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MSA at 100 and why optical mineralogy still matters: The optical properties of talc

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Abstract

MSA's 100 years are memorialized herein with a combination of: 1) events marking our centennial, 2) publications devoted to it, and 3) my series of six MSA president letters in Elements written specifically for this moment. In some of those letters I stressed the importance of optical mineralogy and the role it played in areas outside of academics. As such new optical data are presented herein on 20 well characterized talc samples from other studies, as there appears to have been no thorough study of the optical properties of talc. Other than of academic interest, these data will find use in the ongoing issue of the purported asbestos content of talc.

MSA at 100

MSA celebrated its 100th anniversary in 2019. Planning for the event occupied MSA Council meetings for several years prior to the event, and we were fortunate that we could celebrate this occasion in person as Covid-19 hit shortly afterward. There were several events in which we came together as a society to celebrate the MSA Centennial, and my goal here is to memorialize them in one place.

Heaney and Gunter (2019) reviewed past MSA celebrations and detailed current issues that MSA should address. Rakovan and Gunter (2019) had a slightly different twist on their article dealing with the centennial, as they discussed Alex Speer, MSA's executive director for 25 years, while pointing out he'd been a member for 50 years; Alex stepped down as director in 2019; the photo in Figure 1B is of Alex and the new executive director Ann Benbow taken at the 2019 MSA awards luncheon at the annual GSA meeting in Phoenix.

Our feature event of the Centennial was the "MSA Centennial Symposium" with organizing co-chairs Peter Heaney and Steven Shirey. Proceedings of the two-day event can be found at: http://www.minsocam.org/msa/Centennial/MSA_Centennial_Symposium.html. The following is a summary of the event written by the organizers that appeared in Elements 15, 285:

"On 20–21 June 2019, 160 mineral enthusiasts gathered in the newly renovated Carnegie Institution for Science (Washington DC, USA) building to celebrate the 100th anniversary of MSA through moderated presentations of exciting advances in the solid Earth sciences. The 14 hour themed colloquia were proposed by MSA members, and they beautifully illustrated the broad reach and profound impact of mineralogy today. The opening session on sustainability included sobering messages from Gordon Brown and Michael Hochella regarding the lasting legacy of open-pit mining in the western USA and the role of incidental nanomaterials in controlling contaminant dispersal in mine wastes. A related theme by David Singer and Michael Schindler emphasized the need to characterize soil horizons across multiple length scales, with evidence that processes at the nanoscale do not extrapolate simply from larger size regimes.

Ross Angel and Lucie Tajcmanov. offered perspectives on the future of metamorphic petrology by stressing that state-of-the-art characterization techniques require a commensurate understanding of the complex physics and chemistry that produce metamorphic textures. In their session on mineral analysis, Michael Wiedenbeck provided a historical overview of SIMS, while Simon Jackson impressed the audience with current capabilities in trace element mapping by LA–ICP–MS. Othmar Müntener and Roberta Rudnick next walked the audience through models of the formation of the lower and upper crust based on field studies and experimental petrology. Fabrizio Nestola and Graham Pearson took the audience even deeper through a review of the exotic inclusions and isotopic compositions that have been observed in diamonds. Kim Tait and Aaron Celestian closed Thursday's session with their perspectives on how mineral museums can thrive in the next century by aligning their missions through close collaborations with the research community.

Friday began with a COMPRES-sponsored overview of synchrotron based studies in mineral physics. Przemysław Dera discussed surprising 5- and 6-coordination states for Si at high pressure, and Jin Zhang described anisotropy in omphacite as a means of detecting eclogite in the Earth's mantle. Elizabeth Rampe and Harry McSween next offered revelations into the early history of Mars through rover-based in situ rock analyses and characterization of the >100 meteorites that originated on Mars. In a session sponsored by Rob Lavinsky, Shaunna Morrison and Simone Runyon challenged the audience to imagine the power unleashed by connecting the dots in the enormously large mineralogic and petrologic datasets that geologists have amassed over the last century. Alexandra Navrotsky closed the morning with an announcement of the next chapter in her multifaceted career as director of a new Materials of the Universe program at Arizona State University. Gilberto Artioli tugged us back in time to consider the earliest uses of minerals in ceramics from 18,000 BCE, and his talk was followed by Michael Tite's history of the earliest Pb–Sn oxide glazes that were innovated in the Middle East in counterthrust to Chinese porcelain. The Gemological Institute of America funded the following session, with Wuyi Wang describing the emergence of synthetic gem diamonds over the last 15 years and Mandy Krebs illustrating trace element and isotope approaches to provenance colored gems. Supported by C2/m Mineralogy, John Hughes and Jill Pasteris expounded on the essentiality of apatite as a pillar for both our civilization and our bodies, and Ann Wylie and Matthew Sanchez concluded the meeting with presentations on the real, and supposed, health hazards of mineral dusts.

The inspirational science was enhanced by a spectacular evening reception among the stunning gem and mineral exhibits in the Smithsonian National Museum of Natural History, highlighted by President Mickey Gunter's toast with specially embossed champagne glasses. The symposium proved that, despite the diversity of our interests, there is more that unites than divides us thanks to our common foundation in the minerals and rocks that support our existence."

The final events of our centennial were held at the annual GSA meeting in Phoenix. GSA was very helpful and accommodating to our centennial; they even surprised us by posting signs stating it was our 100th (Figure 1B). They allowed us to have back-to-back sessions on Monday with a celebratory lunch between them. A highlight of that lunch was the presentation to MSA by the current president and executive director of GSA of a memento of this occasion (Figure 1C). MSA also recognized Alex Speer for this 25 years of service as our Executive Director. The scientific portion of the all-day session was titled "Mineralogical Society of America (MSA) at 100: Reflections, refractions, diffractions, intrusions, subductions, reactions, etc. from MSA past presidents." Sixteen former presidents submitted abstracts to this session, and in a break from tradition, the current presidential address was also given. Abstracts for this session are available at:
https://gsa.confex.com/gsa/2019AM/meetingapp.cgi/Session/47772 and
https://gsa.confex.com/gsa/2019AM/meetingapp.cgi/Session/48800 sites.

What follows are slightly modified versions of my MSA president letters that appeared in Elements over the 100th year of the Society. These letters were written with the intent to form a portion of this paper and all directed to "MSA at 100" with different themes:

A look backward: It was indeed an honor for me to be the 100th MSA president as MSA turned 100; a time in which we celebrated our successful past and plan for a similar future. Figure 1D shows (from left to right) MSA presidents #100, #62 (Jerry Gibbs), #58 (Don Bloss), and #68 (Paul Ribbe). I was blessed to have had them as my mentors. Looking back, each of them also had at least one past MSA President as their graduate advisor. In what would seem like a strange diversion at this point - a story seems fitting. At the 2002 IMA meeting MSA President #83 (Rod Ewing) started to introduce me to MSA charter Executive Director (Alex Speer). I mentioned to Rod, who I'd met in 1981, that I had met Alex two years sooner. Rod replied "our world is small, perhaps too small." Of course, this was intended as a joke, but could be taken negatively. However, this statement has stuck with me for years and I have concluded it is the mentoring, learning, friendships, and all the other positive things in life, that does result from this "small world", as essentially we are world-wide network of mineralogists who have very close ties. In fact, it came back again in this study as one of the talc samples was collected by Al Chidester; turns out he was Don Bloss' TA in optical mineralogy when Don was an undergrad at the University of Chicago pre-World War II. A corollary to this is the motto used by Google Scholar "Stand on the shoulders of giants." I truly believe this is a reason our society has lasted 100 years, and if we the members continue the efforts put forth by those who have come before us, our society can look forward to a bicentennial celebration in 2119; of course *sans* any of us reading this letter. (Above modified from Gunter 2018b.)

Professional Service: It's easy to overlook professional service as part of our "job"; however, I would view it as one of the most important things we do. And although all of us might not teach or do research, we all should be performing professional service. My former department chair once told me that for every paper I submit, I should review two to three – this made sense as I knew my papers would be reviewed by two of three other scientists. My largest service effort was to co-organize the 2005 Goldschmidt Meeting in Moscow, Idaho. Although it might be easy to determine how many papers we should review, I think it's harder to determine how many international meetings we should organize! Regardless, meetings don't organize themselves nor do professional societies run themselves nor do journals publish themselves; these all depend largely on the volunteer efforts of members or dedicated staff.

A major part of MSA's organization consists of 31 committees with 148 individuals filling them. So for a society of roughly 2,100 members one can see that at any one time 7% of us are involved in the operation of the society. Most of these committees are filled on a three-year term, so much of the "memory" in our system resides in our Executive Director of going on 25 years (yes, 25% of MSA's life!), Alex Speer. As many of you know Alex will be retiring in at the end of 2019 and I have the pleasure to announce Alex's replacement - Dr. Ann Benbow. Ann comes to us most recently as the Executive Director of the Archaeological Institute of America, and before that she'd spent over a decade as Director of Geoscience Education and Public Understanding as well as the Director of Education, Outreach, and Development at the American Geosciences Institute. Her official start date is March 1, 2019 so there will be a 10-month overlap with Alex.

I've always viewed service as the most important role of an academic, or as I stated at the outset, all of us, as we give or most important commodity - our time. MSA clearly is a society run by dedicated volunteers, and I'd like to take this opportunity to thank all of them, and encourage all of you to become more involved with MSA. Finally, along with giving time, giving money is also a good thing! As such, my major goal as president will be to establish a centennial fund so MSA can fully fund our outreach activates (i.e., the lecture program, Mineralogy-4-Kids, MSA-talk, etc.). Much of this will be done in collaboration with our incoming executive director as Ann has had considerable experience in this area - so stay tuned for more on that. And really finally just in case you are wondering how often you should serve as president of MSA, based on our current membership, it would be once in 2,100 years! (Above modified from Gunter 2019a.)

Teaching mineralogy: This president's letter may seem more fitting for a Triple Point column as an opinion piece, but based upon a career of teaching and learning basic and applied mineralogy, I think it is a subject we all need to consider regardless of our professional status. I stated that I thought it was important to "return the pure study of mineralogy back to geological sciences curricula" in my write-up when I ran for vice president and president. Many of the more senior readers of this article will recall when mineralogy was taught as a year-long course, often with mineralogy the first semester followed by optical mineralogy. Not to leave out the petrologists, as petrology used to be a full-year course as well. And now, many schools have condensed two years' worth of courses into one half year, while our knowledge in these areas have only grown!

Perhaps we are a victim of our own success, as over the last 100 years our science has matured to the level where, although there are still unanswered questions, we do have a deep understanding of our field. For instance, look no further than the Reviews in Mineralogy and Geochemistry series where there are entire volumes dedicated to mineral groups from A to Z (i.e., amphiboles to zeolites). We have also been able to design entire families of instruments that allow us to accurately and precisely determine the composition of minerals and their internal structure at several scales, as well as send a miniaturized version of one of those to Mars; and, to understand the theory of how these instruments work. So it might seem to many there is less of a need for a year-long course in mineralogy because we have made all of these accomplishments in the last 100 years. But they could not be further from the truth, as a basic understanding of mineralogy underlies most of the geosciences. In fact, this might also explain why "pure" mineralogy is being taught less, as there are so many non-mineralogists who can teach mineralogy more as a means to an end, rather than an end in itself. In fact, one of my petrology colleagues used to joke that my mineralogy course should be taught as an introduction to petrology course, and named likewise as it was required for his petrology course.

Specifically, let us take optical mineralogy and use of the polarized light microscope as an example, although most certainly we could pick other areas such as crystallography (Gunter 2004) A. The outgoing MSA executive director Alex Speer and incoming executive director Ann Benbow. A few years back I conducted a non-scientific survey on MSA-Talk. Two-thirds of those who responded stated their institution used to teach a semester long course in optical mineralogy, while only 1/3rd do now. Although there might be many reasons (e.g., inclusions of other courses, courses on more "modern" instrumentation, reduction in credits hours for the major, etc.) the end result is fewer students learn this much-needed basic skill. And to "prove" it is much-needed, look no further than the private sector where several companies teach week-long courses in polarized light microscopy; the cost of these courses is approximately $2,000. Of course, there are many other reasons to teach optical mineralogy and use of the polarized light microscope often pointed out in lively discussions on MSA-Talk.

Although there are new things to learn over the next 100 years, there most certainly needs to be a return to teaching more of the fundamental principles of mineralogy that have been removed from our curriculum, and I only need point to the example of optical mineralogy; MSA most certainly has teaching resources to help accomplish this. But as we teach those new things, let us not forget the old things that are the foundations for building the new things! (Above modified from Gunter 2019b.)

Mineralogy Research: The orientational dependence of the physical properties of minerals is one of the answers I give when someone asks my research interests. The main physical properties that interest me are the refractive indices, and I was fortunate enough to study how they change as a function of composition and structure for andalusite. This resulted in my first paper in *American Mineralogist* back in 1982, and also showed how an orthorhombic mineral could be optically isotropic (Gunter and Bloss 1982). This paper contrasted with the first paper published in the American Mineralogist in 1916: "The occurrence of lamellar calcite in Rhode Island"; although they could measure optical properties, composition was done with wet-chemical methods and diffraction of X-rays by crystal had just been discovered in 1912.

"X-rays" were not mentioned in an American Mineralogist title until 1927 when Stockwell (1927) used them to determine the unit cell of garnets and in turn use it to help predict the garnet's composition. Before that refractive index and specific gravity had been used; thus, this paper showed for the first time how the physical properties of minerals relate to their structure. At this point, indirect methods to determine composition were very useful as it was easier to perform them than to determine the composition by wet-chemical methods. Following the next year was a paper titled "The oscillation method of X-ray analysis of crystals," Gruner (1928a); I suspect there are few dues-paying members of MSA who have ever taken an oscillation photo, although several senior members may have; regardless, this was the first method used to obtain crystal structure information. The same year Gruner (1928b) used this method to determine the crystal structure of analcite as isometric with a = 13.64Å and "16 molecules of $NaAlSi_2O_6 \cdot H_2O$" in its "unit cube." Among other things, these data allow us to calculate the density instead of determining the specific gravity. And 91 years later his formula and cell edge remain the same; all that has changed is we now call this mineral analcime.

Turning to the composition of minerals, when our society was formed it was not uncommon to see ideal formulas for minerals written in terms of their oxides and instead of the now-used chemical formulas. For example, analcime would be written as $1/2Na2O \cdot 1/2Al_2O_3 \cdot 2SiO_2 \cdot 1H_2O$. This practice was followed for two reasons: 1) at this point we lacked the understanding of how elements would fit into a mineral as we did not know their structures and 2) compositions were determined by wet-chemical methods. Many of us will recall the inorganic chemistry lab where we were given a solid unknown, dissolved it, then precipitated portions of it, and very carefully weighed each; at the point I most certainly did not realize I was determining the composition of the material as I was so concerned on performing the "technique." Fortunately, just like X-rays allowed us to determine structures, the development of electron beam techniques, especially

Castaing's development of the electron microprobe - which occurred unbeknownst to me as I was in grade school -- allowed for precise and accurate determination of the composition of micron-sized mineral grains in polished grain mounts or thin sections.

We can now use synchrotron radiation to understand the orientational dependence of absorption spectra (for example Dyar et al. 2002). To study these, we use a spindle stage, whose precursor was described in a 1924 American Mineralogist article by Kerr entitled "A simple rotation apparatus." Of course, it would be helpful if we could calculate these spectra from first principles, but we have yet to accomplish that or to even be able to calculate refractive indices. We have also yet to fully understand what external shape minerals will take as they crystalize, which is basically the question asked in the paper published in 1914. However, as noted above, we have made many advancements in the first 100 years of our society, and there are many yet to come in the second 100! (Above modified from Gunter 2019c.)

The other IMA and... : I write this letter a few days after returning from MSA's Centennial. The first session at that meeting discussed mineral resources, which we could relate to IMA. To a mineralogist, the acronym IMA means the International Mineralogical Association; however, there's another meaning closely related to what many of us do - the Industrial Minerals Association (https://www.ima-na.org). It is an umbrella organization helping industry to provide the very materials we use daily. Some of these minerals are familiar to all of us (e.g., feldspars, talc, etc.), whereas others are less well known (e.g., barite, wollastonite, etc.). Regardless, in developed countries, we consume about 130 pounds of these minerals per day per person. And, while the 842 pounds of lunar material returned to earth during the Apollo missions may provide more excitement than the approximately 70 million tons of industrial minerals we use in the USA yearly, the latter are much more important for daily lives.

Over my career, I have worked on projects dealing with several industrial minerals, from aluminosilicates used as refractories, to zeolites used in water purification systems and radioactive waste treatment. I viewed this research as proactive and positive with the potential to help society. Over the past 10-20 years, my efforts in this field have turned more to defending this industry against claims of purported asbestos content of their products. Asbestos contamination of commercial products is most certainly of concern, but what is critical in this area is something as straightforward as the correct identification of common rock-forming minerals. For example, shards of talc are often misidentified as anthophyllite asbestos because their Mg/Si ratios (3/4 vs 7/8, respectively), easily overlap in semi-quantitative EDS spectra. Also, they both yield a 5.2Å repeat in electron diffraction, where that repeat is used to "prove" a particle is an amphibole in routine asbestos methods. The last talk of the Centennial session gave several examples of incorrect identification being used against industry in the ongoing talc litigation. We also hear in these cases that miners cannot tell talc from country rock, so the talc gets "contaminated." Yet I’ve spent time in mines where there is no question of the contact between ore and “country rock”, it’s not that hard to tell talc from marble!

While many reading this article might find this hard to believe, you will find it harder to believe the following sampling of mineralogically incorrect statements I have read in legal and regulatory documents: Anthophyllite and chesterite are polymorphs; one cannot distinguish monoclinic from orthorhombic amphiboles by electron diffraction; or better (really worse) yet, that amphiboles cannot be distinguished from pyroxenes in soils, and finally "Mica is mica. If it has aluminum silicates and phosphorus, phosphates, that's mica. It's just aluminum silicates is a type of clay." In Chapter 19 of our book (Dyar and Gunter 2019) titled "Mineral Identification" we state, when handed a mineral: "Do you want me to guess what it is or tell you? If you want me to tell you, it will take a little work, but we'll know for sure." Our community can correctly identify minerals with the appropriate choice of analytical methods.

The final participant comment in the last session in DC was a plea that we "take back mineralogy." This was a fitting way to end the meeting. But how do we do this? It should be clear from my above comments that mineral misidentification is a common practice in the "real world." Perhaps it is time we mineralogists consider professional licensing, as exists for geologists, engineers, and many other fields. No doubt both IMA can support this to aid in something as simple as proper mineral identification. (Above modified from Gunter 2019d.)

Looking forward: As I compose my final president's letter, I ponder the future of our society and discipline. As I look at the smiling faces of three of my former PhD students above, it gives me great hope (Figure 1E). There are many like them without grey hair who will carry on with the service, teaching, and research in mineralogy that the grey-haired ones among us did. What I fret about can also be represented in the photo by the word "asbestos." It is not the fact that asbestos has presented health problems in modern society, but more how we tend not to be involved in some of these problems, as they can be very controversial.

What I have noticed over my career is a trend, especially among us academics, to look for problems more than to solve them. This hit home when I was working with an industrial hygienist for an industrial minerals company, and he said "no problems, no funding." This was further reinforced when we went to visit a small industrial mineral mine, and the president of the company did not want to let us in as we were professors. It was not always this way, as "in the good old days" we used to work more closely with such industries. Of course, in the USA, federal funding and university expectations play a role in what is "valued." Regardless, I think we need to work to help industry solve its problems, and not create more for them.

What I had thought less of over my career is how MSA has been the catalyst for many other professional societies and journals. The outcome of this has been to reduce our number of members. This might be good or bad overall for the geosciences, but it is important for us to be aware of. Something I do believe to be bad is, along the way, how we have given much less attention to what are sometimes referred to as "amateur mineralogists." They really are the heart of MSA, as they are the ones who collect the minerals we study.

Yes, this letter reads more like what one might see on the opinion page of a newspaper. In fact, I have never written one of those, and have only written one thing that might be close - A Triple Point article in Elements a decade ago on - you guessed it – asbestos (Gunter 2009). Regardless, for our society and discipline to exist over the next century, I think we will need to put more effort toward rebuilding our ties to industry and the collecting community. Also, we need to change the priorities of the funding agencies and universities to allow us to accomplish this.

Finally, I would like to thank all the members, past and present, of MSA for a successful 100 years, for the honor it has been to be the 100th president, and all you have done for mineralogy in the last century. (Above modified from Gunter 2019e.)

Why optical mineralogy still matters

As noted above, and well known to many, we have decreased the teaching of optical mineralogy at the college level in the United States. As a result, the teaching of this much needed discipline is taken on by the private sector. At the same time active research in this area is also on the decline. For those interested in the capabilities of optical mineralogy research see the final chapter in Bloss (1981), the forwards in Bloss (1999, 2020), and Bloss' MSA president's paper (Bloss 1978). Obviously Bloss championed optical mineralogy in both teaching and research, and the most updated results of Bloss and coworkers research are given in Gunter (2020). Specifically, for the spindle stage methods Steven and Gunter (2017, 2020) present an Excel spreadsheet capable of many optical mineralogy calculations (e.g., those performed by EXCALIBR). That program and other spindle stage related materials can be found on MSA's website at: http://www.minsocam.org/msa/Monographs/#Spindle_Stage

Unbeknownst to many of us the use of the PLM is widespread in industry and the regulatory world, specifically for screening materials for asbestos (McCrone 1974, ISO 2012). Herein I use as the definition of asbestos as the asbestiform variety of serpentine (i.e., chrysotile), crocidolite, amosite, tremolite, actinolite, and anthophyllite when the latter three occur with an asbestiform habit. Thus, this is a two part definition: 1) first identify one of the six mineral species and 2) the mineral must occur in an asbestiform habit. The former is more-or-less a straight forward task for a mineralogist, but can be challenging for others. The latter presents several challenges, but definitions and methods to ascertain morphology were developed last century to resolve this issue (e.g., Campbell et al.1977; Crane 1992; Perkins and Harvey 1993; and Yamate et al. 1984). However, confusion does occur when certain regulations for asbestos used in an occupational setting are applied to the natural environment or areas were commercial asbestos was not used (Gunter et al. 2010), specifically for talc (Gunter et al. 2018). The application of some of these regulations to the natural environment would make much of the Earth asbestos "contaminated" (Thompson et al. 2011; Gunter 2018a). The main issue in the natural setting deals with the mineral group amphiboles (Gunter et al. 2007); both their occurrence in commercial asbestos as well as their natural occurrence composing 5% of the Earth's crust.

The purported asbestos content of talc has been a concern for decades, but has gained recent attention based on litigation directed to toward cosmetic talc. I believe the role of the mineralogist in this area is as straightforward as the correct identification of talc and minerals that might be associated with it. Examples of these issues are given in Buzon and Gunter (2017) and Gunter et al. (2018). However, the ongoing misidentification issues made by others is not published in the peer reviewed literature but occurs in documents used for litigation support. Lacking is a thorough study of the optical properties of talc, which will help refine methods to determine the purported asbestos content of talc. The issues are two-fold: 1) there is not a clearly defined range of refractive indices for talc ores from different locations, which are used in several products and 2) dispersion data are unavailable and needed to aid in identification with the dispersion staining method. (Rutstein et al. 2020) propose a method using a combination of

PLM and XRD for bulk talc samples, and these data will find immediate use in those regulatory efforts.

Optical properties of talc

The need: Over the past decade we have characterized talc with one goal being to better understand its potential asbestos content. One of the many analytical methods we have used is PLM, as the optical properties of talc differ from potential asbestos minerals. For example, chrysotile has lower refractive indices, whereas amphiboles have higher. Even though the differentiation is easy for those who understand mineralogy and PLM, talc can be misidentified for chrysotile as the α value of talc (i.e., the smallest refractive index value for talc, which is perpendicular to the talc elongation) is similar to chrysotile; thus, a talc particle viewed on edge can be confused with chrysotile. Of course, the talc index changes on stage rotation to β or γ (i.e., the large refractive index, N), as this direction is parallel to the elongation of the talc. Another problem occurs with the acceptable range of refractive index deemed to match talc. A similar issue occurred in identifying the winchite and richterite amphiboles in Libby, Montana. The compositional range of these amphibole species was limited, as was their refractive indices (Bandli et al. 2003), but the full range (i.e., the high Fe end-members) could cause labs to identify low-Fe pyroxenes as amphiboles. Sanchez and Gunter (2013) discuss this problem at length, and provide a solution.

To better understand the optical properties of talc a literature review is first presented, as well as noting the refractive index values given in reference books. Table 1 lists several references and the ranges given. Values of β and γ are very similar and often lumped together. An unanswered question is, where did these values come from? Apparently, many of them came from the Doelter and Dittler (1912) paper. Table 2 lists specific values; the α value in general does not agree with Table 1, whereas the γ ones do, and β is rarely given. Chidester (1962) does provide compositional data and values for γ from talc samples he collected in active Vermont talc mines, but there was no correlation of increasing γ to Fe concentration. Forbes (1969) likewise provided γ values and Fe concentration for synthetic samples, but again no correlations occurred. In both cases this might be due to small datasets, low precision measurements, or small variation in composition. Dispersion data are only provided in two studies (McCrone and Delly 1973) and (McCrone et al. 1979), and these data are not self-consistent. Dispersion data are important as discussed below in methods used to identify talc by commercial labs. Finally, Phillips and Griffen (1980) do provide a plot of γ increasing as a function of Fe content, but no details are given on the source of their data.

It is somewhat understandable why no thorough optical study of talc has been conducted. In fact, my attempts to determine the optical properties of talc on single crystals with the spindle stage failed as talc edges tend to scroll, making Becke line determinations difficult to impossible. However, talc particles will sometimes lie "on edge" in grain mount. When this happens, they appear as a fiber or an elongate particle. In this case the long direction coincides with either β or γ and the perpendicular direction is α. Given these types of particles the refractive indexes perpendicular and parallel to the elongate talc can be measured in grain mounts, and these are referred to as n and N, pronounced "little n" and "big N" (Bloss, 1961) to distinguish them from α, β, and γ.

Sample selection: Twenty samples were selected, 18 of the 98 characterized by EPMA in Buzon (2016) and two from McNamee (2013), to span the observed compositional range in these two studies. The remaining sample of Johnson's Baby Powder was purchased in Moscow, Idaho on May 20, 2020. In these previous studies, talc varies very little in composition, with Fe and F being the elements most effecting the optical properties, and the only elements to correlate to them. Table 3 lists the selected samples from high- to low-Fe concentration. The table also lists the sample number from Buzon (2016), a brief description, location, and who collected them. In addition to compositional variation, efforts were made to select samples that represent several of the talc producing regions in the world. World-wide deposits are discussed in general in McCarthy et al. (2006), and Buzon (2016) characterizes samples from many of these locations. Chidester et al. (1964) reviews talc deposits in the United States, and Van Gosen et al. (2004) discuss them with a focus on their potential amphibole content as related to formation conditions and protolith. More information on the geological formation and mineralogical characterizations for certain deposits of samples used herein are provided in: Gouverneur Talc mining district (Engel 1962; Ross et al. 1968; McNamee and Gunter 2013, 2014; Gunter et al. 2018), southwestern Montana (Berg 1979; Buzon and Gunter 2017), Death Valley region, California (Wright 1968), Vermont (Gunter et al. 2018), and Val Germanasca, Italy (Sandrone and Zucchetti 1988).

Analytical methods: Methods to determine the refractive index of minerals were first discussed in the American Mineralogist by Emmons (1928) by use of Becke lines, which required determining a "match" by correct interpretation of Becke line colors in polychromatic light (for examples see Figure 2). These were further refined in Emmons and Gates (1948) by what is now known as the double variation method, whereby one changes the temperature of the immersion media, thus changing its refractive index, and finds a "match" in monochromatic light making the grain actually disappear. Bloss (1981, 1999) describes the double variation and refinements made with advancements in temperature controls and wavelength variation. Computer programs were developed by Su et al. (1987) to increase the precision and accuracy of this method, precision being increased by multiple measurements at different temperatures with associated matches at different wavelengths, and accuracy being increased by calibration of refractive index liquids and measurements of glass standards with refractive indices known to the sixth decimal place in the visible wavelengths.

Figure 3 shows the PLM used in this project with a heating/cooling stage mounted on the rotating stage, and a slide monochromator below. Figure 4 shows images of three different minerals from sample #14 in cross-polarized polychromatic light with the first order waveplate inserted. Also shown are three inserts in plane polarized where the refractive index of the liquid was changed to the values shown by heating or cooling to match the three separate grains. The range of heating/cooling allows for a variation in the liquids of approximately 0.060. Thus, there is no need to make separate grain mounts with different liquids to aid in mineral identification if the minerals refractive indices do not differ by more than 0.060.

As noted above, dispersion staining is also used to aid in mineral identification discussed in *American Mineralogist* by Dodge (1948) and Wilcox (1983), especially for asbestos identification (Bloss 1999, McCrone 1974); dispersion staining colors are shown in Figure 2. Figure 5 shows dispersion staining images of sample #3 in a 1.545 liquid (Figure 5A) and a 1.595 liquid (Figure 5B). For both figures note the elongate, blueish particle near the center of the field of view; this dispersion staining color indicates a near match between the particle and the liquid at 589.3 nm. Because the lower polarizer is E-W (i.e., horizontal) the particle in Figure 5A is a near match to 1.545, the n of the grain, while that in Figure 5B is a near match to 1.595, the N of the grain (NB: Values for N and n are, as usual, give for 589.3 nm). In Figure 5A many of the plate-like particles, which are talc sheets, appear yellow, which indicates the grain is greater than the liquid, while in Figure 5B they appear bluish, indicating a near match. While matching Becke lines colors or dispersion staining colors in polychromatic light aids in mineral identification, measurements in monochromatic light are more precise and accurate due to characterize the optical properties of minerals.

Figure 6 shows a higher magnification view of the particles at the center of the field of view in Figure 5B, with two elongate talc particles in different orientations, labeled 1 and 2, and a larger calcite grain. Again, the sample is immersed in a 1.595 liquid, but the temperature is raised so the liquid matches particle 1 based on the Becke line color (Figure 2). The match for N is obtained when the talc's long axis is parallel to the lower polarizer by slightly lowering the stage (Figure 6B). Particle 2 also matches when it is rotated E-W (Figure 6D). To precisely find a match at 589.3 nm, the Becke lines are observed in monochromatic light. Figure 7A shows a magnified image of particle 1 from Figure 6. In Figure 7B the temperature of the liquid is changed until the grain disappears; this would be the precise match for 589.3 nm. In Figure 7C the liquid is greater than the grain, so a light colored Becke line enters the liquid when the stage is lowered, whereas in Figure 7D, the light colored Becke line enters the grain. For the measurements herein, the temperature of the liquid was adjusted until the grain had a near match around 550 nm, then heated in 5° increments to obtain talc / liquid matches to below 486.1 nm, and then cooled to obtain them to at least 656.3 nm. With these data dispersion equations could be obtained for each sample, and refractive index values calculated over the range from 486.1 nm to 656.3 nm. For samples #2 to #21 a 1.595 liquid was used for N and a 1.545 liquid for n, whereas for sample #1 1.605 and 1.555 liquids were used respectively.

Figure 8 shows an example of colored Becke lines and dispersion staining colors for sample #16 for wavelength matches at N (Figures 8A and 8B), Nf (Figures 8C and 8D), and Nc (Figures 8E and 8F). Compare these to the colors shown in Figure 2; although both methods are used to obtain a match between the liquid and grain, the double variation method as shown in Figure 7 allows for more precise refractive index determination.

Results and discussion: Table 4 lists the N and n values for the 21 samples in this study, the calculated birefringence (δ), and compositions (i.e., Fe and F) for 20 of the samples; note the Fe is expressed in FeO% as well as Fe/(Fe+Mg). As is typical, the refractive index values given in Table 4 are for Na light (i.e., 589.3 nm). From the literature review there are scant optical data on talc from known locations. However, samples #14 and #16 correspond and agree with the data in Table 2 for the samples from New York of Wright (1960) and Ross et al. (1968). Sample

#3 is from the same mine as the samples measured by Chidester (1962), and have similar values for N or his γ. Finally, the data from McCrone et al. (1979) are from the same deposit as sample #2 with similar optical data.

Table 5 provides observed refractive index values at 486.1 nm (i.e., Nf and nf) and 656.3 (i.e., Nc and nc). Nf-Nc, the dispersion coefficient, is then calculated for both N and n values. The dispersion coefficients are required to assign a matching refractive index to a material based on the dispersion staining colors as described in detail in Su (1993, 2003). The only other published values for dispersion for talc are given Table 2. For both references the value for α (which correlates to n in this study), appear incorrect, too high (McCrone and Delly 1973) and too low (McCrone et al. 1979). Also, the value for γ (which correlates to N in this study) appears too low (McCrone and Delly 1973), whereas β and γ are in agreement with the data herein (McCrone et al. 1979). Regardless, their data are not self-consistent, so the data presented in Table 5 appear to be the only reliable dispersion data for talc.

Figure 9 shows plots of N and n as a function of FeO%. As would be expected, the refractive indices increase as Fe replaces Mg in talc (see Chapter 18 of Dyar and Gunter (2019) for a more thorough discussion of the relationships of optical properties and composition). For each plot 16 of the samples are shown as black dots, whereas samples #14 and #16 are plotted as red plus signs and samples #19 and #20 are plotted as green boxes. For N (Figure 9A) the plus signs follow the trend, but for n (Figure 9B) they plot above it; the green boxes plot below the trend for both n and N. In Table 4 sample #19 and #20 have both the lowest values for Fe and the highest for F. Although Fe increases the refractive index as it replaces Mg because it increases the electron density, F will lower the refractive index as it forms more ionic bonds. For this reason, these samples depart from the trends in Figure 9. The larger n values for samples #14 and #16 relates to how these talc crystals formed, and the associated remnants of randomly orientated elongate anthophyllite between (i.e., parallel to) the talc layers. McNamee et al. (2015) discuss this in detail and show images of talc formation on the {210} planes of anthophyllite. Although these have an effect on n, they have little to no effect on N because of the preferential orientation to light vibrating parallel to the layers is effected more than for that normal to the layers. Finally, the values obtained for N and n of these samples agree with those obtained by Wright (1960) and Ross et al. (1968).

Based on the above samples #19 and #20 are excluded from the regression data in Figure 9A and 9B, whereas #14 and #16 are excluded from Figure 9B. A regression analysis then yields the following two equations:

$N = 1.5851(3) + 0.0027(2)$ FeO%, $R^2 = 0.91$ Eqn 1
Prob>t <0.0001 <0.0001

$n = 1.5379(6) + 0.0017(3)$ FeO%, $R^2 = 0.64$ Eqn 2
Prob>t <0.0001 0.0002

There is a statistically better fit for N than n, but both are statistically significant. Also, the slope for n is less than for N, which makes structural sense as Fe would preferentially increase the electron density within the sheets has compared to perpendicular to them. Similar relationships are shown for andalusite (Gunter and Bloss 1982) where Fe increases the refractive index at a faster rate parallel to edge-sharing chains of octahedral, and for olivine as Fe substitutes for Mg parallel to octahedra in the β direction (Dyar and Gunter 2019).

In general, sheet silicates are optically negative because the electron density is greater within the sheets than perpendicular to them. This is similar to other minerals with ring structures or channels in that the majority of the bonding – and thus electron density – is parallel to the rings or channels (Palmer and Gunter 2000). Also, trioctahedral sheet silicates are often nearly uniaxial negative, while dioctahedral ones are not (Dyar and Gunter 2019). Curiously, a literature search found no other published study showing the relationship of the optical properties of sheet silicates to composition, except for chlorite (Albee 1962), which at first glance appears not to follow this trend. Figure 10 shows a plot of the trend lines for Albee's α, β, and γ values versus composition as modified by Bloss (1985). Chlorites plotting on the left side of the diagram (i.e., high Mg) are optically positive, whereas those on the right side (i.e., high Fe) are optically negative. Also, on this illustration the three lines interest near the middle and in turn mark the change in optic sign, whereas the refractive index values parallel to the *a*-axis and *b*-axes increase at a faster rate than parallel to *c*-axis.

The reason in the different rates of change is explained by consideration of the crystal structure of chlorite (Figure 10B). The chlorite structure is similar to that of talc, but with a layer of octahedra between each "talc layer." The octahedral layer has H atoms (small black spheres) bonded perpendicular into it. The OH bonds contribute to the refractive index direction along *c*-axis, and for the Mg end-member, cause this direction to have the largest refractive index. As Fe substitutes for Mg the refractive indices parallel to the sheets increase at a faster rate than perpendicular – the same effect seen for talc, but in this case the trends cross and Fe-rich chlorite becomes optically negative, like all other sheet silicates. Gunter and Ribbe (1993) show a similar effect for the natrolite group zeolites, and how the orientation of channel H_2O has a differential impact on refractive index as a function of orientation. Palmer and Gunter (2000) also show how mean refractive index of heulandite group zeolites can be used as a proxy to determine the H content in cation-exchanged samples. Thus H, OH, and H_2O all play a major role in the interpretation of the refractive index of minerals.

Final thoughts

It was most certainly one of the highlights of my professional career to be able to serve MSA as president during its centennial year. But I'm only one of now 100 presidents and hundreds of additional members, to serve MSA in its first century. I also feel fortunate to have selected optical mineralogy as my specialty. I recall being told the world only needed three optical mineralogists when I chose this field for graduate studies. Based on my experiences, the need for optical mineralogists, especially outside of academics and geology, is greater than any other area in geology. At least I know at this point the demand for our skills far exceeds the people with those skills, and, as mentioned above, the private sector is trying to meet this need with week-long "training" courses designed to convey only the most basic principles of the method, but of course one cannot hope to learn optical mineralogy in a week! I think the main role of optical mineralogy, or mineralogy in general, is the correct identification of minerals. This, of course, can only be done once the minerals are correctly characterized, which is most certainly also our realm. Perhaps it's time we spend more effort on outreach and education and less time on our research, as recent trends show us that it seems hard for society to just "follow the science"; maybe we should try and lead in that area– just a final thought.

Acknowledgements, disclosure, and dedications

As I end my "official" academic career, and the majority of my MSA service, there are so many people I would like to acknowledge - my mentors, colleagues, 10's of graduate students, 100's of mineralogy students, and 1,000's of physical geology students; you all contributed to what could only be described as a very fulfilling career for me. While I would like to list many of you by name – and many of you are listed as co-authors in the reference section -- I'm afraid I would omit someone. I will thank John Hughes, an anonymous reviewer, and the editorial staff of the American Mineralogist for improving the manuscript and accepting the tardiness of a "retired" professor. There is one more person who I will list by name – Suzanne Aaron - my wife of forty years; thank you for everything!

I work as a consultant and expert witness in matters dealing with the purported asbestos content of mainly natural materials. And most of the recent work deals with the purported asbestos content of talc, both industrial and cosmetic grades. Several of the companies I work with provided samples and funding to collect the samples used in this study. They also provided funds for some of the analytical work performed on those samples. However, there were no support for production of this paper, or interaction with them.

I would like to dedicate the first part of this paper to the memory of Paul Ribbe, Emeritus mineralogy Professor at VPI&SU. Paul served as MSA's 68th president, and Councilor before that. Although he never knew it, we nicknamed him Uncle Paul, as he was always there to help. To the rest of our community he is known as the creator of the Reviews in Mineralogy series and sole editor of the first 41 volumes. For these accomplishments, as well as other MSA service, he received the MSA Distinguished Public Service Medal in 1993. Although less known, he suggested to Alex Speer that he apply for MSA's Executive Director position. Along with the crystal chemistry of various silicate mineral groups, specifically – feldspars, powder X-ray diffraction, and electron microprobe, he taught me the most useful thing in life we can do is the help others.

I would like to dedicate the second part of this paper to Malcom (Mac) Ross, retired USGS. Mac served as MSA's 71st president, was treasurer prior to that, and the son of Clarence Ross, MSA's 16th president – making them the only father/son MSA presidents. Mac was the first recipient of MSA's Distinguished Public Service Medal, in 1990– it would be an understatement to say this award was created for him based on his efforts to educate both our community, the public, lawmakers, and the regulatory community about asbestos, specifically that not all asbestos is the same and that a 3:1 aspect ratio of an amphibole does not asbestos make. Although he might not have convinced everyone, he did convince me, thus providing me the motivation to work to some of his goals.

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Tables

Table 1: Literature refractive index ranges for talc

reference	year	α	β	γ	δ
Doelter & Dittler	1912	1.538-1.545	NA	1.575-1.590	0.030-0.050
Larsen	1921	1.539	1.589	1.589	0.05
Winchell & Winchell	1929	1.545	NA	1.590	0.045
Ford / “Dana 4th”	1932	1.539	1.589	1.589	0.05
Larsen & Berman	1934	1.539	1.589	1.589	0.05
Wahlstrom	1955	1.539-1.545	1.589-1.590	1.589-1.590	0.030-0.050
Kraus et al.	1959	1.539	1.589	1.589	0.05
Bloss	1961	1.539	1.589	1.589	
Deer et al.	1962	1.539-1.550	1.589-1.594	1.589-1.600	~0.05
Winchell & Winchell	1964	1.540	1.575	1.575	0.035
Kerr	1977	1.538-1.545	1.575-1.590	1.575-1.590	NA
Troeger	1979	1.539-1.550	1.589-1.594	1.589-1.596	0.046-0.050
Phillips & Griffen	1980	1.538-1.550	1.575-1.594	1.575-1.600	0.05-0.05
Fleisher et al.	1984	1.545	1.584	1.584	0.039
Anthony et al.	2001	1.539-1.550	1.589-1.594	1.589-1.600	NA
Perkins & Harvey* “EPA”	1993	1.54	NA	1.60	NA
Klein & Dutrow / “Dana 23rd”	2007	1.539	1.589	1.589	NA
Dyar & Gunter	2008	1.539-1.550	1.589-1.594	1.589-1.600	0.05
Deer et al.	2009	1.53-1.55	1.58-1.59	1.58-1.60	~0.05
ISO 22261-1*	2012	1.539-1.550	1.589-1.600	1.589-1.600	NA
Nesse	2013	1.539-1.550	1.589-1.594	1.589-1.600	~0.05
Mindat	2021	1.538-1.550	1.575-1.594	1.575-1.600	0.037-0.05
This paper	2021	1.5310-1.5485	ND	1.5753-1.5975	0.0374-0.0524

* Values used in the regulatory arena

Table 2: Literature refractive index values, with Fe data where provided.

reference	year	location	α	β	γ	FeO	Fe/Fe+Mg	nf-nc
Deer et al.	1962/1935*	Sweden	1.550		1.596	2.46	0.05	ND
Deer et al.	1962/1956*	Murphy NC	ND	1.572	1.580	0.79	0.01	ND
Wright	1960	New York	1.545	1.582	1.585	ND	ND	ND
Chidester**	1962	Vermont	ND	ND	1.588-1.593	ND	0.04-0.09	ND
Ross et al.	1968	New York	1.545	ND	1.580	0.0	0.0	ND
Frobes***	1969	Synthetic	ND	ND	1.562-1.580	ND	0.00-0.10	ND
McCrone & Delly	1973	NA	1.539	ND	1.588	ND	ND	α=0.016 γ=0.001
McCrone et al.	1979	Vermont	1.546	1.588	1.589	ND	ND	α=0.001 β=0.007 γ=0.007
Fleisher et al.	2001	NA	1.554	NA	1.589	ND	14.9	ND

* year sample was measured
** range given for 6 samples
*** range given for synthetic 17 samples

Table 3. Sample locations and source. Numbers in parentheses refer to Buzon (2016) while sample #14 and #16 are from McNamee (2013).

1. (44) outcrop sample, Argonaut Mine, Vermont (MEG)
2. (46) milled product, Argonaut Mine, Vermont (MEG)
3. (33) mine sample J50, Johnson Mine, Vermont (AHC)
4. (184) Treasure Mine, Montana (MEG)
5. (119) talc single crystal, Argonaut Mine, Vermont (MEG)
6. (9) mine sample, former Willow Creek Mine, Montana (MEG)
7. (180) ore sample, former Gianna Mine, Italy (MEG)
8. (NA) mine sample, Talc City Hills, California (MEG)
9. (55) Johnsons Baby Powder, Moscow, Idaho (MEG)
10. (3) ore sample, Guangxi Guilin mill, China (DVO)
11. (101) milled product, Rodoretto Mine, Italy (MEG)
12. (175) ore sample, Regal Mine, Montana (MEG)
13. (153) former Grantham Mine, California (RBB)
14. (NA) mouldene - milled product, Talcville, New York (JWK)
15. (14) ore sample, former Western Talc Mine, California (MEG)
16. (NA) Nytal 100 – milled product, former Arnold Pit Mine, New York (JWK)
17. (16) ore sample, former Western Talc Mine, California (MEG)
18. (93) ore sample, Liaoning, Haicheng, China (RBB)
19. (91) ore sample, Guangxi, China (RBB)
20. (92) ore sample, Guangxi, China (RBB)
21. (NA) Johnsons Baby Powder – May 20, 2020, Moscow, Idaho

MEG = Mickey Gunter, University of Idaho
AHC = Alfred Chidester, USGS
DVO = Drew Van Orden, RJ Lee Group
RBB = Richard Berg, Montana Bureau of Mines
JWK = John Kelse, Vanderbilt Minerals

Table 4. Optical and compositional data for samples in this study.

Sample	N	n	δ	FeO%	Fe/Fe+Mg	F%
1	1.5975(7)	1.5451(4)	0.0524	4.46(13)	0.0801	0.11(2)
2	1.5930(7)	1.5415(8)	0.0515	2.72(28)	0.0501	0.04(4)
3	1.5919(2)	1.5440(3)	0.0479	2.52(10)	0.0446	0.07(2)
4	1.5897(6)	1.5414(4)	0.0483	2.24(12)	0.0413	0.20(1)
5	1.5909(3)	1.5415(3)	0.0494	1.78(7)	0.0316	0.03(1)
6	1.5901(4)	1.5436(7)	0.0465	1.63(64)	0.0288	0.19(5)
7	1.5867(5)	1.5376(3)	0.0491	1.30(13)	0.0240	0.27(2)
8	1.5863(3)	1.5384(4)	0.0479	0.91(20)	0.0168	0.26(5)
9	1.5876(2)	1.5403(3)	0.0473	0.75(13)	0.0148	0.11(3)
10	1.5876(3)	1.5413(4)	0.0463	0.71(20)	0.0138	0.11(4)
11	1.5856(3)	1.5377(4)	0.0479	0.58(26)	0.0107	0.14(8)
12	1.5873(4)	1.5371(3)	0.0502	0.52(13)	0.0095	0.10(1)
13	1.5861(2)	1.5403(4)	0.0458	0.24(4)	0.0044	0.46(2)
14	1.5859(3)	1.5485(3)	0.0374	0.21(3)	0.0040	0.31(4)
15	1.5863(2)	1.5389(9)	0.0474	0.20(4)	0.0038	0.12(3)
16	1.5847(3)	1.5444(4)	0.0403	0.19(11)	0.0032	0.25(5)
17	1.5872(4)	1.5372(4)	0.0500	0.08(2)	0.0015	0.05(2)
18	1.5845(6)	1.5369(2)	0.0476	0.03(1)	0.0005	0.10(2)
19	1.5774(2)	1.5310(3)	0.0464	0.02(1)	0.0004	1.24(9)
20	1.5753(7)	1.5311(4)	0.0442	0.01(1)	0.0002	1.38(2)
21	1.5881(3)	1.5468(6)	0.0413	ND	ND	ND

Table 5. Dispersion data for samples in this study

Sample	Nf	Nc	Nf-Nc	nf	nc	nf-nc
1	1.6057(8)	1.5966(9)	0.0091	1.5513(4)	1.5444(4)	0.0069
2	1.5979(8)	1.5922(8)	0.0057	1.5461(9)	1.5411(9)	0.0050
3	1.5984(3)	1.5895(3)	0.0089	1.5501(4)	1.5439(3)	0.0062
4	1.5957(7)	1.5894(7)	0.0063	1.5468(5)	1.5404(4)	0.0064
5	1.5986(3)	1.5893(3)	0.0093	1.5478(4)	1.5407(4)	0.0071
6	1.5945(5)	1.5898(4)	0.0047	1.5509(7)	1.5429(9)	0.0080
7	1.5929(5)	1.5856(5)	0.0073	1.5437(3)	1.5367(4)	0.0070
8	1.5931(3)	1.5855(3)	0.0075	1.5462(4)	1.5384(4)	0.0078
9	1.5946(2)	1.5860(2)	0.0086	1.5504(3)	1.5395(3)	0.0109
10	1.5935(3)	1.5865(3)	0.0070	1.5495(6)	1.5405(5)	0.0090
11	1.5933(3)	1.5856(5)	0.0077	1.5433(5)	1.5367(5)	0.0066
12	1.5937(5)	1.5856(5)	0.0081	1.5448(4)	1.5375(3)	0.0073
13	1.5925(3)	1.5857(3)	0.0068	1.5460(4)	1.5400(4)	0.0060
14	1.5920(3)	1.5852(3)	0.0068	1.5558(4)	1.5483(4)	0.0075
15	1.5933(2)	1.5854(2)	0.0079	1.5445(9)	1.5388(10)	0.0057
16	1.5920(4)	1.5831(4)	0.0089	1.5512(5)	1.5429(5)	0.0083
17	1.5940(5)	1.5873(5)	0.0067	1.5463(5)	1.5364(5)	0.0099
18	1.5917(8)	1.5834(7)	0.0083	1.5445(3)	1.5361(2)	0.0084
19	1.5852(3)	1.5770(2)	0.0082	1.5386(4)	1.5298(4)	0.0088
20	1.5820(8)	1.5746(7)	0.0074	1.5386(5)	1.5307(4)	0.0079
21	1.5929(3)	1.5880(3)	0.0049	1.5516(7)	1.5470(7)	0.0046

Figure captions

Figure 1: Photographs to celebrate MSA's 100th. A. The outgoing MSA executive director Alex Speer and incoming executive director Ann Benbow. B. Greeting signs for the 2019 annual GSA meeting in Phoenix announcing MSA's 100th. C. a memento given to MSA by GSA, D. former MSA presidents and my mentors, and E. some of my former PhD students. The photos in D and E are meant as a metaphor to show how we arrived at our career and how we help others to obtain theirs.

Figure 2: Back cover of Bloss (2020) showing both colored Becke lines and central-stop dispersion staining colors for liquid and solid matches at different visible wavelengths. These colors are often described in texts, but actually seeing them is more helpful.

Figure 3: A polarizing light microscope equipped with a heating / cooling stage and monochromator. This is the set-up used herein to employ the double variation method for precise refractive index determination.

Figure 4: An example of the use of a heating / cooling stage to identify minerals with differing refractive indices in the same grain mount for sample #14. A near index-matching fluid (i.e., 1.58) was chosen for talc, then cooled to 1.61 to match tremolite and heated to 1.55 to match serpentine. (Modified from Gunter et al. 2018.)

Figure 5: Central-stop dispersion staining images of sample #3 in a 1.545 liquid (A) and 1.595 (B) with an E-W polarizer. In A the liquid matches n (i.e., the vibration direction perpendicular

to the long axis), as indicated by the blue vertically orientated particle in the photo's center, while in B the refractive index of the fluid is higher, thus matching N (i.e., the vibration direction parallel to the long axis). Also, the talc plates in A appear yellow indicating their refractive index exceeds the liquid, while in B they are blueish indicating a near match (refer to Figure 2 for a guide to dispersion staining colors).

Figure 6: The same area is imaged as in Figure 5B in a 1.595 liquid, except at a higher magnification and in plane polarized light showing two elongate talc particles in different orientations (labeled 1 and 2) and a larger calcite grain. The temperature of the liquid is raised so N of the talc particles matches the liquid at 1.5919. In A particle 1 is parallel to the lower polarizer and shows very low relief (i.e., is a near-match to the liquid), while particle 2 shows high relief (i.e., does not match the liquid). In B the stage is slightly lowered and particle 1 exhibits colored Becke lines for a grain liquid match at 589.3 nm, while a light colored Becke line goes into the liquid for particle 2. In Figures C and D the stage is rotated so as to bring particle 2 parallel to the lower polarizer, thus showing its N matches that of the liquid.

Figure 7: These four images are of single elongate talc particle from sample #7 immersed in a 1.595 liquid. The temperature of the liquid is raised until N of the grain matches that of the liquid, for this sample – 1.5867. While this match can be based on the color of the Becke lines in polychromatic light as seen in A, a more quantitative method to determine this match is made in monochromatic light where the grain disappears in B at 589.3 nm. In C the liquid is greater than the grain as a light colored Becke line goes into the liquid, while in D the liquid is less the grain. This is the visual example of the double variation method and precise determination of the

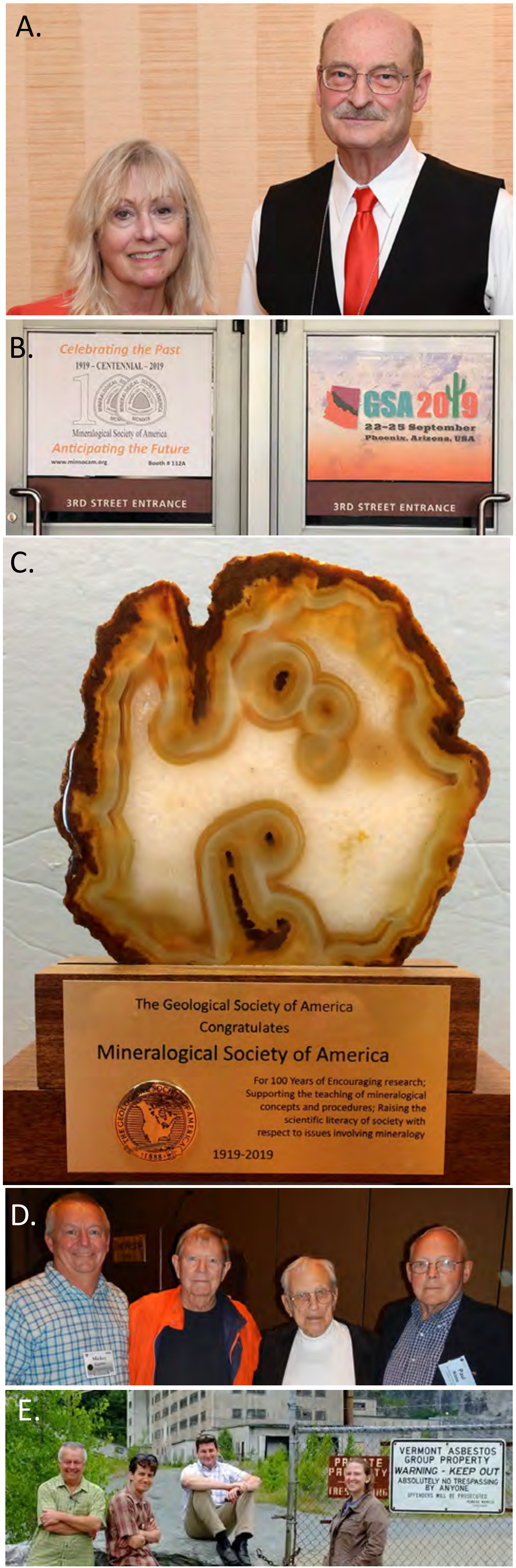
refractive index of a solid.

Figure 8: These six images are of a single elongate talc particle from sample #16 immersed in a 1.595 liquid, with the temperature changed so the grain and liquid match at different wavelengths. The images in the left column are in plane polarized light showing different Becke line colors, and those on the right show different dispersion staining colors. A and B show matches at 589.3 nm, C and D at 486.1 nm (or Nf in Table 5), and E and F at 656.3 nm (or Nc in Table 5).

Figure 9: Plots of N (A) and n (B) vs. FeO% for the 20 samples in Table 4, with associated best fit linear regression line. The green block symbols are for samples #19 and #20 which deviate from the regression lines based on high F content. The red plus signs are for samples #14 and #16 which deviate from the regression line for n, probably because these samples contain remanent anthophyllite as explained in the text and shown in McNamee et al. (2015). Finally the slope of N is greater than n.

Figure 10: A graph of refractive indices vs composition (Albee 1962) for chlorite group minerals with the three refractive index relationships relabeled for this biaxial mineral by Bloss (1985). Mg-rich chlorites (those plotting on the left of the diagram) are optically positive, so the largest refractive index is perpendicular to the layers. Chlorites change to optically negative near the middle of the graph as higher atomic number cations replace Mg. Because the structure of chlorite has O-H bonds near parallel to the c-axis in the octahedral layer, this results in the largest refractive index value for Mg-rich chlorites, but with increased electron density in the

sheets Mg-poor chlorites become optically negative like most sheets silicates.


A.
B.
Celebrating the Past
1919 – CENTENNIAL – 2019
Mineralogical Society of America
Anticipating the Future
www.minsocam.org
Booth # 112A
3RD STREET ENTRANCE
GSA 2019
22–25 September
Phoenix, Arizona, USA
3RD STREET ENTRANCE
C.
The Geological Society of America
Congratulates
Mineralogical Society of America
For 100 Years of Encouraging research; Supporting the teaching of mineralogical concepts and procedures; Raising the scientific literacy of society with respect to issues involving mineralogy
1919-2019
D.
E.
VERMONT ASBESTOS GROUP PROPERTY
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ABSOLUTELY NO TRESPASSING BY ANYONE
OFFENDERS WILL BE PROSECUTED

Figure 1

A series of photographs of colored Becke lines showing the matching wavelength between the liquid and a tremolite grain mounted on a spindle stage, with the microscope stage slightly lowered. Precise matches were achieved by changing the temperature of the liquid and confirming the match in monochromatic light. These colors correspond to those described in Figure 5-9 (page 48) of this text. *Photographs courtesy of Mickey Gunter of University of Idaho.*

A series of photographs of central stop dispersion staining colors showing the matching wavelength between the liquid and a ground smithsonite cone on a spindle stage. Precise wavelength matches were achieved by mounting the smithsonite with its c-crystallographic axis perpendicular to the axis of rotation of the spindle stage. Then using a monochrometer the desired wavelength of light was chosen and the crystal was rotated until a match was observed, the monochrometer was then removed and a photograph was taken. These colors correspond to those described in Table 5-1 (page 55) and Figure 5-15 (page 56) of this text. *Photographs courtesy of Matthew Sanchez of The RJ Lee Group.*

9 781946 850058

Figure 2

Figure 3

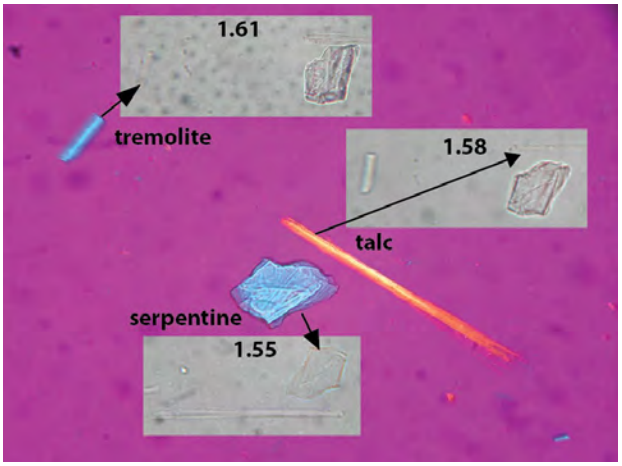

Figure 4

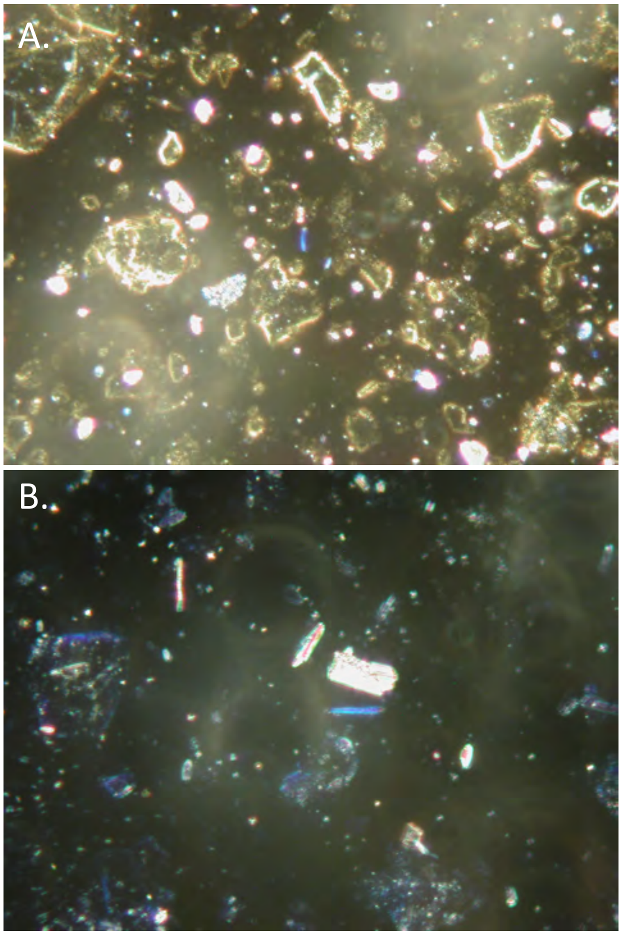

Figure 5

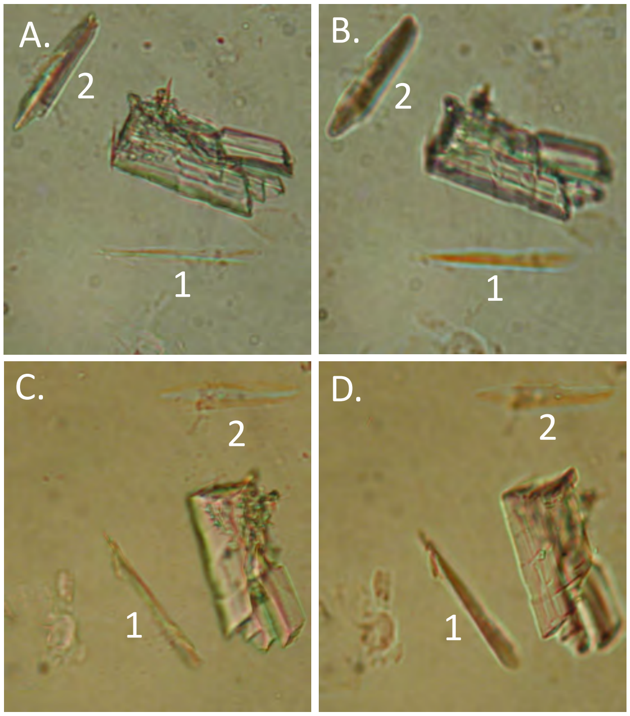

Figure 6

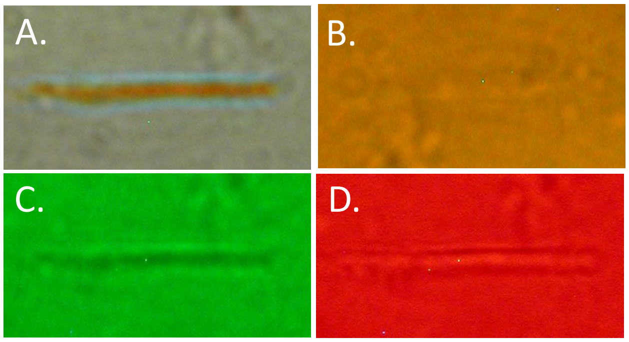

Figure 7

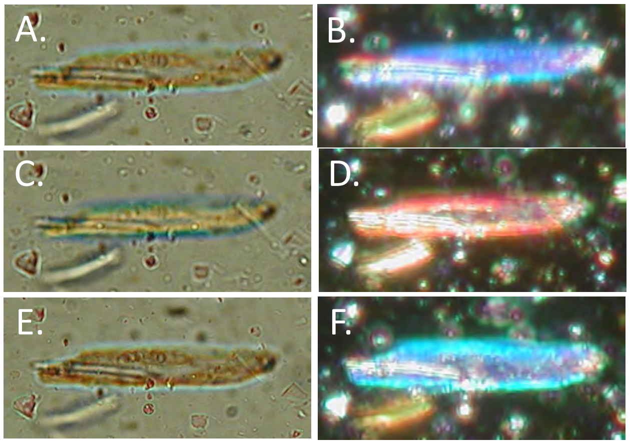

Figure 8

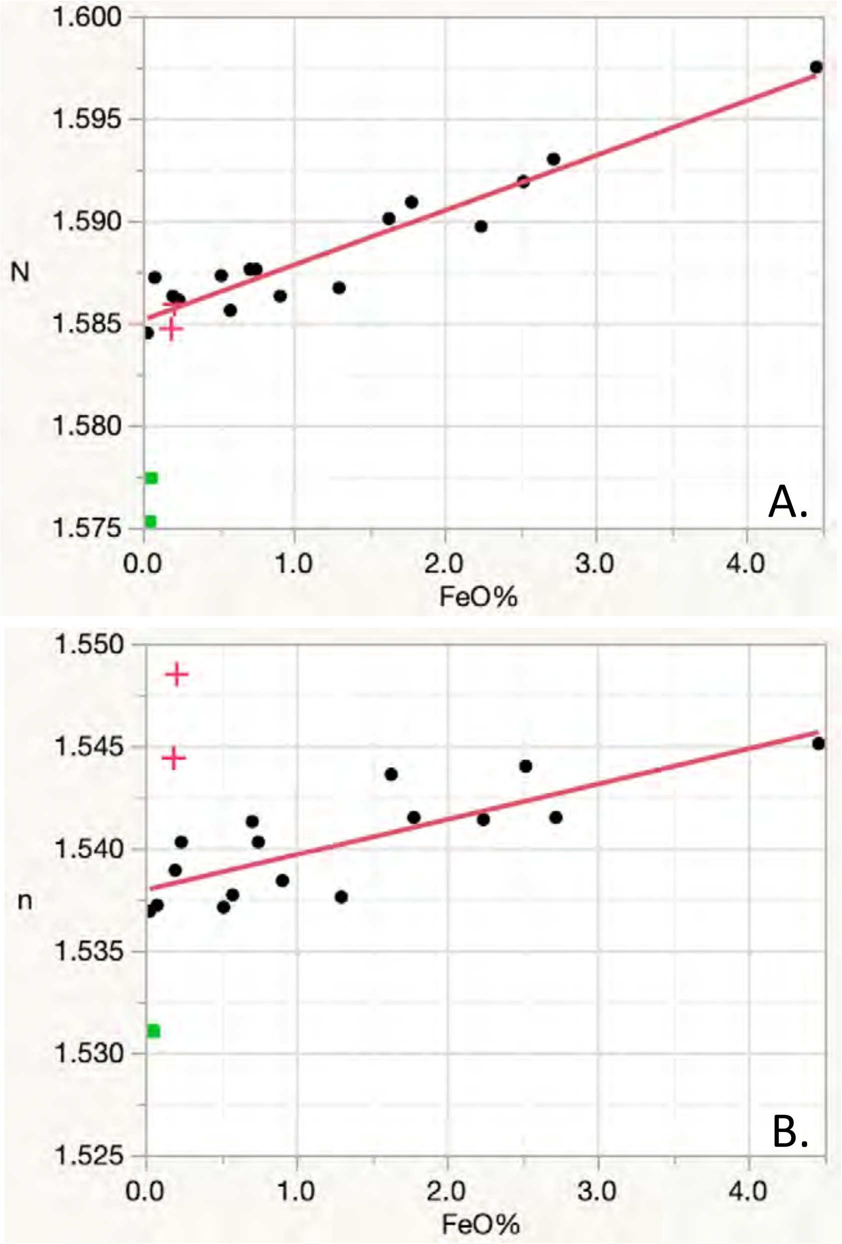
1.600
1.595
1.590
N
1.585
1.580
1.575
0.0
1.0
2.0
3.0
4.0
FeO%
A.
1.550
1.545
1.540
n
1.535
1.530
1.525
0.0
1.0
2.0
3.0
4.0
FeO%
B.

Figure 9

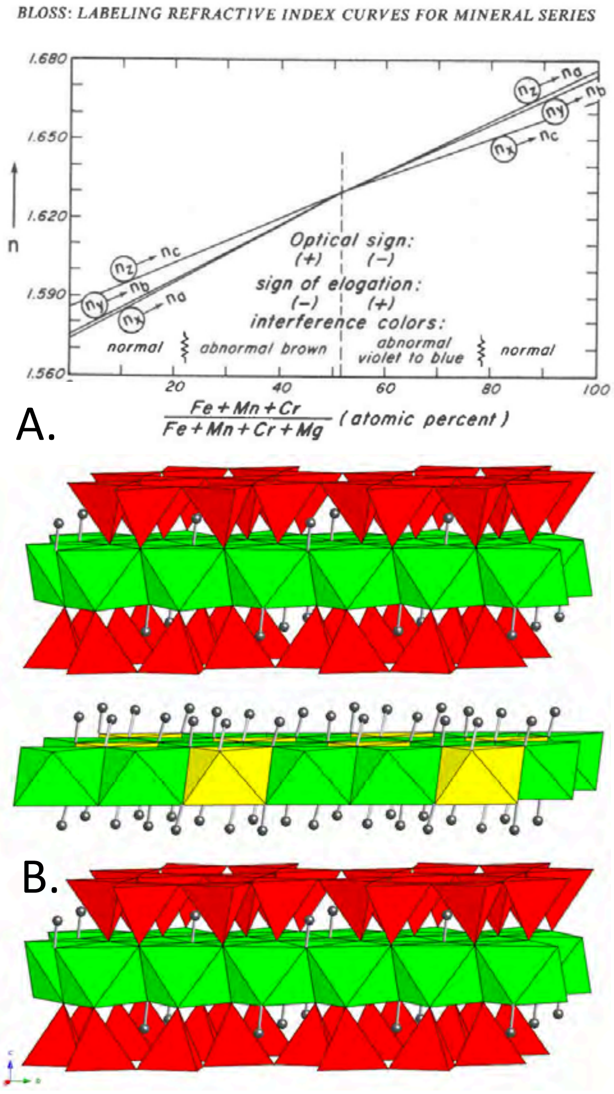
BLOSS: LABELING REFRACTIVE INDEX CURVES FOR MINERAL SERIES
1.680
1.650
1.620
1.590
1.560
n
n_z → n_a
n_y → n_b
n_x → n_c
n_z → n_c
n_y → n_b
n_x → n_a
Optical sign:
(+) (−)
sign of elogation:
(−) (+)
interference colors:
normal
abnormal brown
abnormal violet to blue
normal
20
40
60
80
100
$\frac{Fe+Mn+Cr}{Fe+Mn+Cr+Mg}$ (atomic percent)
A.
B.
c
b

Figure 10