Rotating Variable Retardation Filter: A Modern Version Of The Victorian Selenite Stage

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Polarization colors were popular with 1860s microscopists and 1960s counter culture youth alike. They still grab your attention (Figure 1), and there is no easier way to produce a splash of color than with a Victorian selenite stage, a 19th Century amateur microscopy device consisting of a stack of rotating birefringent filters. A selenite stage dramatically alters polarization images: backgrounds shift from black to the colors of Newton's interference scale, and go through an ever changing series of colors as the filters rotate. To paraphrase Mark Twain, no other apparatus provides such wholesale return of color for such a paltry investment in equipment.

The selenite stage has always had more of art than of science about it. Although it has features in common with rotary compensators, it is uncalibrated, and retardation varies in a complex manner. It is not what you would use to determine birefringence, but not all uses of polarization need to be quantitative. I had some 1/4 wave and full wave retardation film left over after adapting some classroom biological scopes for polarization, and thought a simplified selenite stage would be a fun way to use it. In this article I describe the stage, its range of retardation colors, and show how the 1/4 wave portion can be used for a bonus feature: circular polarization. Examples from my favorite area of study – marine geology and micropaleontology – illustrate the qualitative use of polarization to provide punchy colors, increase contrast, and assist in seeing and understanding structural detail.

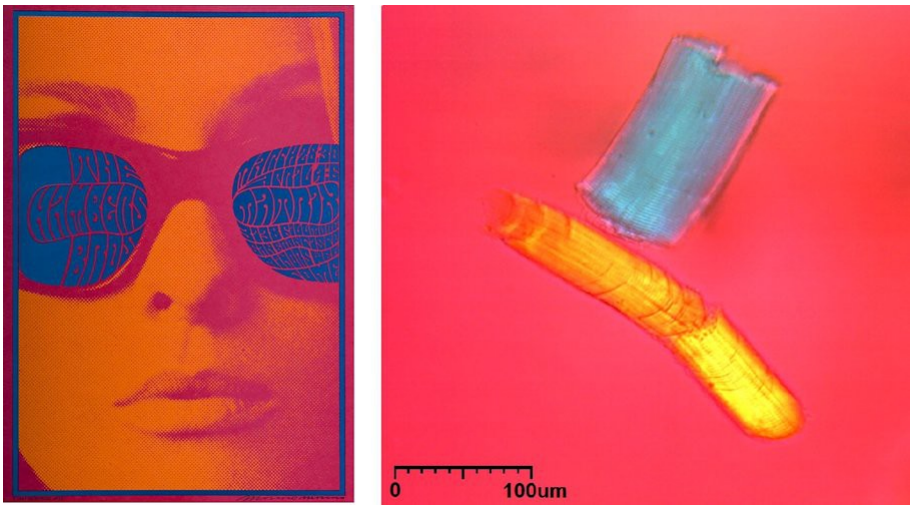
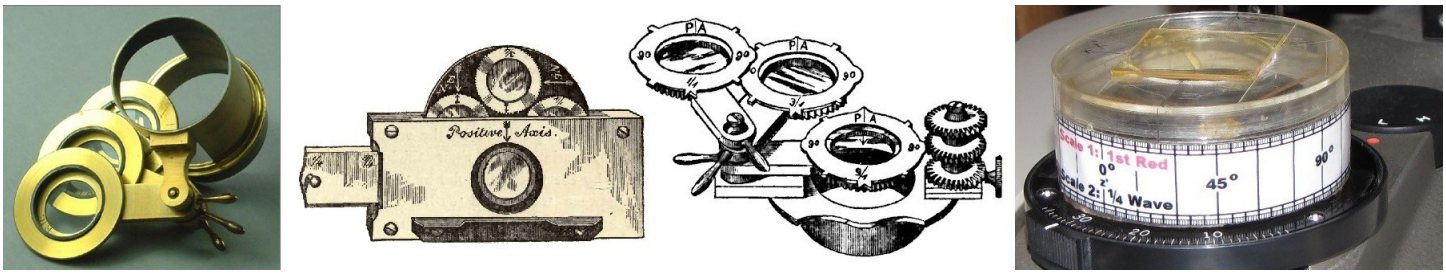


Figure 1. *Polarization colors.* ***A:*** *Sixties psychedelic art. "Neon Rose #12", an iconic 1967 poster by Victor Moscoso that gains impact from its use of polarization 1st order red colors (called "vibrating colors" by the artist). Text reads (in part): "The Chambers Bros. Matrix. San Francisco."* ***B:*** *Fluid whole-mount of striated muscle fiber viewed with the variable retardation filter described in this article. Specimen and background are colorless in normal light; Example 1 explains the optical origin of the colors. Fig. 1A is copyrighted by Victor Moscoso; it is reproduced in accordance with copyright fair use laws for discussion of a work of art. Originals of this poster are available here.*



A B C D

Figure 2. *Selenite stages.* ***A.*** *Victorian selenite stage sold on eBay a few years ago. The filters can be individually inserted in the light path and rotated. This design was called "Darker's selenites".* ***B.*** *Swift's selenite stage was placed on the microscope stage under the specimen.* ***C.*** *A design with gears to rotate the filters. Retardations are 1/4, 3/4, and 9/4 wavelengths (all odd quarters give circular polarization).* ***D*** *is the variable retarder described in this article, shown on the light exit window of an Olympus BH polarizing microscope. It has birefringent plastic filters of 1/4 wavelength and 1 wavelength. Rotation scales allow settings to be repeated. B and C are from Davis (1882).*

Polarized Light Background Information

Many ***Micscape*** readers are familiar with polarized light, so rather than go over familiar ground, I'll refer those who wish a refresher to Davidson and Others on the Molecular Expressions optical microscopy website. The polarization section begins here; the section on retardation plates and variable compensators is here. I also recommend Delly's (2003) article on the Michel-Lévy interference color chart.

Two related terms need to be defined. **Birefringence** is the difference between maximum and minimum index of refraction; it is constant for a given material. **Retardation** is a linear offset; it is the distance two components of a light beam are out of phase due to passing through a birefringent material. Retardation is the product of birefringence and specimen thickness. In a given material, greater thickness gives greater retardation. Retardation is cumulative, and is the algebraic sum of the individual retardations of all the birefringent objects the light beam passes through.

Ian Walker's (2006) ***Micscape*** article on a do-it-yourself Berek tilting compensator covers related ground to this article; Gordon Couger's (2007) follow-up article discusses splitting mica to make retardation filters. Walker's tilting compensator operates on a different principle from the rotating compensator described here, so the devices affect images differently. An advantage of the selenite stage is that it fills the field of view with a uniform color. Brian Johnston's (2005) ***Micscape*** article uses a setup functionally equivalent to this variable retardation filter, although it has fewer adjustments, and with three major brand name retardation plates, it is a lot more expensive (perhaps 50 times the price).

Retardation And The Newton Interference Color Scale

Figure 3 shows the colors obtained with varying amounts of retardation; these are the colors you see in oil slicks, soap bubbles, and polarized light. This scale, when combined with additional data on specimen thickness and birefringence, gives us the Michel-Lévy chart – a graphic solution to a 3-variable equation: know 2 variables, find the third.

The first 2 orders have intense colors; at higher retardations, colors repeat and become increasingly muted. The higher order colors don't make good backgrounds. A variable retardation filter with 2 orders of retardation is sufficient if your main interest is colorful backgrounds and increased specimen contrast.

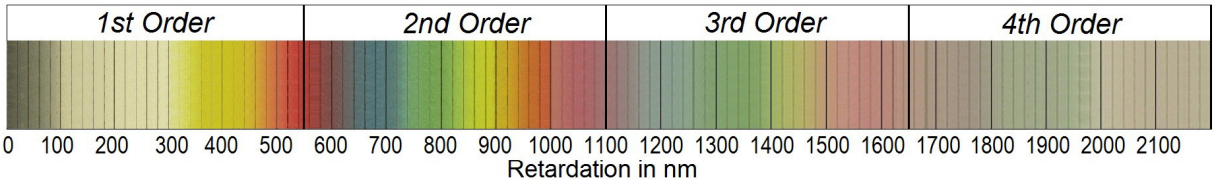


Figure 3. *Newton Interference Color Scale adapted from Michel-Lévy's original color chart of 1888. Boundaries between orders are at intervals of 1 wavelength (550 nm).*

Example 1: Origin of the colors in Figure 1B

Figure 1B is an elementary exercise familiar to everyone who works with the polarizing microscope. You see these colors often – whenever low retardation specimens are combined with a 1st order red plate. In Figure 1B, the filter is set to a little less than 1st order red (about 500 nm, 0.9 wavelength), giving a rose instead of magenta background. This flexibility to pick your retardation (and color) is an advantage of the selenite stage. Figure 4 shows how the blue and yellow colors originate from addition and subtraction of component retardation. The sample is a thick mount of beef muscle fiber in fluid. The sample is colorless; colors in the image are the result of optical interference in the microscope.

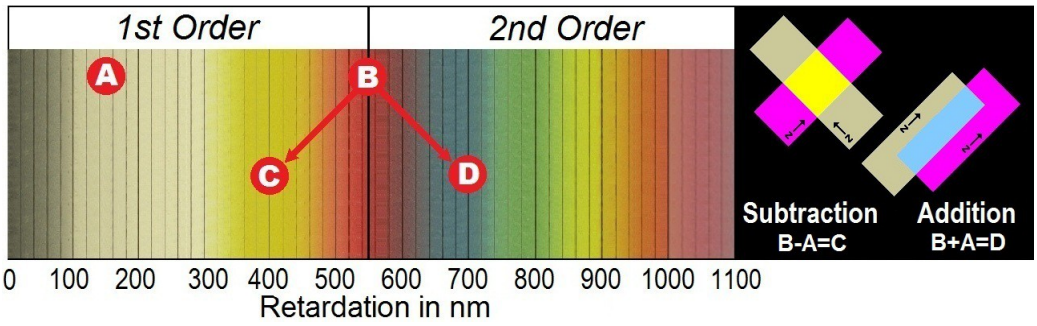


Figure 4. *Action of a 1st Order Red Plate. Under cross-polarized light, the background is black. **A:** a specimen with retardation = 150 nm appears gray. **B:** Overlap the specimen with a second specimen (or retardation plate) having a 1st order red retardation = 550 nm. **C:** If the two specimens have their slow directions (Z ⟶) crossed, their retardations **subtract**. 550 – 150 = 400 nm, a 1st Order yellow. **D:** If, on the other hand, the two specimens have their slow directions aligned, their retardations **add**. 550 + 150 = 700 nm, a 2nd Order blue.*

Design Of A Multi-Plate Variable Retarder

Figure 5 is a schematic for the variable retardation filter. There are only two requirements: 1) you need polarized light, and 2) the retardation filter and specimen must both be between the polarizing filters. On-line dealers offer polarizing and retardation plastic film at low cost. The material I purchased is no longer available, but one current source is Knight Optics (link). 25 to 50 dollars/Euros/pounds buys enough polarizing and retardation film to outfit a couple of scopes. Ian Walker's ***Micscape*** article and Gordon Couger's follow up tell you how to split mica to make your own retardation plates.

The body is a circular plastic box selected because it is a good fit for the light exit window of my Olympus BH pol scope (Figure 2D). The box bottom was removed, and a large hole cut in the lid, so the plastic box doesn't affect the light path. The base and lid freely rotate 360°; the retardation plates can be rotated independently or together. A computer-printed scale shows degrees of rotation, and allows settings to be repeated; placing both scales at 0° puts each filter's z-direction North-South.

Determining The Value Of Retardation Film. Inexpensive or home made films have a degree of latitude, and you don't always know just what you have. Use the colors to determine values. For example, my retardation film was sold as "**1/4 wave (140 ± 20 nm)**" and "**full wave (560 ± 25 nm)**". You expect the combined filters to have about 700 nm retardation (140+560). This is a 2nd Order blue (Figure 3), but the filters actually reach a higher retardation 2nd Order green. By observation, the minimum subtractive retardation is about 420 nm (1st Order yellow), and the maximum additive retardation is about 740 nm (2nd Order green). A little algebra gives the values of the filters:

$$x - y = 420$$
$$x + y = 740$$

These equations solve to give retardations of 160 nm and 580 nm. These values are the high end of the factory specification, but in this case, that is a good thing; it adds an additional color (green) to the variable retardation filter's range.

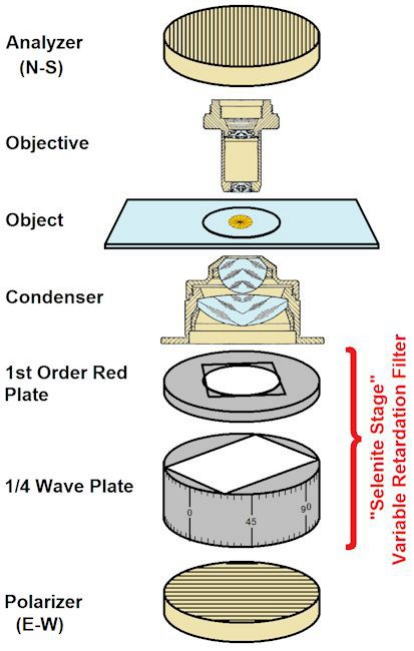


Figure 5. *Schematic diagram of variable retardation filter.*

Colors Produced By The Filter. Figure 6 shows examples of the colors available from superimposing 1/4 wave and full wave rotating filters. Some images have subtractive retardation (yellow specimen); others have additive retardation (blue or green specimen). For higher retardation values (and additional colors), add a third filter to the optical system. I put a 1st order red plate in the accessory slot of my polarizing scope, but you could also lay another retardation film on top of the variable retardation filter stack.

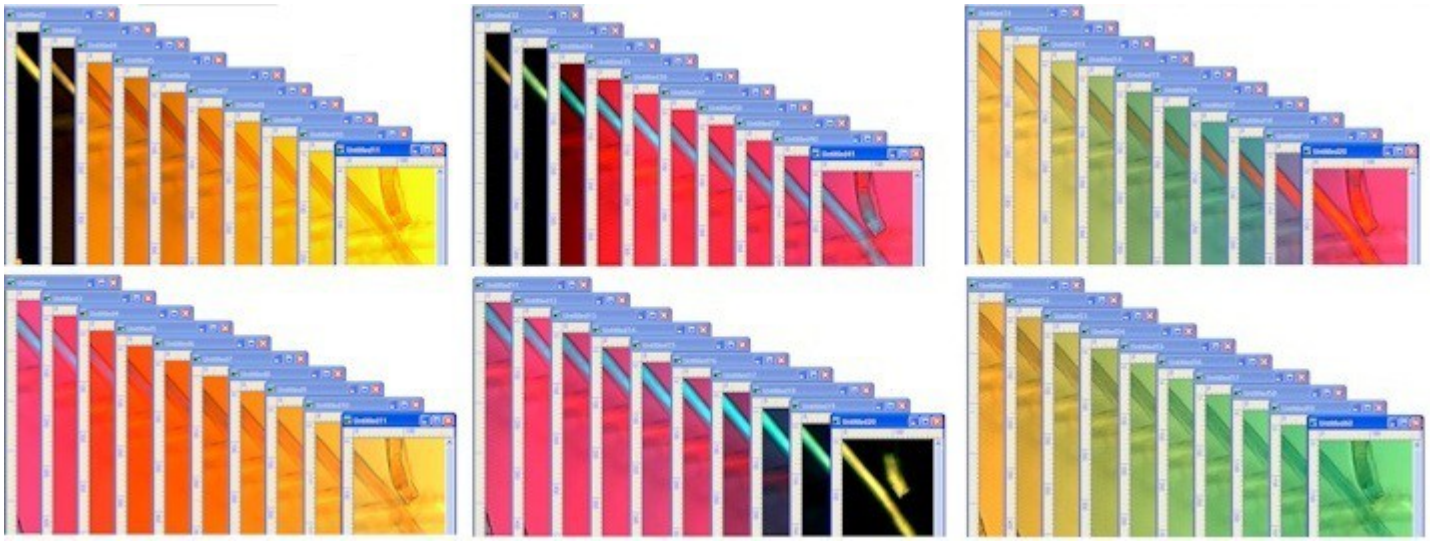


Figure 6. *Examples of colors produced by the variable retardation filter when one component is stationary, and the other component is rotated in 5° steps.*

Circular Polarized Light (Benford Plate)

Setup (see Craig, 1961). The 1/4 wave portion of the variable retardation filter is set at 45º; this changes linear polarized light to circular polarized, and is known as a Benford Plate. A matching 1/4 wave plate above the specimen is set at right angles to the first filter; this changes circular polarized light back to linear polarized (Figure 7). The background remains black, but the light beam in the vicinity of the specimen has circular polarization.

Benefit 1: Increased Contrast. Colorless particles with an index of refraction close to the mounting medium are nearly invisible in plain light. This examination method uses polarization to add contrast to particles that also happen to be birefringent.

Benefit 2: No Extinct Particles. A birefringent particle rotated in polarized light usually goes extinct (that is: dark) once every 90°. An extinct particle is invisible – not a good situation if you're counting particles. Without going into detail, the configuration in Figure 7 is a special case where extinction does not occur; the background is dark and birefringent particles remain bright as they rotate. In a strew of randomly oriented birefringent particles, all are visible (except for the rare case where a birefringent object appears to be isotropic due to its optic axis orientation).

Benefit 3: No Pseudo-Extinction Crosses. Foraminifera with radial calcite walls have pseudo-extinction crosses that look like the interference figures seen on the back of the objective with a Bertrand lens, but they are on the specimen itself (Examples 3 and 6). Coccoliths show related effects because they are formed from overlapping components, each of which is a calcite crystal (Example 4). Extinction and pseudo-extinction effects provide useful information, but they can obscure surface detail. Circular polarization with a Benford Plate removes these effects.

Benefit 4: Simplified Interference Figures. This is the purpose for which the Benford Plate was originally designed (Craig, 1961).

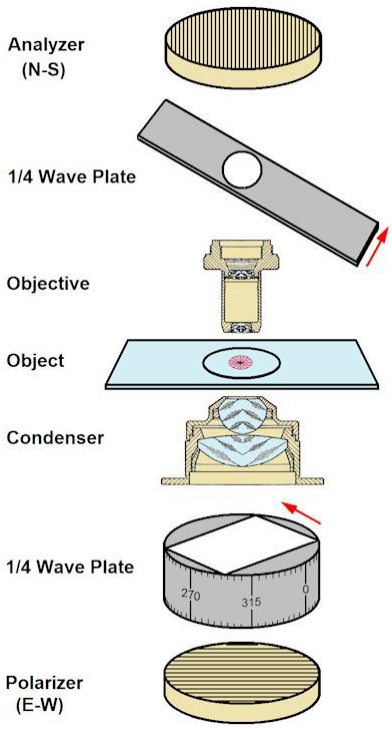


Figure 7. *Circular polarized light.*

Example 2: Cambrian siliceous oölite from Centre County, Pennsylvania, U.S.A.

Figure 8. *"State College" siliceous oölite from the Mines Member of the Gatesburg Formation (Late Cambrian, about 500 million years before Present).* ***A.*** *slide.* ***B, C,*** *and* ***D****. Three fields of view through a 2.5x plan objective. The top row is plane-polarized; the middle row is cross-polarized; the lower row uses the variable retardation filter.*

Figure 8 is a British Victorian mount I purchased on eBay. It probably dates from around 1890-1900, because "Trenton Period" was out-of-date terminology for this sample shortly after that time. The preparer is unknown, but another example of his/her work is this zircon syenite slide on the Victorian Microscope Slides website. The oölite is from a well-known collecting locality now lost to urbanization in the town of State College, Pennsylvania.

This siliceous oölite is a 500 million year old sample from a world strangely different from today. There was no Atlantic Ocean; State College, PA was next door to Scotland, and both were south of the equator in a tropical carbonate bank similar to the present day Bahamas (but without the palm trees; life on land had not yet evolved). Hugh Mitchell-Tapping's (2010) ***Micscape*** article shows modern Bahaman oöids, complete with palm trees.

For years, the "State College" siliceous oölite was one of the interesting little puzzles of geology. Present-day oölites develop in carbonate environments. Did a different chemical environment in the ancient sea allow primary deposition of siliceous oölites? At first, the majority opinion was "yes", but geologists now believe this is an ordinary carbonate oölite that was replaced by silica at some later time. Moore (1912) and Choquette (1955) discuss this oölite.

Figure 8B is a typical oöid with concentric laminated shells surrounding a core seed particle. In this case, the core is a sand grain weathered from a multi-crystalline quartz rock. The concentric shells formed as carbonate, but were replaced by silica. Figure 8C shows two oöids, each with a weathered and rounded single quartz crystal as its core. Figure 8D shows an interesting phenomenon: regeneration of lost crystal shape. Sand-size quartz crystals were rounded by water action before being incorporated into oöids. Later, at the time of silica replacement, newly precipitated silica followed the existing crystal lattice of the rounded sand grains, and rebuilt well-formed crystal shapes, seen as dark hexagonal outlines. Henbest (1945) first published on this process.

Example 3: Foraminiferal Wall Composition, Mineralogy, And Structure

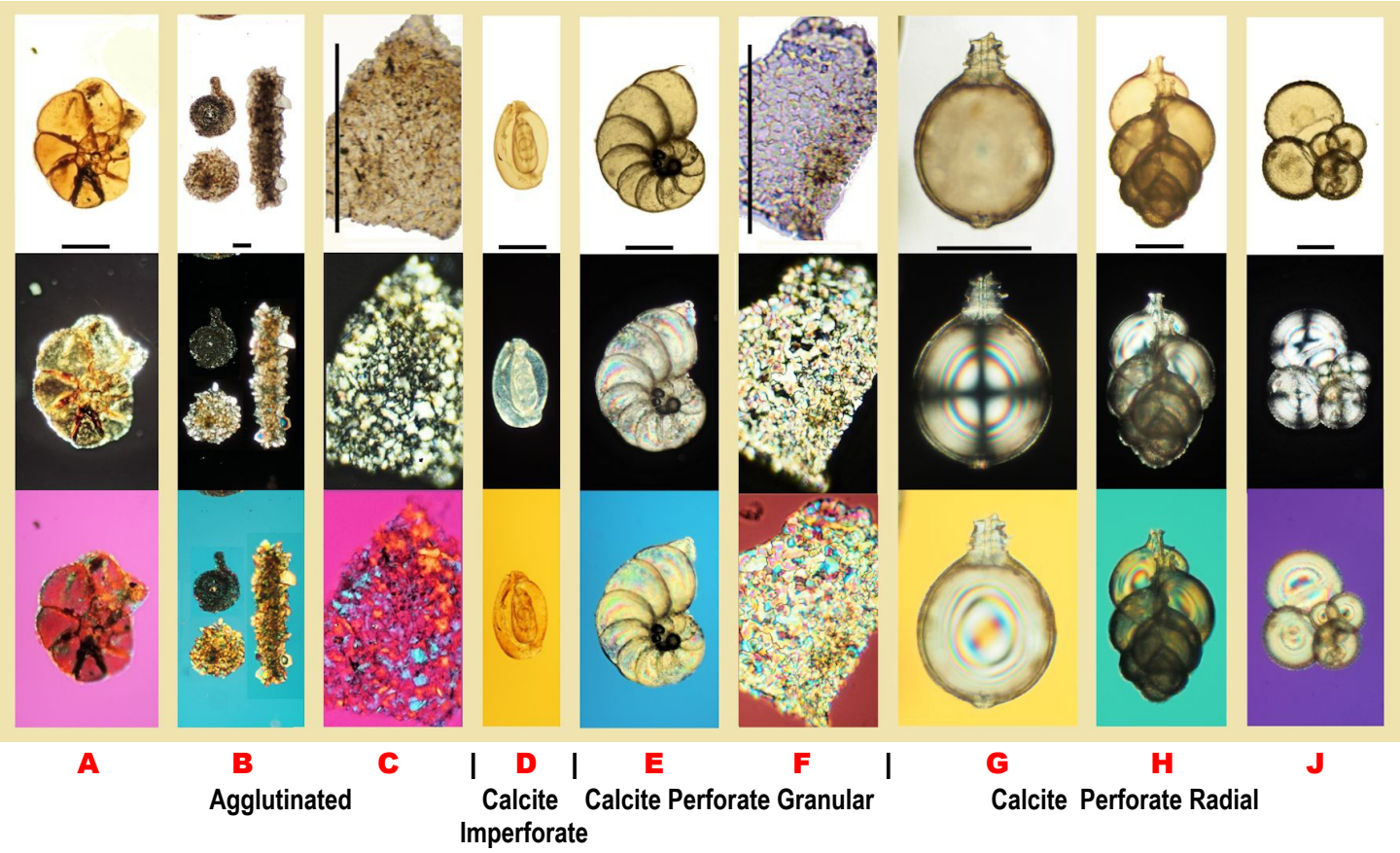


Figure 9. *Foram wall structure. The top row is plane-polarized; the middle row is cross-polarized; the lower row uses the variable retardation filter. Images were taken with 4x, 10x, or 20x objectives; bar scales are 0.1 mm (100 µm). Specimens are from a wide range of sample locations and ages.* ***A.*** *Jadammina.* ***B.*** *Late Devonian (360 million years before Present) agglutinated forams.* ***C.*** *close-up of Textularia wall fragment.* ***D.*** *Spiroloculina.* ***E.*** *Nonion.* ***F.*** *close-up of Chilostomella wall fragment.* ***G.*** *Lagena.* ***H.*** *Uvigerina.* ***J.*** *Globigerina.*

The polarizing microscope highlights differences in foram wall structure, an important attribute used in classification. Figure 9 shows the common wall types; there are a few others including organic, micro-granular (fusulinids), aragonitic, and siliceous.

The **agglutinated** (also called **arenaceous)** wall consists of particles gathered from the environment and bound together in an organic matrix. Figure 9A is a weakly agglutinated species whose test (shell) is mostly organic. The high magnification view in Figure 9C shows that the wall components are separate from one another and are bound together by a matrix, making this wall structure analogous to a sedimentary rock.

The **imperforate calcite** (also called **porcelaneous**) wall consists of secreted small calcite spicules randomly packed at various orientations. This randomness scatters polarized light, giving the dark gray color seen in Figure 9D.

The **granular calcite** wall is secreted by the organism. It has clusters of crystals at different orientations, giving an overall granular appearance. The high magnification view in Figure 9F shows that the crystals grew in place, interlocking with one another, making this wall structure analogous to an igneous rock.

The **radial calcite** wall is secreted by the organism, but in this case, crystals in a chamber are arranged radially so they act as a unit and produce distinctive pseudo-extinction crosses. The more spherical the chamber, the more perfect the cross.

Example 4: Nannofossil In Circular Polarized Light

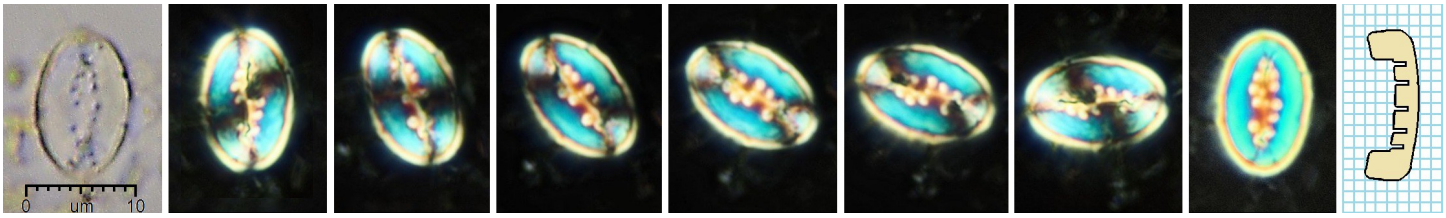


Figure 10. *Nannoplankton* Pontosphaera distincta*. 100X oil immersion objective; bar scale is 10 µm.* ***A.*** *plane polarized.* ***B-G.*** *Cross-polarized at various angles of rotation showing movement of the extinction lines.* ***H.*** *circular polarization, which removes the extinction lines.* ***J.*** *Schematic using thicknesses from retardation color. Grid is 1 µm squares.*

Figure 10 is the calcareous nannoplankton genus *Pontosphaera* (called *Discolithus* in some older publications). This specimen has just the right thickness to develop good retardation color – not too thin, and not too thick. Most small calcareous nannoplankton have low 1st order gray retardation because they are so thin. But if too thick, the high birefringence of calcite quickly pushes retardation color off the chart into the "high order whites". It takes a thin piece of calcite to drop retardation to the 1st and 2nd orders, and that is what we have with this nannofossil. It is from the Alhambra Shale near Martinez, California; its age is Middle Eocene (about 40 million years before Present).

Figures 10B-G show the specimen in cross-polarized light at various angles of rotation. A single crystal would go extinct somewhere in this 90° rotation, but that doesn't happen. The scanning electron microscope image in Figure 11 of a related species shows why: this is not a single crystal, but a large number of oriented overlapping crystals whose dimensions are below the light microscope's resolution. Crystal orientation follows the periphery of the specimen; there is always a group of crystals at extinction position. As the specimen rotates, a different group comes into extinction, causing the dark extinction lines to move, but not to go away.

Figure 10H uses the setup of Figure 7 to obtain **circular polarized light**. This removes the extinction lines and makes it easier to see what is structural on the surface of the specimen. The extinction lines are diagnostic and need to be seen; the circular polarized view is a useful supplemental image. At these high magnifications, diffraction is taking over the light microscope image; we have the same effect you see when viewing diatom punctae. A slight focus change moves from "white dot focus" to "black dot focus", and it is difficult to know if you are looking at a bump or a pit.

Retardation colors were converted to thickness with the Michel-Lévy chart. Values for calcite are:

2nd order blue = 4 µm thick
1st order red = 3 µm thick
1st order yellow = 2 µm thick

These values were used to sketch the approximate cross-section shown in Figure 10J. If you want to know what this nannofossil really looks like, the scanning electron microscope reveals all.

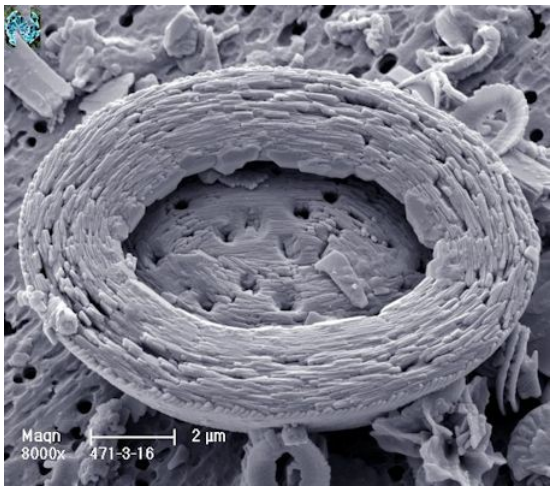


Figure 11. *Scanning electron micrograph of a related species,* Pontosphaera multipora*. Photo by Jeremy R. Young, Natural History Museum, London. From Nannotax on-line database.*

Example 5: *Braarudosphaera bigelowii*

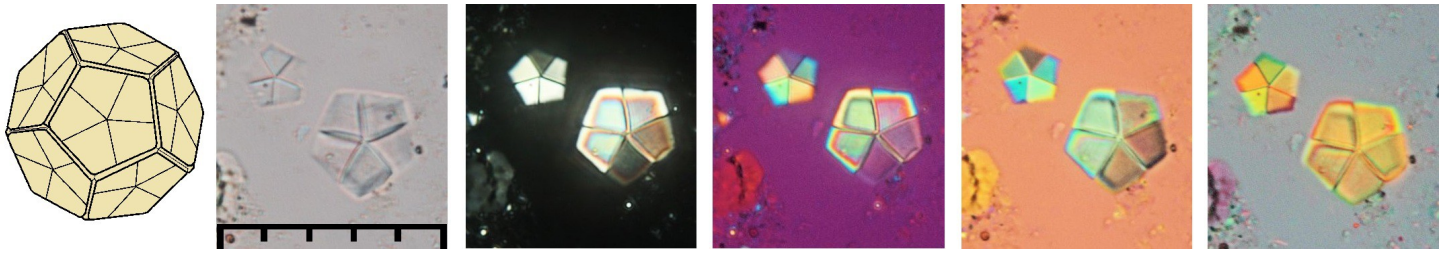


Figure 12. *Braarudosphaera bigelowii. Pentaliths from two individuals, one large, one small. 40X high dry objective; bar scale is 50 µm.* ***A.*** *Schematic of an entire algal cell.* ***B.*** *Plane-polarized light.* ***C.*** *Cross-polarized light.* ***D.*** *Cross-polarized with variable retardation filter at 1st order red.* ***E.*** *and* ***F.*** *Other settings of the variable retardation filter.*

Braarudosphaera bigelowii is a calcareous phytoplankton species that is interesting on several points. First of all, it has an unusual shape for a living organism (Figure 12A). It secretes a protective casing of 12 calcite pentagons (called pentaliths) that join along their edges to form a regular dodecahedron. It looks as much like a crystal as a living organism.

Secondly, it has a very long geologic range from the Late Cretaceous to the Present. Can a species from the time of the dinosaurs still be living? Maybe, but probably not. The fossilized hard parts haven't changed through more than 70 million years, but one suspects the soft parts and DNA probably have changed. So, if our present-day *B. bigelowii* species didn't swim with the dinosaurs, its ancestor species – which looks just like it – did.

Another interesting point: *B. bigelowii* algal blooms can be a sign of ecological hard times. *B. bigelowii* tolerates degraded marine conditions such as low salinity better than most other calcareous phytoplankton. When stressful conditions cause a local die-off of other species, *B. bigelowii* can increase dramatically in numbers. One instance is the terminal Cretaceous event 65 million years ago that exterminated the dinosaurs and most of the calcareous nannoplankton. *B. bigelowii* survived, and is often present in large numbers above the Cretaceous-Paleocene boundary. This sample from the Lodo Formation of central California is Late Paleocene (about 57 million years before Present).

What can our various illumination methods tell us about the structure of *B. bigelowii's* pentaliths? In this example, I used a dry 40x objective with high-aperture and correction collar instead of oil immersion. This gained a little depth of field at the cost of a little resolution. Even so, the large and small specimens have their best focus in different planes.

Figure 12B. The plane-polarized view shows pentaliths are divided into 5 segments with boundaries midway along faces.

Figure 12C. Cross-polarized light shows that each segment is a separate calcite crystal. The small pentalith is thin and has low 1st order retardation where the grays are difficult to tell apart (see the retardation scale in Figure 3). Uniform color indicates uniform thickness (about 1 µm). The large pentalith, on the other hand, has a color topographic map on its surface, showing it is thick enough to build up retardation, and thickness varies across the specimen. Areas with the same color have the same thickness; the Michel-Lévy chart tells us that for calcite, the 1st order red color is 3 µm thick.

Figure 12D. With the variable retardation filter at 1st order red, each segment crystal has a different retardation color. This tells us each segment crystal is rotated with respect to adjacent segments. In fact, the crystallographic C-axes are tangential to the pentalith outline. The segments blink off, then on again, as they rotate past their extinction positions.

Figures 12E and F. The variable retardation filter allows us to be artistic and pick different background colors, as well as select a retardation that highlights points of interest on the specimen.

Example 6: Deep Sea Sediment Strew

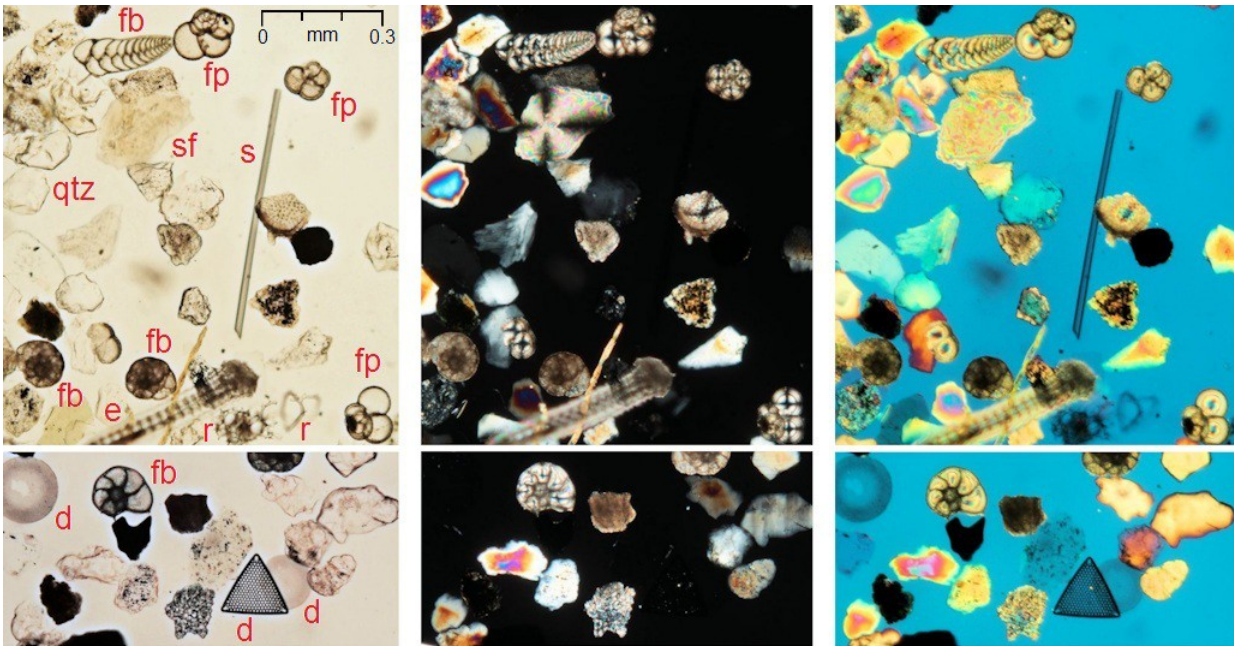


Figure 13. *Grain mount of Atlantic Ocean deep sea sediment. 4X objective; bar scale is 0.3 mm (300 µm).* ***A.*** *plane-polarized.* ***B.*** *cross-polarized.* ***C.*** *cross-polarized with the variable retardation filter. Key to objects:* ***d****=diatom;* ***e****=echinoderm spine (out of focal plane);* ***fb****=benthic foram;* ***fp****=planktic foram;* ***qtz****=quartz grain;* ***r****=radiolarian;* ***s****=sponge spicule;* ***sf****=shell fragment of larger organism.*

This last example is a random strew of particles from an Atlantic deep sea sample collected off North Carolina. The sample was washed through sieves to select fine sand and very fine sand (1/4 to 1/16 mm; 250 – 63 µm); other size fractions were prepared separately. The age of the sediment is possibly a few thousand years.

Biological calcite in this size fraction is mostly foraminifera, with some echinoderm spines, and an occasional shell fragment of a larger organism. The biological calcite is birefringent and is visible in cross-polarized light.

Biological silica takes the form of amorphous opal; it is isotropic. In this sample we have diatoms, radiolarians, and sponge spicules; these all disappear in cross-polarized light.

Compare Figures 13A and 13B. One third of the particles disappear in cross-polarized light. In addition to losing the biological silica, some minerals also go dark. The minerals might be isotropic, opaque, at extinction, or aligned along an optic axis so they are apparently isotropic.

In Figure 13C, the variable retardation filter adds retardation, which makes the background brighter, and all particles are visible again.

By using the variable retardation filter, we have the benefit of some polarization information, but at the same time, we have not caused a significant portion of the sample to become invisible. And, as an 1860s microscopist or a 1960s hippie would tell you, we have a flashy image with more visual impact than the original. “Far out, man!” “Indubitably!”

Error Correction

Figure 8 caption. “Gates” Formation corrected to “Gatesburg” Formation.

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