking Navigators*.



On-going collaboration with Cornell's Professor Emeritus William A. Bassett is truly priceless to me for this and other projects in the wings, as well as for those over the past eight years of work and research together. Bill shares my enthusiasm for exploring the fascinating aspects of the classical science of mineralogy, and as my co-author he sets the highest bar for accuracy. All students should be so lucky to have such a mentor.

*Elise A. Skalwold, 2015
Ithaca, New York*

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Figure 1: The Vikings were thought to have used a birefringent mineral as an aid to navigation during voyages across the North Atlantic. Strongly pleochroic blue cordierite (iolite) such as the two pebbles at right, and highly birefringent optical quality calcite are popular candidates for the “Fabled Viking Sunstone” of the Sagas. The wooden box carved by Norwegian-American Leif Karlsen held his 65 x 45 x 35 mm cleavage rhomb from Iceland which he used to test his theory of calcite’s use by Vikings, set forth in his 2003 book *Secrets of the Viking Navigators*. The strong doubling of the Norwegian flag can be seen through the calcite’s cleavage face; an ancient sailor’s secret? Maybe!

Prelude

Optical mineralogy has many fascinating though often complex concepts which underlie common effects observed in minerals and lapidary specimens fashioned from them. Doubling of images such as seen through a calcite rhomb is perhaps one of the most readily observed of these properties and could well have been one put to use centuries ago in a very practical way (Figs. 1, 10 & 12). The intriguing theory of the Viking’s use of a coveted stone to find their way in arctic waters has its roots in the ancient Viking Sagas, optical mineralogy, and in practical application by modern navigators. The proposed minerals thought to be the Viking “sunstone” are excellent models for understanding the optical phenomena of birefringence and pleochroism; the very properties which make them useful for navigation are also those which make them valuable to mineral and gem enthusiasts today (see Skalwold 2008, *The Fabled Viking Sunstone* <http://www.nordskip.com/vikingcompass.html>). There are several candidates

for the stone. Among them are “Iceland Spar” calcite of which a coveted optical-quality variety was found abundantly in eastern Iceland, and the blue variety of the mineral cordierite, found in Norway and popularly known as “Viking’s Compass” and as the gem “iolite.” While the latter’s extraordinary pleochroism is explored in the authors’ article “Blue Minerals: Exploring Cause & Effect” (Skalwold and Bassett 2016), the more likely candidate, Iceland spar, is *the* classic model for demonstrating the phenomenon of birefringence and doubling in optically anisotropic minerals. However, whether one’s adventures with minerals are land-bound or at sea, before venturing far there is some trouble with doubling to untangle first.

Sailors – beware the typo lest you run aground!

First, a brief review is in order. From a standard textbook on optical mineralogy, the following definitions:



Figure 2: Compared to calcite’s birefringence of 0.124, that of quartz is relatively low at 0.009. Nevertheless, doubling will still be visible if the specimen is large enough and is viewed at the correct angle to maximize the effect. Here the larger 71.49 carat stone’s table facet is inclined approximately 45 degrees to the optic axis, there is maximum doubling, but mid-range partial birefringence. The effect is noticeable on the pavilion facets at the back of the stone as seen through its table; maximum depth is 20.15 mm at the culet (center point). The table facet of the smaller 29.39 carat quartz is cut in a plane parallel to its optic axis. Looking in a plane perpendicular to the table surface, there is maximum birefringence, but zero doubling of the pavilion facets. Both stones were cut by Art Grant and were part of the collection of Harold Dibble. The smaller stone was cut from a left-handed crystal and the larger stone is from a right-handed crystal (for more on handedness, see Skalwold and Bassett 2015); 19.20 x 15.55 and 25.50 x 20.15 respectively. Photo: Jeff Scovil.

“*Birefringence* is when light passing through a mineral is split into two beams vibrating at planes that are approximately at right angles to each other. In certain directions the two beams follow different paths; this is *double refraction*” (Kerr, page 84-85). Each of those beams will have a different refractive index (a *slow ray* and a *fast ray*) and the difference between their maximum and minimum as measured perpendicular to the optic axis is the mineral’s *birefringence*; any direction not perpendicular to the optic axis is called *partial birefringence* (Wahlstrom 156-7). Note: only uniaxial minerals are considered in the present paper.

Some authors use the terms *birefringence* and *double refraction* interchangeably. While this is arguably acceptable, other authors exchange either of these two words with the term *doubling* when they are talking about the *visual effect* of doubled images. This is a source of confusion

and perhaps the source of repeated errors in literature. “Doubling” refers to the manifestation of two images for individual features residing *within* the mineral (such as inclusions), on the *back surface* of the mineral or a lapidary item (such as etching, growth marks, scratches and, as seen in Figure 2, facet junctions), or of items directly *behind* the mineral as seen through it (such as the classic classroom demonstration using dots and a calcite cleavage rhomb).

For any given thickness, there is an absence of doubling for two very different reasons:

1. There is no doubling seen when looking parallel to a mineral’s optic axis because there is no birefringence in that direction (other than that produced by strain). It is often referred to as the direction of single refraction.



Figure 3: Maximum doubling is seen at approximately a 45 degree angle with the optic axis in this 60 mm quartz sphere.

2. While it is the direction of maximum birefringence, there is no doubling seen when looking *perpendicular* to the optic axis because the slow ray is traveling directly behind the fast ray along the same path.

Additionally, for any given thickness maximum visible doubling occurs midway between the optic axis and the plane perpendicular to it; an observation easily approximated with a sphere, crystal fragment or a faceted gem as seen in Figures 2, 3 & 4 (to locate the optic axis, see the author's article "Quartz: a Bull's Eye on Optical Activity," Skalwold and Bassett, 2015). Forty-five degrees is a transition point where doubling decreases either in a direction towards the optic axis as birefringence also decreases, or in the opposite direction as birefringence increases, but the rays begin to merge (note: maximum strength of pleochroism in a colored transparent mineral occurs perpendicular to the optic axis; see Skalwold and Bassett, 2016).

Unfortunately, throughout current and classic popular books and articles on mineralogy, gemology and faceting, as well as educational materials in those areas, a misunderstanding has proliferated, either as an erro-

neous statement (for example: "maximum *doubling* occurs perpendicular to the optic axis") or as an "error of omission" (for example: "there is *one* direction where no doubling is seen," leading a reader to believe there is *only one*). Sometimes older editions of titles are correct while newer editions are not, and vice versa. While it is not necessary to enumerate a long listing of publications with this shortcoming, two very important classic and otherwise infallible texts present serious typos - called a typo here in deference to the authors' renowned expertise. These avidly sought-after out-of-print publications are widely used by mineral collectors, gem enthusiasts and students around the world and so are important to mention here.

In reference to a diagram of a prismatic calcite crystal in both *Mineralogy* and *Mineralogy for Amateurs*, author John Sinkankas writes:

"The maximum doubling occurs along the plane of the horizontal axes, but diminishes steadily toward the c axis until none at all is seen when looking parallel to this axis." (Sinkankas 1964, both page 212)

In both editions of the classic textbook, *Gemology*, in reference to faceted gems, the authors write:

"If [the table] is at right angles [to the optic axis] and one looks through the table, there is no double refraction and the back facets appear sharp. However, if the optic axis is parallel to the table, the light reaching the eye through the table is from both the O and E rays with maximum double refraction. If the birefringence is high, two images are seen; that is, there is doubling of the back facets" (Hurlbut and Switzer 1979, page 75; Hurlbut and Kammerling 1991, page 98).

This is not the first time such a typo has been pointed out in an authoritative text, though to the best of the present authors' knowledge, it is the first record for these particular publications. In 1877 Professor A. K. Eaton of Brooklyn, New York similarly questioned the authorities of the day in a letter penned to the Editor of the journal *The American Chemist*:

"Sirs – Some months since whilst engaged in cutting and polishing Iceland-spar at a variety of angles with the axis, I discovered properties that seem quite contrary to, or, rather, inconsistent with, the statements of all the authorities." (Eaton 1877, p.314).

He went on to describe the cutting of demonstration plates parallel and perpendicular to calcite's c-axis. Having learned that maximum birefringence was to be found perpendicular to that axis, he assumed this is where he would be able to demonstrate maximum doubling as well. He was surprised to find doubling inexplicably absent in that direction, despite authorities stating that the optic axis was the *only* direction in which doubling was "wholly wanting." Irwin constructed an ingenious brass instrument to hold a calcite sphere which he had polished for the purposes of demonstrating doubling. With it, one could observe the manifestations of birefringence in three directions: parallel, perpendicular and at 45 degrees to the optic axis of the calcite crystal. The latter exhibited the largest separation images; the very observation he was looking for and had expected to find at 90 degrees. He wrapped his letter up with:

"From this demonstration I must conclude, then, that the direction of the axis of the crystal is not 'the only direction along which there is no double refraction,' as everywhere is asserted; but that it is also true of any line passing through a plane perpendicular to the axis." (Eaton 1877, p. 314)

This letter resounded with the scientific community of the day enough to merit a note regarding it in the then weekly edition of *Scientific American* a few months later:

"Hitherto the statement has been currently made and accepted that the axis of the crystal is the only direction along which there is no display of the curious property of the spar – double refraction...From Professor's Eaton's diagram it appears that the greatest divergence is to be attained by passing the ray through at an angle of 45 degrees to the axis of the crystal." (Munn and Beach 1877, 291)

In frustration over the misuse of the terms quartz and quartz glass, Robert B. Sosman quipped the following sentiment, perhaps applicable today regarding doubling:

Figure 4: Maximum doubling is seen at approximately a 45 degree angle with the optic axis in this 40 mm calcite sphere. The distance between the two images of the single letter "V" is indicative of calcite's high birefringence (compare with Fig. 3). This sphere fashioned by Wolfgang Mueller is also remarkable given the level of difficulty calcite's easy cleavage presents the lapidary; it could easily have become many small cleavage rhombs!

"This matter of nomenclature is by no means to be considered an idle amusement for fastidious and impractical scholars. When the scientist or engineer calls two different things by the same name, the man in the street assumes that they are in fact the same. We have recently witnessed the widespread disastrous effects of such an assumption concerning wood-alcohol and grain-alcohol." (Sosman 1927, p.44)

For this author (EAS), a revelation similar to Eaton's occurred while pursuing a lifelong interest in Vikings and their methods of navigation, a passion shared with my late father, Bob Skalwold, a professional engineer, sailor and navigation instructor. Having come through the "back door" of mineralogy via the sister-science of gemology, I am especially aware of the confusion which arises from the previously described typos and errors of omission encountered in gemological training and in literature of various other fields. Fortunately, getting at the roots of such discrepancies actually propelled me deeper into the study of mineralogy and optical mineralogy in particular, facilitated by discussions with my co-author (WAB), Dr. Mickey Gunter and mineralogist and sailor Darko Sturman, curator emeritus of the Royal Ontario Museum. In 2008, the latter met with me in the courtyard of the Gemological Institute of America in Carlsbad, California with iolite fragments and calcite rhombs with which to explore the worthiness of each as an aid to navigation; the cu-



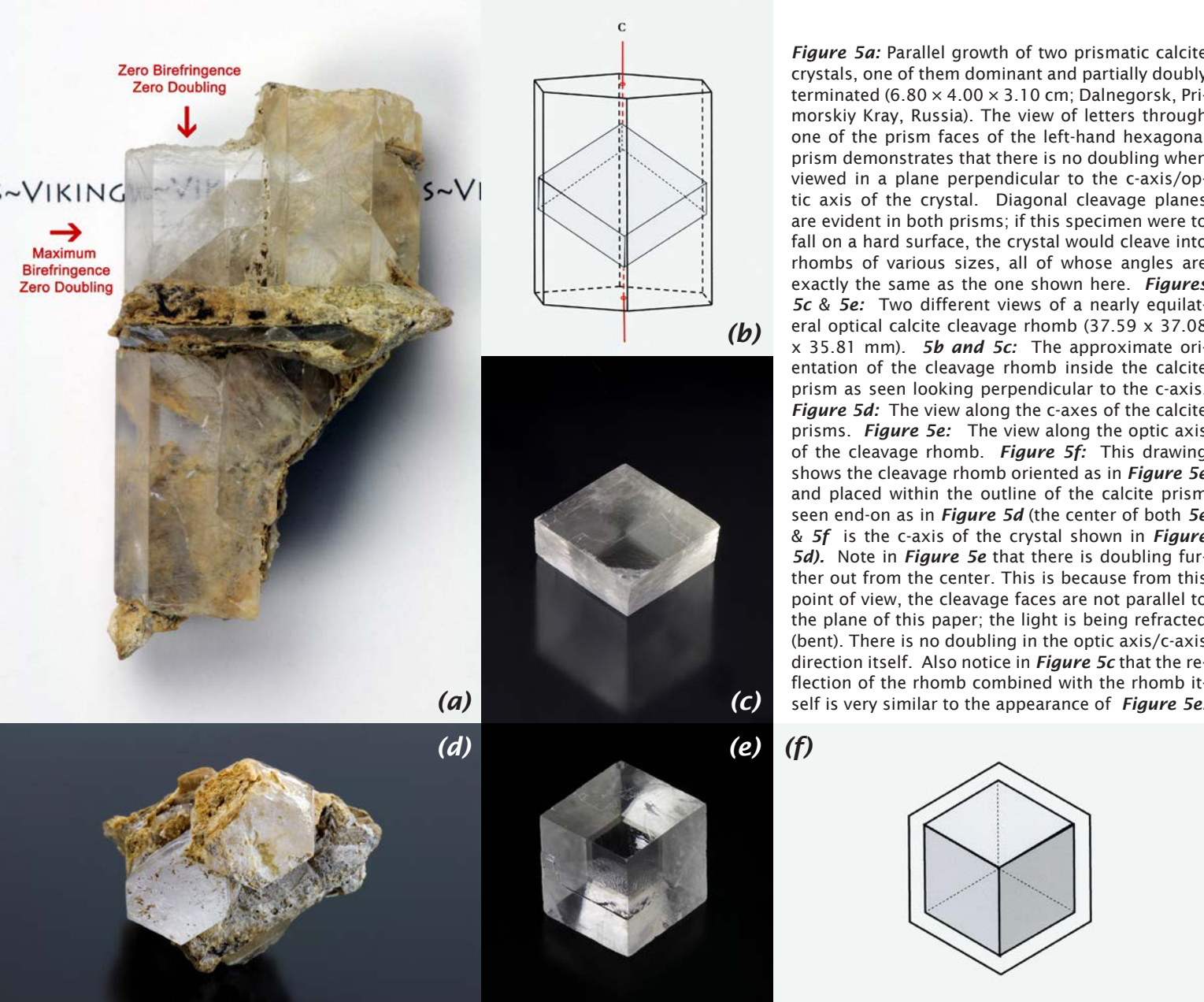


Figure 5a: Parallel growth of two prismatic calcite crystals, one of them dominant and partially doubly terminated ($6.80 \times 4.00 \times 3.10$ cm; Dalnegorsk, Primorskiy Kray, Russia). The view of letters through one of the prism faces of the left-hand hexagonal prism demonstrates that there is no doubling when viewed in a plane perpendicular to the c-axis/optic axis of the crystal. Diagonal cleavage planes are evident in both prisms; if this specimen were to fall on a hard surface, the crystal would cleave into rhombs of various sizes, all of whose angles are exactly the same as the one shown here. **Figures 5c & 5e:** Two different views of a nearly equilateral optical calcite cleavage rhomb ($37.59 \times 37.08 \times 35.81$ mm). **5b and 5c:** The approximate orientation of the cleavage rhomb inside the calcite prism as seen looking perpendicular to the c-axis. **Figure 5d:** The view along the c-axes of the calcite prisms. **Figure 5e:** The view along the optic axis of the cleavage rhomb. **Figure 5f:** This drawing shows the cleavage rhomb oriented as in **Figure 5e** and placed within the outline of the calcite prism seen end-on as in **Figure 5d** (the center of both **5e** & **5f** is the c-axis of the crystal shown in **Figure 5d**). Note in **Figure 5e** that there is doubling further out from the center. This is because from this point of view, the cleavage faces are not parallel to the plane of this paper; the light is being refracted (bent). There is no doubling in the optic axis/c-axis direction itself. Also notice in **Figure 5c** that the reflection of the rhomb combined with the rhomb itself is very similar to the appearance of **Figure 5e**.

rious goings-on were of obvious delight to those with their noses against the windows watching us turn the crystals in the brilliant sun!

Darko had earlier recognized that there was a misunderstanding about doubling amongst gemologists and so had published an instructive paper in the *Journal of Gemmology* illuminating its relevance in the study of faceted gems (Sturman and Back 2002). No doubt he would be amazed to know the misunderstanding is found also in the mineral world, at different times in history and including today. In “Doubling of Images in Gemstones,” Darko describes what he believes to be “the first attempt to present equations and diagrams for determination of doubling effects” (Sturman and Back 2002, p. 210). Ironically, in his classic optical mineralogy textbook, Revel Phillips writes that while these calculations can be made, it is “a hollow

reward” (Phillips 1971, p.86). We beg to disagree, for while the context is gems, the concepts illustrated in Darko’s *Journal of Gemmology* article can be applied to mineral specimens, intact or as fragments, and are useful as aids in identification and for gaining greater appreciation of their optical properties. Safe to say it also furthers the understanding of the Vikings’ ancient skills with crystals. Mankind has ever been inquisitive when it comes to minerals!

Seeing double – it’s not the Vikings’ mead!

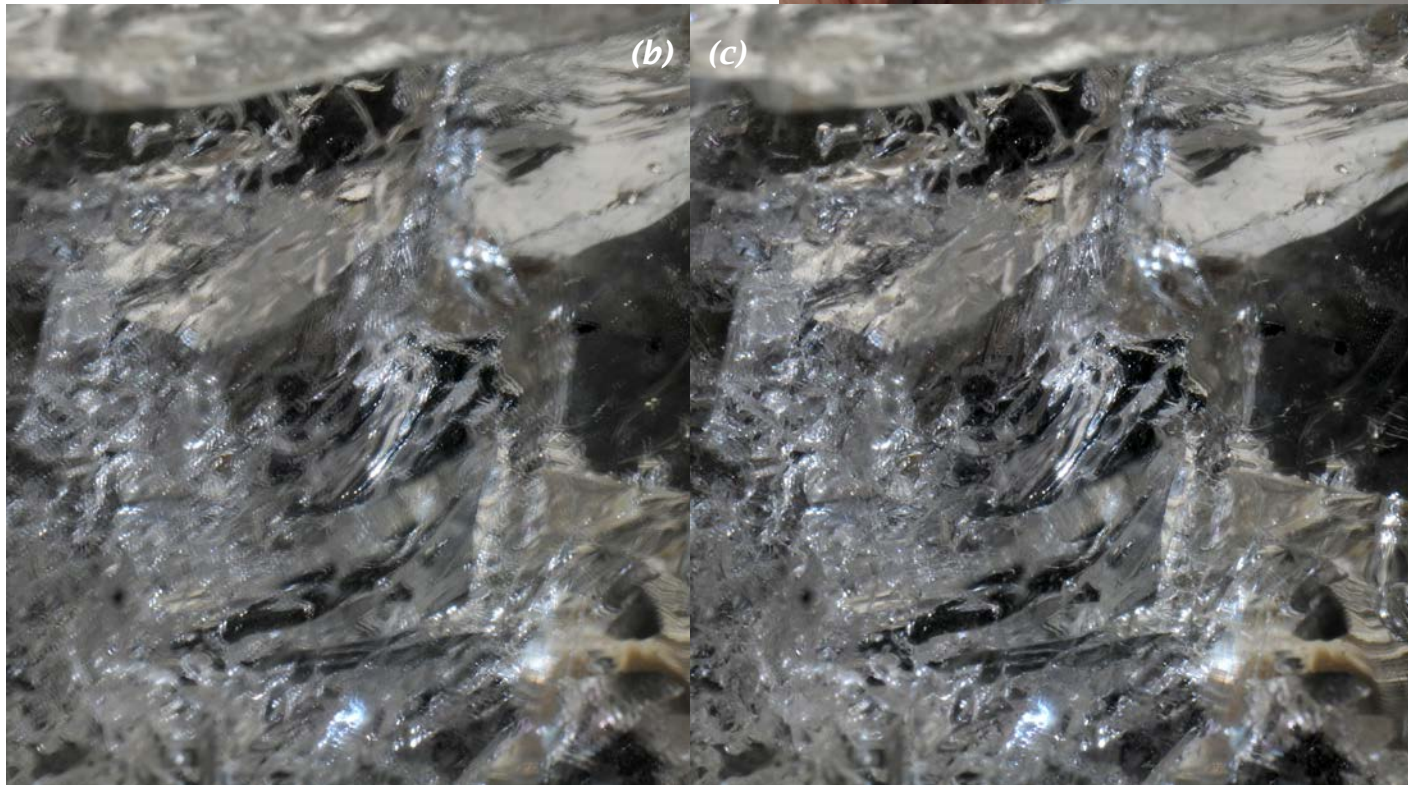
At the heart of the theory of Viking navigation as proposed by Leif Karlsen is the separation and intensity of images seen in the calcite cleavage rhomb (Karlsen 2003). The observed degree of separation of doubled images in anisotropic minerals is dependent on several contributing factors, including thickness and

(a)



Figure 6a: A handful of Herkimer “diamonds” (quartz, Little Falls, New York). The normal to the rhombohedral face on a quartz crystal has an angle of 51.8° with respect to the optic axis (c-axis), and so it is the face that will result in the largest separation of ordinary and extraordinary rays emerging from an inclusion inside the quartz crystal as seen in **6b**.

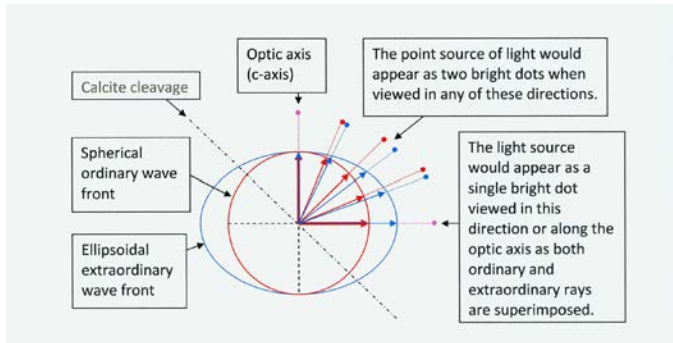
Sometimes while a mineral specimen or fragment isn't outwardly aesthetic, under magnification its interior reveals a wonderland of inclusions. Even with quartz's low birefringence, if the specimen is large enough, doubling can confuse the view when seen through the rhombohedral face; the use of a polarizing filter will eliminate one of the images and make viewing the microworld easier (**6c**).



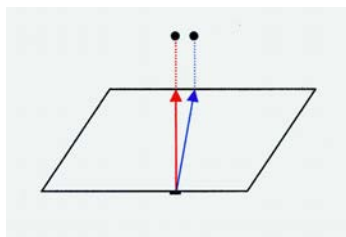
birefringence, the latter of which is determined by crystal structure. Various minerals display very different amounts of separation; for example, quartz must be 15 times as thick as calcite to give the same separation of images (Kerr 1977). Point of view also affects what is observed; unless otherwise stated, observations are for views normal to the specimen's surface. Please note again that this paper features the uniaxial minerals calcite and quartz and does not address biaxial minerals. For more information on biaxial minerals, see Wahlstrom 1969 and Sturman 2002.

To understand a cleavage rhomb's relationship to the parent calcite crystal, see Figure 5. Maximum linear doubling in calcite measures approximately one tenth of its thickness or approximately the tangent of 6 degrees for a light ray traveling normal to a cleavage rhomb's face (Kristjansson 2002). Why do calcite cleav-

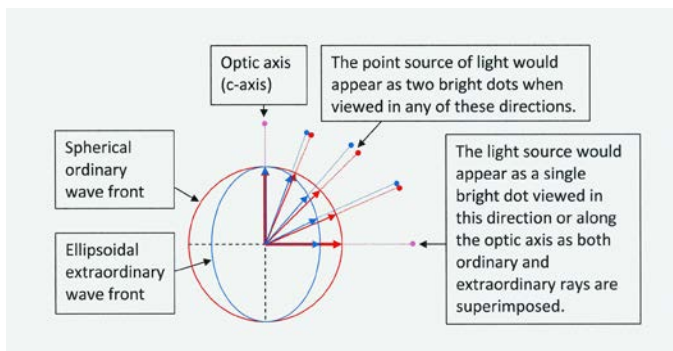
age rhombs show such great doubling? To answer this question, let's consider the explanation for the separation of rays in a double refracting calcite crystal if a point source of light were to be placed at the center of the cleavage rhomb. The largest separation between the two rays is at approximately 45 degrees from the optic axis. In the diagram below, the red rays are the ordinary rays and the blue ones are the extraordinary rays. The red sphere is the ordinary wave front and the blue oblate ellipsoid is the extraordinary wave front. There are two reasons that calcite shows doubling so well: 1) calcite has a large birefringence, i.e., the ordinary and extraordinary rays travel at very different velocities; 2) the excellent rhombohedral cleavage which is oriented 44.6° from the optic axis (c-axis) causes a cleavage fragment of calcite to have a nearly perfect orientation to show the maximum separation of the ordinary and extraordinary rays.



The dot/dash line (above) representing a cleavage face can be set to pass through the light source at the center. Then the point source of light would be located at the cleavage face instead of inside the crystal and a black ink dot could replace the light source. This is the more familiar way of observing doubling (right). The angle between the c-axis and cleavage in calcite is $44^{\circ} 36 \frac{1}{2}'$ (44.608°) - what an amazing coincidence that it is so close to the maximum separation!

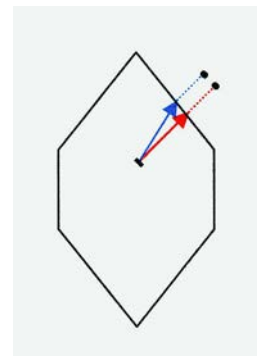


In contrast, the following is an explanation for the separation of rays in a doubly refracting quartz crystal if a point source of light were to be placed at the center of the crystal. Again, the largest separation between the two rays is at approximately 45 degrees from the optic axis. In the diagram below, the red rays are the ordinary rays and the blue ones are the extraordinary rays. The red sphere is the ordinary wave front and the blue prolate ellipsoid is the extraordinary wave front. Although quartz has a relatively low birefringence, i.e., the velocities of the ordinary and extraordinary rays differ by only a small amount, large crystals of quartz do display doubling, i.e. the separation of ordinary and extraordinary rays (also see Figs. 2 & 3).



The normal to the rhombohedral face on a quartz crystal has an angle of 51.8° with respect to the optic

axis (c-axis), and so it is the face that will result in the largest separation of ordinary and extraordinary rays emerging from an inclusion inside the quartz crystal (also see Fig. 6 on previous page).

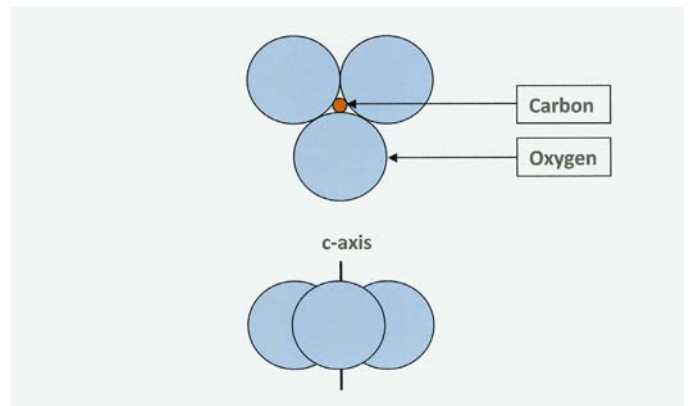


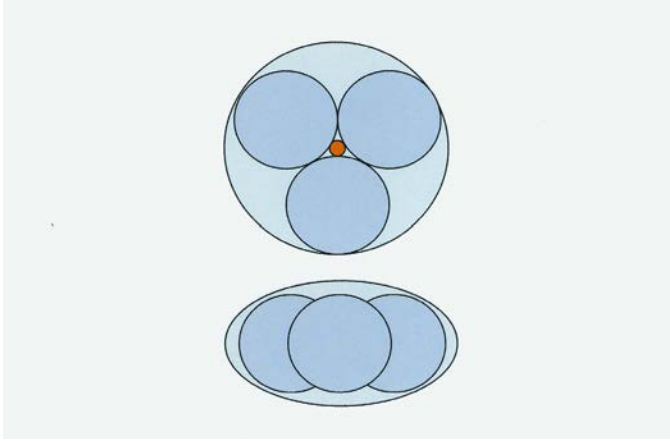
Birefringence and the crystal structure of calcite

To understand the underlying birefringence responsible for calcite's extreme doubling effect, consider first this abridgment from Ernest Wahlstrom's textbook on optical mineralogy:

"The uncommonly high birefringence of calcite (0.172) is attributed to the fact that the CO_3^{--} radical is flat, and the polarizability of the radical by oscillations of transmitted light energy vibrating in the planes is much greater than the polarizability normal to the plane containing the carbon and oxygen ions. Thus, the birefringence depends more on the nature and disposition of the CO_3^{--} radicals than on the positions of the Ca^{++} ions and their bonding with oxygen atoms. Substances that do not have strongly linear or planar groupings of ions or flat radicals generally do not exhibit strong birefringence. Birefringence is not dependent on the actual values of the refractive indices. The magnitude of the refractive indices are determined by ionic or molecular refractivities of ions and radicals in various kinds of environments in crystal structures." (Wahlstrom 1969, page 225-226) An illustration of these concepts follows below.

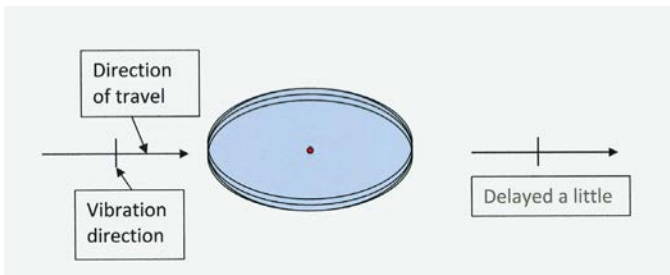
The oxygen atoms in carbonate groups are responsible for nearly all the optical properties of calcite. This is because the electron cloud of each oxygen atom is large and interacts with the light passing through a calcite crystal. All of the carbonate groups are triangles that are perpendicular to the c-axis (below).



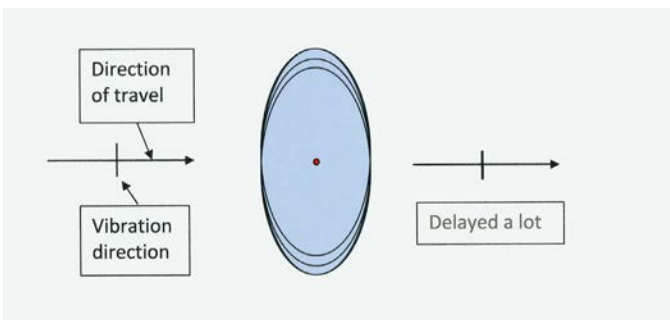


Although the carbonate group is a triangle, it interacts with light as if it were a disk shaped as an oblate ellipsoid of revolution as represented by the light blue (see above).

As a simplification we can think of calcite as having the same properties as the ellipsoid shown as light blue consisting of a cloud of negative light-weight electrons surrounding a small positively charged heavy-weight nucleus. That is, such an item is expected to show the same optical properties as calcite, especially as concerns refractive index and the doubling observed in calcite. In the diagram below, light travelling to the right with vibration up and down makes the electron cloud vibrate up and down. The light is slowed down because of the electron cloud, but because the ellipsoid is thin in that direction, the light isn't slowed down significantly.

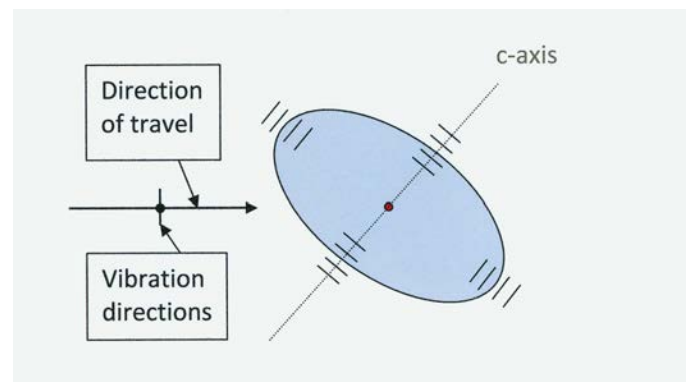


In the diagram below light travelling to the right with its vibration direction up and down makes the electron cloud vibrate up and down. The light is slowed down much more than in the previous diagram because the electron cloud is bigger in that direction and as a result causes the light to experience more delay.

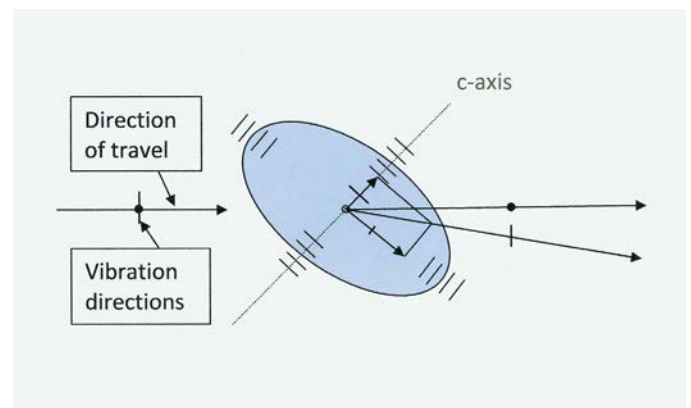


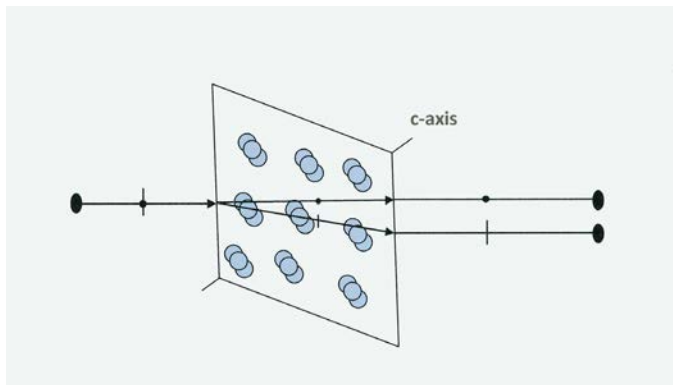
Alternatively, we can think of the vibrating electrons of the carbonate group or the oblate ellipsoid as re-emitting light much as a radio antenna does. However, the re-emitted light is slightly delayed by each carbonate cluster or each ellipsoid due to a lag in the vibration of the electron cloud. The accumulated delays have the effect of slowing the progress of the rays even though light travels at c (the speed of light in a vacuum) between carbonate clusters.

But what happens if we turn the “atom” by 45 degrees? We can think of the vibration direction of the light setting the electron cloud vibrating in both directions, along the thin direction and along the thick direction of the ellipsoid.



Once again, we can think of the two modes of vibration as two transmitters of light that act independently. The ray with its direction of vibration along the greater dimension of the ellipsoid travels to the upper right more *slowly*. The ray with its vibration direction parallel to the smaller dimension of the ellipsoid travels to the lower right *faster*. Once these two rays emerge from the ellipsoid they combine according to the rule of vector summation. The rule of vector summation states that the new direction is the diagonal of a rectangle with sides parallel to the slow and the fast directions and has a velocity intermediate between them as shown below.





Let's return to the calcite structure which can be thought of as consisting of many such carbonate groups all parallel to each other and bonded together by calcium ions that have negligible effect on the strange behavior of doubling that we observe; so we ignore the calcium ions and leave them out of the illustration above.

For those wishing to explore these concepts further, the authors highly recommend the following textbook passages in *Optical Crystallography* (Wahlstrom 1969, pages 218-226) and *Mineralogy and Optical Mineralogy* (Dyer & Gunter 2008, pages 413-418); also the excellent paper "A Lucky Break for Polarization: the Optical Properties of Calcite" (Gunter, 2003).



No trouble with double

With its perfect easy cleavage and soft nature, calcite is an unlikely candidate for faceting or, for that matter, making a sphere such as the one shown in Figure 4. However, having realized the potential design possibilities of such high birefringence, a few skilled lapidaries have developed techniques to successfully facet this fragile mineral with astonishing results. While a faceted untwinned crystal shows off the appealing clarity and interesting doubling effects of optical calcite (Fig. 7), colorless twinned calcite, unsuitable for the optics industry and in the right hands, unleashes a dizzying phantasm of color and movement. In the 1970's, Elvis "Buzz" Gray and his son Michael pioneered a technique which combines faceting angles and precise placement of multiple twinning planes to bounce and split the two rays all around within a stone until a kaleidoscope of colors emerges to greet the viewer (Gray 2003; also see Hurlbut and Francis 1984). The elder Gray later taught Art Grant the technique and he in turn mentored Brad Wilson and Jay Medici. It remains a rarefied skill and these magnificent creations are sought after by collectors and museums around the world (Skalwold 2015). This author (EAS) had the opportunity to examine one such gem first-hand several years ago – the 1,030 carat stone seen in Figure 8. Already intrigued by the optical analysis of the 1,156 carat Ross calcite faceted by Art Grant, it was quite another matter to actually see one of these calcites for myself. Moving it around in the light caused spectral colors to combine and recombine in a dance unlike any object I've ever encountered (see Hurlbut and Francis 1984, freely available at <http://www.gia.edu/gems-gemology/winter-1984-calcite-hurlbut>).

Taking advantage of calcite's optical properties is not limited to artisans and scientists. Nature has also found a unique use: the eyes of many species of long extinct trilobites employed calcite prisms as corneal lenses! And it seems Nature knew the directions of zero doubling: each part of the animal's complex eye

Figure 7: A faceted untwinned optical calcite paired with a cleavage rhomb, formerly part of a very large "rough & cut" collection compiled by Bill Hoeft. Such pairings dramatically show off the optical properties of minerals. The gem's optic axis is oriented approximately at a 45 degree angle to the table facet thus maximizing the doubling effect seen face up. Though aesthetic for other reasons, this gem lacks the colors exhibited by those cut from twinned crystals such as seen in Figure 8. Note the cleavage marks on the rhomb's surface which distinguish it from a specimen that has been polished and perhaps thus is less desirable if doing so has changed the angles between faces.

contained a single calcite crystal with its *c*-axis/optic axis oriented perpendicular to the curve of the outer surface, thus eliminating any doubling of images except those viewed off-axis while also providing a large depth of field. It is well worth seeking out one of the initial studies which includes the author's photo of a non-doubled smiley face taken through the actual lens of a trilobite's eye (Towe 1973, p. 1008, Fig. 1j). Further research revealed that the lens was actually a doublet and that this orientation in which calcite's refractive index is maximal (1.66) yields "the largest possible relative aperture (and thus optimizing light-gathering)" (Clarksen 1975, p.666), a distinct advantage in low-light ocean environs where the animal must balance snatching prey with not becoming prey! This type of calcite bifocal eye has so far been thought to be unique in nature (for more information, the authors recommend: Gál, et al 2000; Clarkson 1975; Towe 1973).

Navigating home

Another of Nature's wonders is evidenced by some animals' use of polarized light to navigate, including such land-bound insects as the desert ant and dung beetle, but also airborne animals such as the honey bee (Kraft et al. 2011). As a student in apiary science at Cornell University in the early 1980's and later as a bee-keeper, I (EAS) was intrigued by the work of Karl von Frisch, author of *The Dance Language and Orientation of Bees* in which polarized light played a key role (later put to good use by turning my 6th grade science students into little bees practicing the waggle-tail dance to communicate caches of candy to their classroom hive-mates). My interest was piqued by my already long-held fascination with Viking navigation, the Viking sunstone and in understanding polarization and crystals as explained earlier in these pages.

In the last decade, there has been a flurry of interesting scientific papers and popular press, along with Internet buzz, regarding the theories of Viking navigation, including the sunstone (for example, see Horváth et al. 2011). It is hoped that our exploration into the nature of birefringence and the optics of calcite will facilitate the understanding of these discussions, as well as serve as a general reference for students and mineral enthusiasts. While the present authors refrain from going into great detail about the sunstone's actual use (for this, see Karlsen 2003, 2006), we believe a little background into the theory's history from the point of view of a modern sailor is relevant here.

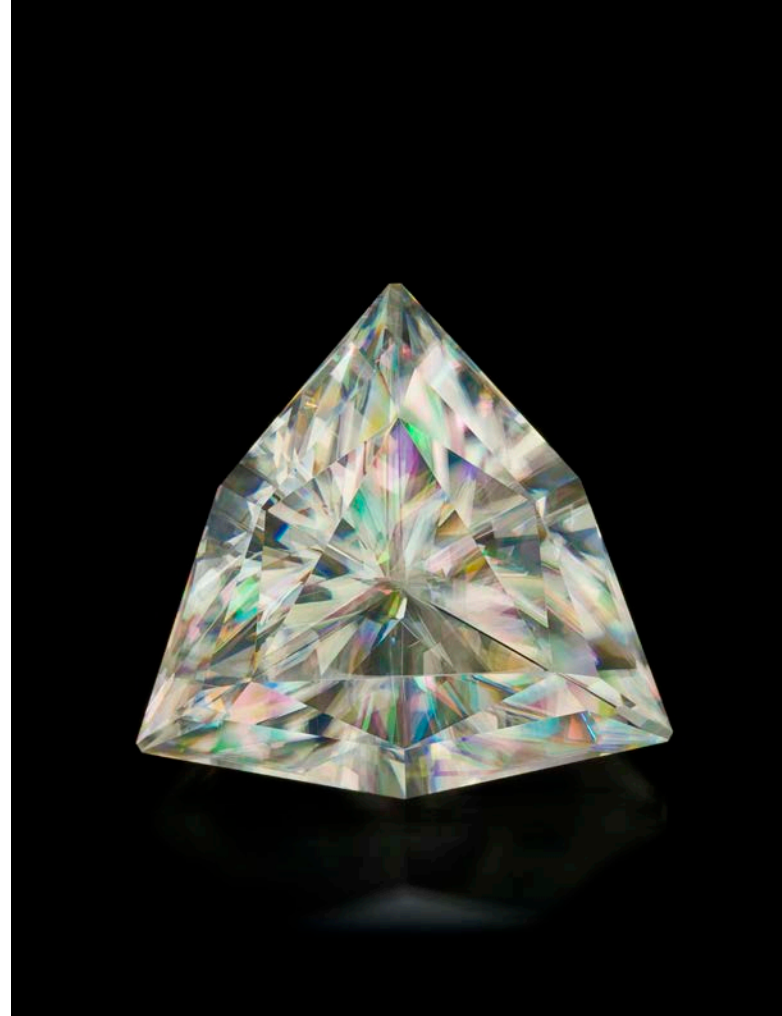


Figure 8: An extraordinary 1,030.50 carat gemstone of twinned calcite, faceted by Jay Medici. 73 mm across x 47 mm deep. Cafarnaum mine, Cerro Cristal, near Corumba, Mato Grosso, Brazil. Terry Huizing collection. Photo: Jeff Scovil.

The theory of a mineral used to locate the hidden sun by the mineral's polarizing properties was first put forth by the Danish archeologist, Thorkild Ramskou, who described it in his books *Solstenen, Primitiv Navigation i Norden for Kompasset* (Ramskou 1969) and *Solkompasset* (Ramskou 1982). He literally coined the expression "Viking Compass" (Vikingernes Kompas) as it is now connected to the mineral cordierite (iolite). The "sunstone" (solstenen) is the historical wording referring to such a mineral which he found in the Sagas, as well as other texts. Though he found these historical references, there was a lack of hard evidence for just how the Vikings might have been able to locate the hidden sun (which would have sometimes been vital to navigation), either as archeological artifacts or detailed directions for their use. Both Ramskou and Leif Karlsen give plausible explanation for this lack of evidence: such a crystal would have been a *very* closely guarded secret skill – literally one's means of survival and not even to be shared with one's captain! Furthermore, Leif was the first to report the finding of a calcite rhomb on a post-Viking era shipwreck (Karlsen

2003, p. 174-176) and it was he “who put the pieces together to first conclude that this particular discovered crystal might have been a sunstone used for navigation” (Burch 2012, p. 3283-3284).

Nomenclature confusion once again comes into this story. The common use of “sunstone” in English refers to several completely different minerals in the feldspar family and is unrelated to the Viking navigation theory. In some translations I have found what I believe is a misinterpretation of “Iceland spar” calcite (“kalspat”, “calkspat” or “calc-spar”) as “feldspar” (“feltspat”) which is then repeated as such in other places, eventually even interpreting it to mean the adventurescent feldspar known as sunstone in English. I have even seen the man-made sunstone simulant, “goldstone” glass, pictured as Viking Compass or sunstone, so one can see where the confusion escalates (“spar” translates to “spat” and vice versa in most Danish and Norwegian dictionaries). Though oligoclase feldspar sunstone is found in Norway, feldspar was never considered as a candidate for the Viking sunstone; extensive twinning and inclusions would have inhibited its usefulness as a navigational instrument.

The notion of the Vikings’ use of polarized light for navigation was an idea sparked by Ramskou’s knowledge of the SAS trans-arctic pilots’ use of a Polaroid based instrument called the Twilight Compass (Kollsmann Sky Compass, Sky Compass or Tussmørke-kompass) to determine the sun’s location. He proposed that a local mineral might have been employed in the same way. Both the strong doubling of calcite and extreme pleochroism of various locally found minerals would have been obvious to anyone examining them – a skilled navigator could have easily surmised the implications for use by just gazing through the mineral and turning it various directions. The choice of iolite is based on its strong pleochroism which can be used to determine the sun’s position; the minerals tourmaline and andalusite have also been suggested for the same reason (Fig. 9). Thorkild Ramskou favored iolite which is found in various regions of Norway, including Kragerø and Arendal. Repeated experiments with

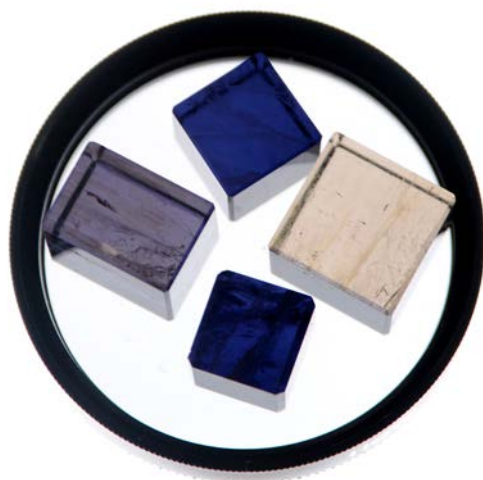


Figure 9: The extraordinary pleochroism of blue cordierite (iolite) has made it a candidate for the Viking Sunstone (see Skalwold and Bassett 2016).

it on a DC-8 flight from Søndre Strømfjord to Copenhagen bore out his theory of its feasibility as a navigational aide. Interestingly, “a type of sky compass incorporating Iceland spar was invented by Ch. Wheatstone in 1848 and later improved on by others. Some models are illustrated in one of the series of papers on polarized light published by W. Spottiswoode in *Nature* ca. 1874, later in book form” (Dr. Leo Kristjansson, personal communication 2008).

In contrast to Ramskou, Leif Karlsten later made a very strong case for Iceland Spar in his 2003 book. Leif was a professional navigator in the Merchant Marines with, as the title of his book suggests, a fascination for Viking navigation. His proposed technique is premised on the ready availability of optical quality calcite in Iceland which can even be found in the surface scree and which relies on this mineral’s high birefringence. He devised a plausible scenario as it might have happened more than 1000 years ago and which he found to be extremely accurate. According to Leif’s research, the type of mineral was never identified in the Sagas, only that it could be used to find the sun and that it was deemed a valuable possession. Sunstones were even found listed in the old Icelandic Church asset records. Some examples from the Sagas:

St. Olav’s Saga: “A stone with which one could see where the sun was in Heaven;” the Flatelyrjarbók: “King Olav (later made Saint) was taught the use of finding the sun with a sunstone;” the Sturlunga Saga: “When Bishop Godmund and Hrafn Sveinbjarnarson came back to Iceland, after having been one winter in Norway, Hrafn sailed west to Arnarsfjord, to his farm in Eyri, now called Hrafnseyri. But before they parted Bishop Gudmund gave Hrafn a good stud horse and a sunstone.” (Karlsten 2003, pages 77-78).

The Vikings reached their destinations by latitudinal sailing, that is to say they sailed in straight east-west courses. They used a myriad of navigational clues and techniques to hold to this kind of course, such as observation of sea-birds, waves, stars and the sun. Leif found that with the help of a calcite sunstone and a

“bearing board,” very accurate determinations of latitude could be obtained. He explains that a particular course was named by its end-points: if a voyage started at Stad, Norway and ended at Torshavn in the Faeroe Islands, then this latitude of approximately 62 degrees was called “Stad-Torshavn.” This was a distance of 332 nautical miles at an average speed of 6 knots. Stad, though located in waters which were known to be very often dangerous, was chosen because it was at the correct latitude to reach Torshavn. To reach Iceland from Stad, they first headed North along the Norwegian coast before turning west on a line to Horn, Iceland (Karlsen 2003, p. 59). Having been to Torshavn, I can say it would be a very skilled navigator who could hit that small rock dead-on as it rises up high out of the sea! It is a very beautiful place right out in the middle of what looks like empty ocean. The island is covered with colonies of seabirds nesting on its sheer cliffs. Once close enough, on a clear day perhaps the crew could see the islands in the distance and find the birds, but never in a fog.

Leif writes:

“When very cold air moves over warmer water, wisps of visible water vapor may rise from the surface as the water ‘steams.’ In extreme cases this frost smoke, or Arctic sea smoke, may rise from a few feet to a height of several hundred feet. The portion near the surface forms a dense fog which obscures the horizon and surface objects, but usually leaves the sky relatively clear.” (Karlsen, 2003, p. 76)

I have travelled by sea in the end and beginning of Winter in the waters around Iceland, the Faeroes and North Norway, as well as Lake Ontario and can say that this description is very accurate. The effect is surreal – rocky islands rise up suddenly out of the mist and clamorous birds fly around nearby out of sight. The mist swirls in phantasmagoric shadows and all the while the sky above is blue. It is in these conditions when such a polarizing device would be useful (see Fig. 10). As a youth, I practiced this with my father, not with calcite, but using polarizing filters instead. Like Leif Karlsen, he was a navigator and sailor interested in the possible techniques used by the Vikings. We were both thrilled

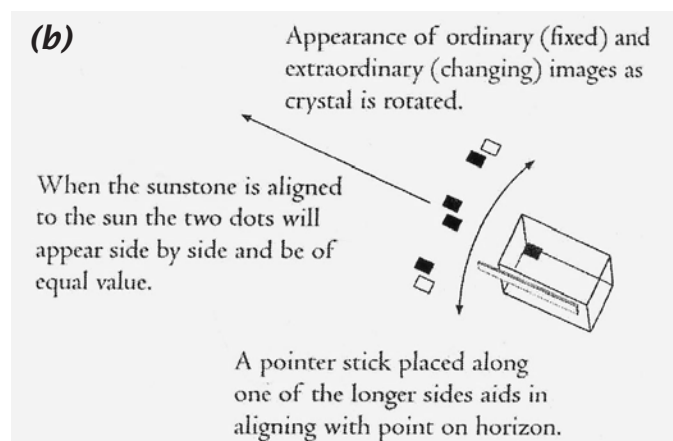


Figure 10a: The author (EAS) with a calcite cleavage rhomb and following the experiments of Leif Karlsen outlined in his book *Secrets of the Viking Navigators* (the rhomb is polished, but its angles are correct). Leif’s drawing in **10b** illustrates the observation he used to detect the location of the sun when it is very low on the horizon and obscured by fog as is often the case in the cold waters of the arctic and subarctic ocean. The view presented is that of above the calcite, but it is “read” from below as in **10a**; in either case, the key observation is that of the equal intensities of doubled images (center). Leif devised an ingenious stand for using the sunstone; one which his Viking ancestors probably didn’t think of. Because the stone had to be “read” from below and, at the same time held level, he built a rotatable stand which employs a mirror so that the viewer need only hold it out in front and look down into the image reflected below the stone (Karlsen 2003, p.80; drawing reproduced with permission of Starpath Publications, www.starpath.com) Photo by James H. Edwards.



Figure 11: In the summer of 1995 the author (EAS) had the opportunity to experience life aboard a Viking longboat while on day trip in the Sandefjord aboard “Gaia,” an exact reconstruction of the Gokstad Viking ship unearthed from a barrow in the nearby Viking-rich area of Vestfold, Norway, the ancestral home of her own relatives. Photo: Kyle Arlen Edwards.

to talk to museum curators in Horten, Norway in 1972 about the sunstone, a subject we explored frequently since that time, welcoming Leif Karlsen’s book gleefully when it was published. As a navigation instructor, my father also believed in understanding many different and mutually confirming methods for accurate navigation; a trait shared by sailors over millennia and which served him well crossing the Bay of Fundy in a fog so thick the bow of the boat was hardly visible, successfully arriving just exactly where he expected to (without GPS or LORAN). That ancient Viking mariners made such voyages sans modern instrumentation inspires awe in many, not least of all me, as I have traveled in those waters in more modern craft, as well as been out on a replica of a cabinless sea-faring longboat (Fig 11). For a glimpse into the Viking sea-faring world, the authors recommend *The Far Traveler: Voyages of a Viking Woman* by Nancy Marie Brown, but in regards to the sunstone, beware the typo which identifies it as “Icelandic feldspar” (Brown 2011, p. 26).

While the historical existence of a sunstone (as well as how the Vikings may have used it) has been enthusiastically debated since Thorkild Ramskou first published his books, the theories he and Leif Karlsen propose offer an exciting way to explore the optical properties of birefringent minerals. In my case, the Viking sunstone has revealed the route into the fascinating world of optical mineralogy and a greater appreciation of minerals!

Figure 12: The original Iceland spar crystal with which Leif Karlsen tested his theory of Viking navigation, as described in his 2003 book *Secrets of the Viking Navigators*. 65 x 45 x 35 mm; origin: Iceland.

Acknowledgments

This article is dedicated to the memories of Robert N. Skalwold, Leif K. Karlsen and Art Grant who all knew just what to do with a chunk of optical calcite. Deepest gratitude to Dr. David Burch of Starpath Navigation School of Navigation for support since 2008 in exploring Karlsen’s theory of navigation and for continued collaboration in educating about Karlsen’s tremendous contribution to understanding Viking Navigation. Elise Skalwold thanks her co-author Dr. William A. Bassett, Dr. Mickey Gunter, and Darko Sturman all for years of insightful and inspirational dialogue surrounding optical mineralogy. Many thanks to James H. Edwards and Betty & David N. Kobernuss, Sr. for careful copy-editing and to Dr. Carl A. Francis, Dr. John Rakovan, *Rocks & Minerals* Editor-in-Chief Marie E. Huizing and Smithsonian National Mineral and Gem Collection Emeritus Curator-in-charge John S. White for their enthusiastic encouragement to publish this paper.



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The Last Page

A Quartz & Calcite Enigma



Three quartz crystals whose growth is thought to have been influenced by that of calcite, though the exact genesis of these crystals remains a mystery. Compare their forms to that of the prismatic calcite specimen in Figure 5 and shown on the back cover.

Origin: Bor Pit, Dalnegorsk B deposit, Dalnegorsk, Kavalero-vo Mining District, Primorskiy Kray, Far-Eastern Region, Russia.

Top left, 55 x 60 mm; middle left, bottom left and bottom center: 25 x 85 mm, both specimens are in the author's collection (EAS); at right and bottom right: 20 x 50.5 mm, John S. White Collection. Photos: Elise A. Skalwold.



Elise A. Skalwold is an Accredited Senior Gemologist and author involved in research and curating with her co-author at her alma mater, Cornell University (B.Sc. 1982). Her primary interests are inclusions, optical mineralogy, and crystallography. Currently serving as Consulting Gemological Curator in the Earth and Atmospheric Sciences Department, she is a Graduate Gemologist (GG), trained in residence at the Gemological Institute of America (GIA) Robert Mouawad Campus located in Carlsbad, California. While living in Thailand she worked in the famous gem markets of both Chanthaburi and Bangkok and pursued studies at the Gem & Jewelry Institute of Thailand (at that time part of Chulalongkorn University) for which she was subsequently elected a Fellow of the Gemmological Association of Great Britain (FGA). She is an active member of the Society of Mineral Museum Professionals (SMMP), a world-wide network linking curators from large and small institutions from which members draw on combined expertise.

As well as having co-authored with Dr. Bassett the 415 page book *The Edward Arthur Metzger Gem Collection* and presently working on a companion volume to it, Ms. Skalwold is an author/co-author of gemology and mineralogy papers featured in *InColor*, *Gems & Gemology*, *The Journal of Gemmology* and *Rocks & Minerals*. The 2014 article “The Microworld of Diamonds: Images from Earth’s Mantle,” co-authored with world-renowned photomicrographer and gemologist John I. Koivula, recently won the 2014 Best Article of the Year Award for the prestigious publication *Rocks & Minerals*. She serves as Contributing Editor for “G&G Micro-World” (a quarterly column exploring inclusions found in minerals and other gem materials) which premiered in the Summer 2015 issue of *Gems & Gemology*, the peer-reviewed scientific journal of the GIA.

Passionate about gemology, she is actively involved in bringing this science into a university setting for the benefit of students and non-students alike – this is the quintessential theme of her paper “Scholarly Treasure: The Role of Gems in a University Setting,” presented at the 2013 GIA-sponsored first-ever Gemological Session of the Geological Society of America (GSA) 125th Anniversary Annual Meeting. Her speaking engagements have recently included the New York Mineralogical Club (co-founded by George F. Kunz in 1886), the 40th Annual Rochester Mineralogical Symposium and the 11th Annual Sinkankas Symposium [Ruby] held at the Gemological Institute of America in Carlsbad, California.

Meet the Authors



The authors prepare the teaching cart for visitors of the Timothy N. Heasley Mineralogy Museum in the Earth & Atmospheric Sciences Department, Snee Hall, Cornell University.

William A. Bassett, PhD, is Professor Emeritus in the Department of Earth and Atmospheric Sciences, Cornell University, where he taught courses in mineralogy and crystallography. After receiving his PhD in Geology in 1959 at Columbia University he conducted research in geochronology in the Department of Chemistry at Brookhaven National Laboratory. In 1961 he took a position as Professor of Geology at The University of Rochester where he conducted research to determine the properties of materials at high pressures and temperatures to provide a means for a better understanding of the composition and physical characteristics of minerals in the Earth’s interior. In 1978 he joined the Department of Geological Sciences (later to become the Department of Earth and Atmospheric Sciences) of Cornell University where he studied not only the properties of minerals, but analyzed specimens brought to the surface from deep within the Earth’s interior.

As well as being one of the pioneers of diamond anvil cell (DAC) high pressure research, in 1994 Dr. Bassett received the Roebling Medal for his work in mineralogy; the highest award of the Mineralogical Society of America for scientific eminence as represented primarily by scientific publication of outstanding original research in mineralogy. He received the Bridgman Award, given by the International Association for High Pressure Research and was awarded a Guggenheim fellowship for study abroad. He has been a visiting professor at the University of Paris, MIT, and Brigham Young University.

Since retirement in 2000 he continues to serve Cornell as Curator of Geologic Collections. As one of the founding members, Board Chairman, and Advisory Board member of the Sciencenter of Ithaca, he has contributed to the designing and building of exhibits and the many other hands-on experiences offered to visitors young and old. Today he continues his research in high-pressure studies and makes diamond anvil cells for sale to high pressure-temperature researchers the world over.

As both a witness to and a participant in the long history of the diamond anvil cell and the impact which it continues to have, Dr. Bassett was invited to share his insights into this unique instrument with his 2009 paper “The Diamond Anvil Cell, 50th Birthday,” published in *High Pressure Research*, 29, 163-18 and freely available at: <http://www.compres.us/files/bassett/50%20Years%20DAC%20Hist.pdf>.



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