Optical Mineralogy in a Modern Earth Sciences Curriculum

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ABSTRACT

Optical mineralogy is a subject firmly integrated into geoscience programs that offer mineralogy and petrology modules. Polarized-light microscopy remains a powerful and cost-effective analytical method, both at the educational and the professional level. It is the ideal analytical tool for the teaching laboratory. Virtually any petrographic work that does not specifically require electron-microscope-scale analysis involves an optical microscope, whether in conjunction with other analytical equipment, or not. However, changes in the perspectives of geoscience education and the necessity to accommodate students with interdisciplinary interests alongside those who opt for a classic geology degree create a need for an optical mineralogy course that is concise, but still meets the demands of subsequent course modules that build on it. There is a range of resources that we can make use of to maintain reasonably high levels of theoretical and practical skills in polarized-light microscopy, such as application-focused lab materials and practice-oriented teaching with a strong interactive component, as well as computer-based teaching aids.

INTRODUCTION

Polarized-light microscopy is of potential interest to any science that is concerned with crystalline materials (geology, mineralogy, materials science, biology, forensic science, to name the most obvious ones). It is traditionally taught as a mineralogy module, even though optical crystallography makes no distinction between natural minerals and synthetic crystalline materials. This article emphasizes geoscience aspects, simply because that is still the main field of application of polarized-light microscopy. Bloss (1999) aptly outlines the significance of mineral optics for geoscientists with his statement “The polarizing light microscope remains the premier tool for rapidly identifying the minerals and mineral reactions that occur in petrographic thin sections of rocks”. However, it must be kept in mind that the use of this analytical tool is by no means restricted to petrography, or even geoscience.

What organisms are for biology, what chemical elements and their compounds are for the chemist, earth materials are for geoscientists (if we, for the purpose of clarity, restrict the term “geoscience” or “earth science” to subjects concerned with the solid earth, including unconsolidated sediments). There is a clear and indisputable demand on geoscientists to have a fundamental understanding of earth materials, irrespective of one’s preference for basic research or for applied aspects of geoscience. The fact that earth materials, with few exceptions (such as melts, fluids, glasses, and organic substance), are composed of minerals underlines the significance of mineral science education for any aspiring geoscientist. The characterization of rocks and minerals remains a basic objective of geoscience education.

We have means to identify minerals on the basis of chemical composition (e.g., electron microprobe), or structure (e.g., X-ray diffraction), or both. Optical mineralogy employs specific physical properties that reflect both composition and structure. These are optical properties in the strict sense (refractive indices, color, birefringence, optic class, optic sign, optic axial angle), but also morphological-structural characteristics (form, habit, cleavage, twinning) and the relation between the two (sign of elongation, extinction behavior). I will restrict myself here to the discussion of transmitted-light microscopy, even though much of what is stated would apply to reflected-light microscopy as well. However, reflected-light microscopy is a more specialized subject commonly taught in conjunction with ore deposits, and is not necessarily part of a standard geoscience education program.

OPTICAL MINERALOGY: STAPLE DIET OR LUXURY SIDE DISH?

For many decades, optical mineralogy has been a core subject in most earth sciences departments. The routine examination of rocks or grain mounts from unconsolidated materials was typically performed with a microscope. With the advancement of other analytical tools, electron microprobe and electron microscopy in particular, the role of the polarizing microscope had been redefined in some ways (e.g., universal stage methods have been largely abandoned), but its significance has not been reduced by that. Rather, for many applications the combination of different analytical tools proves to be more powerful than each one by itself. It is also a matter of working efficiently to study samples with the microscope before using more specialized equipment such as a microprobe. The importance of the polarized-light microscope for microstructural studies remains unchallenged. Methods of collecting data may have changed (e.g., from measuring quartz c-axis patterns on the universal stage to image analysis methods), but the instrument of choice is still the same.

Yet, where questions are raised about the appropriateness of mineralogy courses in a geoscience curriculum, optical mineralogy appears to be one of the prime targets. The reasons for that are not entirely rational, it seems. To suggest that the availability of apparently more sophisticated methods has made “classic” petrographic microscopy redundant is nonsensical. Such a perception merely indicates a (possibly widespread) misconception about the capabilities and the range of applications of the polarized-light microscope.

The questioning of the appropriateness of teaching optical mineralogy in general is a relatively recent phenomenon which mostly relates to the restructuring of geoscience departments and programs. It is evident that many departments have focused on environmental and/or technical aspects, some perhaps to attract more students, some perhaps reacting to the periodical resurfacing of the demands for teaching more applied topics and less basic science. Geoscience is also branching out into new areas of research (such as geobiology and biomineralogy). Has all this made optical mineralogy less important in any way? The answer is clearly “no”, as will be discussed below.

There are other aspects that may have an impact on discussions about the viability of such a course module. Firstly, optical mineralogy has a reputation of being difficult to master, mainly on the theoretical side, where the indicatrix concept has almost legendary status amongst geologists. However, this is a teaching-learning problem that should not affect a rational decision about the significance of a course. As long as the course is taught with expertise, within an appropriate time frame, there is no reason why it should have a low rating with students. Secondly, furnishing a complete laboratory with good quality polarizing microscopes is an enormous expense which is partly balanced, though, by the low running costs once the laboratory is set up. Nevertheless, it must be conceded that the equipment costs may be prohibitive for smaller geoscience departments.

Hence, apart from the cost factor, three main questions need to be addressed in the discussion about optical mineralogy course modules:

- How relevant is the an optical mineralogy course within a modern geoscience education program?
- What could be the appropriate format of an optical mineralogy course?
- How can we teach the essence of this subject within a limited timeframe, without cutting too many corners?

RELEVANCE OF TEACHING OPTICAL MINERALOGY

Optical mineralogy as a course module cannot be assessed out of its context within the geoscience curriculum. It is (and must be) firmly interlocked with a variety of courses. Geology modules at lower level typically include macroscopic mineral and rock identification. Mineralogy in a stricter sense is taught on the next level, before or simultaneously with optical mineralogy. Petrology courses, including petrography of igneous, metamorphic and sedimentary rocks, follow. All three of the "petrologies" would commonly build on microscope skills. For petrography teaching, the polarized-light microscope is the instrument of choice in the classroom. Additional teaching of other analytical methods and equipment is desirable by any means, but it cannot replace microscopy at the interface between mineralogy and petrography.

What has been outlined above is a classic set-up of geology modules. However, we would grossly underestimate the versatility of the polarized-light microscope if we would see its use restricted to petrology. The important role of this instrument in basic and applied mineralogical research is underlined by the many examples discussed by Gunter (2004; this issue). The asbestos example in particular stresses the demand for skills in optical mineralogy in the expanding field of environmental mineralogy.

The optical microscope bridges the viewing range between macroscopic examination (eye, hand-lens) and the electron microscope. As grain sizes of typical metamorphic and igneous rocks fall into the tens-of-microns to centimeter range, the optical microscope is an obvious choice for studying rock textures. Examples are studies of the order of crystallization, mineral intergrowths and crystal alignment in igneous rocks, mineral sequences, reaction textures, and deformation microstructures in metamorphic rocks. In structural geology, the use of polarized-light microscopy in the study of microstructures remains an obvious necessity. The bandwidth of applications has even expanded here, on the experimental side (e.g., in situ deformation studies of natural or synthetic materials; Means, 1989) as well as on the analytical side (e.g., analysis of crystallographic-preferred orientation by image processing; Panozzo Heilbronner & Pauli, 1993). In economic and applied geology, transmitted-light microscopy is essential for the characterization of alteration styles, assessment of rock-mechanical properties, weathering index and weathering behavior. These are just a few selected examples.

Evidently, the strength of the polarized-light microscope lies in its versatility and cost-effectiveness. For the teaching lab, the following aspects are of particular relevance:

- Virtually all major minerals can be identified and described by optical means as long as the crystals are large enough, even to the extent that mineral compositions can be estimated (if not determined precisely);
- Most rocks have a grain size range that allows an overview of the rock on the scale of a thin section, as well as allowing detailed examination of single grains;
- Bulk rock composition can be estimated from the modal proportions of the constituents;
- Reaction textures and deformation-related microstructures (shape-preferred orientation, crystallographic-preferred orientation, grain-scale deformation, recrystallization) can be studied;
- Compositional and textural material properties can be examined simultaneously;
- Microscopes are easy to handle, with no need for continuous supervision, once the initial skills have been taught;
- Teaching of a large group is possible while each student works on his/her own microscope;
- The operating costs (replacement costs excluded) are very low.

When teaching systematic mineralogy, the polarizing microscope helps to form visual images of minerals in addition to what we observe macroscopically, in hand specimen or in outcrop. For many typically fine-grained minerals, it is the common image to recall. Also, properties such as cleavage or color may be easier to observe in the microscope than in a macroscopic specimen.

From both the professional and educational perspectives, we can safely state that polarized-light microscopy remains a powerful and cost-effective analytical method in the geosciences. The extent of information that a well-trained person can extract from a simple rock thin section in a short amount of time is exceptional, even taking into account the obvious limitations with determining mineral compositions. Importantly, polarized-light microscopy is a method that is almost exclusively taught in geology and mineralogy, as opposed to any other analytical method of similar significance in earth sciences. A graduate applying for a position that involves laboratory work is likely to face competition from non-geoscientists in almost all areas of analysis - unless skills in polarized-light microscopy are asked for. It seems irresponsible to give up that competitive edge for no good reason at all.

The answer to whether optical mineralogy should be taught to geoscience undergraduates is quite simple. As long as petrography and mineral analysis are part of the curriculum, there is no real choice. Without an optical mineralogy course in the curriculum, the teaching of petrology courses is without substance. Furthermore, it makes the teaching of mineralogy for geologists much less practical.

The basic question is therefore whether mineralogy and petrology remain core subjects in geoscience. As long as geologists and mineralogists are expected to provide expertise on earth materials, they will. However, geoscience branches out in very different directions, towards chemistry, physics, biology, materials science, and engineering. Many teaching institutions would struggle to cover all this variety. Nevertheless, those institutions specifically offering general geology degrees must consider very carefully whether they want to give up teaching what many consider as fundamental skills of a geologist.

CONSIDERING THE OPTIONS: HOW BRIEF OR HOW EXTENSIVE?

Assuming that the optical mineralogy course is not taught as a subject completely detached from systematic mineralogy, we may consider three possibilities:

1. A basic course teaching a very restricted selection of 10 to 15 of the most abundant minerals.

2. A single course integrating mineral optics theory and systematic mineralogy, covering a standard range of minerals sufficient to form the basis of subsequent petrography courses. These would commonly include igneous, metamorphic and sedimentary petrography, but perhaps also microstructural studies as part of a structural geology course.

3. A multi-semester sequence of interrelated modules, starting with a course on optical principles and crystal optics, followed by a course on systematic optical mineral determination, then proceeding to advanced analytical methods and/or petrography courses with emphasis on microscopic work (as in 2).

Option 3 is or was, in one variety or another, the classic arrangement of teaching mineral optics and follow-up courses in many geology and mineralogy departments. Provided the courses are delivered in a competent fashion, this "luxury edition" of optical mineralogy is still the best and most logical way of developing professional skills with the polarizing microscope. However, students who follow a career that does not suggest microscope work will be of much importance, could indeed question the amount of time spent on this subject during education. Hence, it is this course structure which commonly sparks most controversy.

The geosciences education programs of many departments cannot accommodate option 3 anymore, or perhaps never could. A basic course (option 1) satisfies the needs of most students who do not study for a geology degree, but take geology courses as part of their program. Option 1 would even allow students to continue with introductory sedimentary and igneous petrography. It is clearly insufficient, however, to study metamorphic rocks, or to do advanced petrographic work in general. This dilemma could be solved, at least in larger departments, by teaching different types of microscopy courses for geology majors and non-geology majors (or wherever the dividing line is drawn). Applied geoscience programs in which petrology and structural geology do not feature prominently, but where teaching objectives include mineral-analytical skills (e.g., for environmental mineralogy) may be served best by an option 1 course extended on the methodical side. However, special quantitative methods that demand a thorough understanding of optical principles should still be taught in advanced mineralogy courses rather than in the introductory module.

Generally, the actual contents of an optical mineralogy course - whatever its extent - would depend very much on the associated modules and the nature of the program. A strong petrological component in the program calls for a sound knowledge of rock-forming minerals. Emphasis on the general mineralogical-analytical side, on the other hand, would perhaps render the systematic approach to minerals teaching less appropriate, with the methodical component then carrying more importance.

In the following, the specific aspects of teaching a concise one-semester course that accommodates students from a variety of programs are discussed in detail, based on personal experience over many years of teaching. In comparison with a full-scale education in optical mineralogy (as in option 3), some of the more specialized topics have been reduced, but the simple solution of leaving out enough material to fit the rest into a tighter time-frame is clearly impractical. There is a certain minimum of theory that is needed and there is a minimum set of minerals to be discussed, in order to meet the entry requirements of higher-level courses. Hence, we have to look at methods and resources to increase the effectiveness of our teaching.

COURSE OBJECTIVES

The specific objectives of an introductory optical mineralogy course are to learn to identify and characterize minerals in thin sections and grain mounts. This encompasses routine recognition of the most common minerals in igneous, metamorphic and sedimentary rocks and unconsolidated materials (minerals of submicroscopic size such as clay minerals excepted), as well as the ability to use optical properties to determine mineral species or varieties with which a student or a professional is less familiar. The development of these skills cannot rely on coursework only. Further practical training and experience are vitally important.

As with any other analytical equipment, the user has to understand the basic functions of the polarizing microscope in order to be able to use it sensibly, and has to have some knowledge about the methods of sample preparation. The polarizing microscope should be taught as being one of several analytical instruments available to the earth scientist for analyzing minerals and rocks. Each of these instruments has its specific uses which need to be understood.

Even though an introductory course in polarizing microscopy concentrates on single minerals and their properties, these minerals are commonly observed in a natural, polymineralic environment (unless we use monomineralic concentrates). Therefore, by looking at thin sections in particular, the experience at the microscope extends beyond identifying single minerals. As the course advances, students will start to get a feel for mineral associations and mineral abundance in common rock types, random and preferred orientations, grain-size variations and more, without being explicitly taught these subjects at that stage.

THEORETICAL ASPECTS OF MINERAL OPTICS

Petrographic microscopy, like so many other analytical methods, is rarely and end in itself, but rather a means to other ends. We should not forget this when we teach the theoretical side of mineral optics. A one-semester course serving a mixed clientele from different science programs cannot dive into every detail of optical crystallography, as interesting as that may be for the specialist. On the other hand, without any theory of crystal optics, even the most fundamental optical properties of minerals cannot be understood. At the very core of this theoretical framework are basic crystallography, principles of optics, and indicatrix theory.

The latter is commonly perceived by students as the most difficult part of crystal optics. Yet, there is no better or easier way to sensibly describe, and communicate about, light propagation in anisotropic materials and resulting optical phenomena. We may distinguish between "inherent" optical properties that are entirely controlled by mineral composition and structure - and hence cannot vary once composition and structure are defined - and "acquired" material properties (mainly grain morphology, including grain surface character, habit and twinning) that are influenced to at least some degree by factors other than structure or composition. All the inherent properties are expressed in the geometry of the indicatrix, apart from cleavage and color. Without the indicatrix concept, the optical properties of anisotropic minerals can be observed, but not understood. This is unsatisfactory for both teachers and students. Science teaching should generally aim to close the gaps between observation and comprehension.

In our present curriculum, optical mineralogy is integrated into a one-semester mineralogy module. Lectures are primarily on theoretical aspects, and practical sessions are taught in the microscope lab. The lectures cover the following topics:

- Basic aspects of optics
  (nature of light, frequency, velocity, wavelength, electromagnetic spectrum, refraction, refractive index, color of minerals, polarized and non-polarized light, optical isotropy and anisotropy)

- Behavior of light in optically isotropic materials
  (light propagation, microscopic identification of optically isotropic materials)

- Behavior of light in optically anisotropic materials: uniaxial and biaxial minerals
  (light propagation, ray velocity surfaces, indicatrix configuration, indicatrix orientation in a crystal plate, relationship between crystallographic axes and optical orientation)

- Examination of anisotropic minerals with the polarized-light microscope
  (birefringence, retardation, interference colors, effect of polarization on fast and slow rays for variable crystal orientation, determination of vibration directions of fast and slow rays, sign of elongation, extinction characteristics, optic axis interference figures)

A total of about 15 full hours of lecturing is required for theory. There is, however, little time to spend on optical experiments. In the practical sessions that run parallel to the lectures, students see the "experimental" side while they work systematically through the various minerals. The one important experiment that is conducted during lectures is the calcite experiment as described in Nesse (1991). The optical principles that can be taught with relatively simple means - a calcite rhombohedron of optical quality and two polarizing filters - are the polarization effect, the splitting of light rays, their vibrations directions, and the geometric relations of these optical phenomena to crystallographic orientation (see also Stoddard, 1997, and Zimmermann, 1997, for details). An additional advantage of the calcite rhombohedron with its sets of lower and upper parallel faces is that the conditions of vertical light incidence and light propagation through a crystal plate can be directly related to the orthoscopic operation mode of the polarizing microscope. Thus, a whole range of observations can be used to start developing the theoretical framework of crystal optics and its applications to the microscope.

COURSE EQUIPMENT, SAMPLE MATERIAL, REFERENCE MANUALS

Ideally, a polarized-light microscopy course is equipped with a sufficient number of quality binocular microscopes with a minimum of three objectives, a demonstration facility such as a petrographic microscope with a video camera, standard teaching aids such as indicatrix models and perhaps ray velocity surface models, interference color charts (Michel-Lévy charts), and all the necessary samples. The basic design of polarizing microscopes has remained very much the same over many decades except for improved optical systems and light sources.

The best technical set-up is wasted if the material used is inferior, difficult or unattractive. Teaching philosophies may differ in what type of material is most suitable for beginners. It is generally a sensible concept to provide different examples for the same mineral species, time permitting. Students should be aware of variations, such as morphological characteristics or color, which can be demonstrated using different samples. The class response is probably more enthusiastic if samples are attractive, easy to work with (not badly weathered), and technically well prepared. Low-quality samples are definitely not a good starting point for novices and are likely to dampen the students' interest in the subject.

Concerning textbooks, relatively compact mineralogy courses require an economic solution that combines

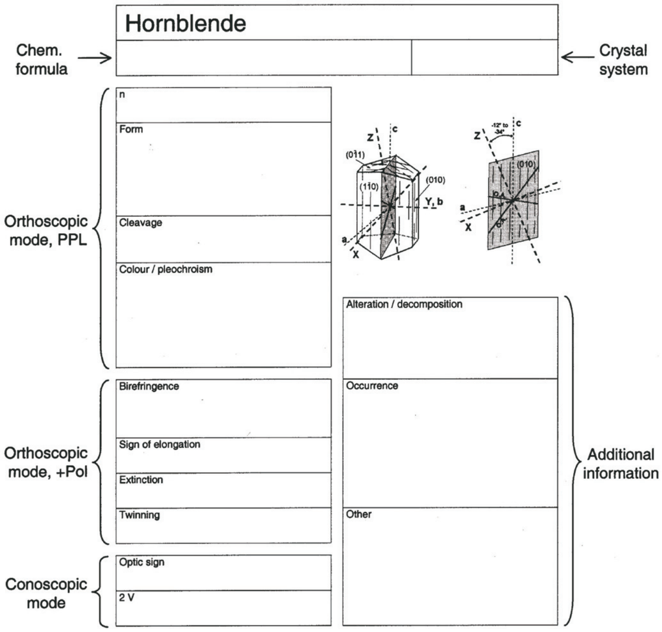

Figure 1. Center: mineral sheet from laboratory manual. Explanations for the various blocks have been added here. Data are entered into the sheet by each student once the mineral has been examined and the properties have been discussed with the class.

"classic" mineralogy and crystallography, analytical methods in theory and practice, as well as systematic mineralogy including mineral properties (as in Nesse, 2000). There is a range of more detailed textbooks that specialize on theoretical and practical sides of optical mineralogy (such as Bloss, 1961, 1999, Wahlstrom, 1979, Nesse, 1991), which can be recommended to students for consultation. Undoubtedly, there will also be increasing competition from learning software in the future.

Whatever the preferred solution may be for learning aids on the theory side, a manual with mineral data is indispensable when actually using the microscope. There are two principal ways to operate: (1) to teach textbook-based practicals, or (2) to provide students with a suitably designed, self-prepared course manual. If we operate in the microscope lab with any of the books that contain extensive compilations of mineral data (such as Tröger et al., 1979, Phillips & Griffen, 1981, Ehlers, 1987, Deer et al., 1992, Gribble & Hall, 1992), then all students should have the same book on the workbench. To ensure that this is indeed so, we would have to make a purchase compulsory, or we provide the class with a set of copies for the duration of the course.

The use of any type of book with a systematic section listing optical properties implies a specific approach to teaching new minerals. Unless the teacher chooses not to use the book temporarily as a new mineral is introduced, all mineral properties will be accessible at any time. Hence, students work on the microscope comparing their observations with the data in the textbook, which would normally correlate perfectly. The learning process is hence restricted to confirmation of what the book says, and errors are virtually excluded. This method can easily mislead a student in believing that he or she is mastering the subject.

After teaching optical mineralogy courses in various departments over many years, I stopped using optical mineralogy books in the microscope lab altogether, except for higher-level petrology practicals. Apart from the problems discussed above, mineral data compilations have one serious disadvantage for the inexperienced: they aim to be comprehensive. The number of minerals described is far beyond what is necessary for a student to know. Furthermore, due to their comprehensiveness and their systematic approach, the descriptions of mineral properties inevitably includes information that is not critical for routine microscope work. It is difficult, though, if not impossible for a novice to judge what is important and what is not. We also need to remind ourselves that beginners have difficulty in judging how common or uncommon minerals are, and hence how likely or unlikely certain minerals are they can think of.

For all purposes of a condensed-format microscope course, only a strictly reduced set of minerals makes sense. Without extensive microscope experience, it is much easier to handle a smaller data compilation of essentials rather than a complete minerals optics book. There is also much less danger in getting lost and spending more time than necessary on unidentified minerals. Perkins & Henke (2000) have explicitly addressed this need with a manual that contains detailed descriptions of some 60 minerals and mineral groups (plus a few opaque minerals). In comparison, MacKenzie & Adams (1994) restrict the description to a mere 15 minerals and mineral groups, which is only just sufficient for a very basic course as outlined above in option 1. The emphasis of this book is on photomicrographs of minerals and rocks, and optical data are not provided. Hence, it can hardly serve as a search manual for routine petrography in geology, even though it is a visually attractive introduction to petrographic microscopy.

Is there yet another alternative? After having taught textbook-based microscope courses for a while, I started to work along two basic lines of approach: (1) If the range of minerals discussed in the course encompasses most of those which students (and professionals, for that matter) have a good chance of observing in common rock types and surface depsoits, we might just as well restrict the lab materials to these minerals; (2) a better learning effect can be achieved if the students determine the optical properties of newly introduced minerals themselves, rather than extracting the properties from books.

Even though the teaching conditions varied between different departments, I found that I can get through a maximum of about 30 minerals and mineral groups in a single-semester course. This forms a fairly solid basis for the subsequent petrology courses. Evidently, the range of minerals that are most relevant for sedimentology and igneous petrology is much smaller than what is required to teach even an introductory course on metamorphic petrology. Still, there is no need to be comprehensive. It must be clear from the beginning that the minerals of the optics course are only a selection and that an important objective of the course is to be able to describe the optical properties of any mineral, whether present on that list or not. Eventually, comprehensive data compilations as those cited above would have to be consulted for less common minerals not discussed in the course.

How can we operate if we need a systematic mineral manual at the microscope, but choose not to provide all the optic properties of newly introduced minerals from

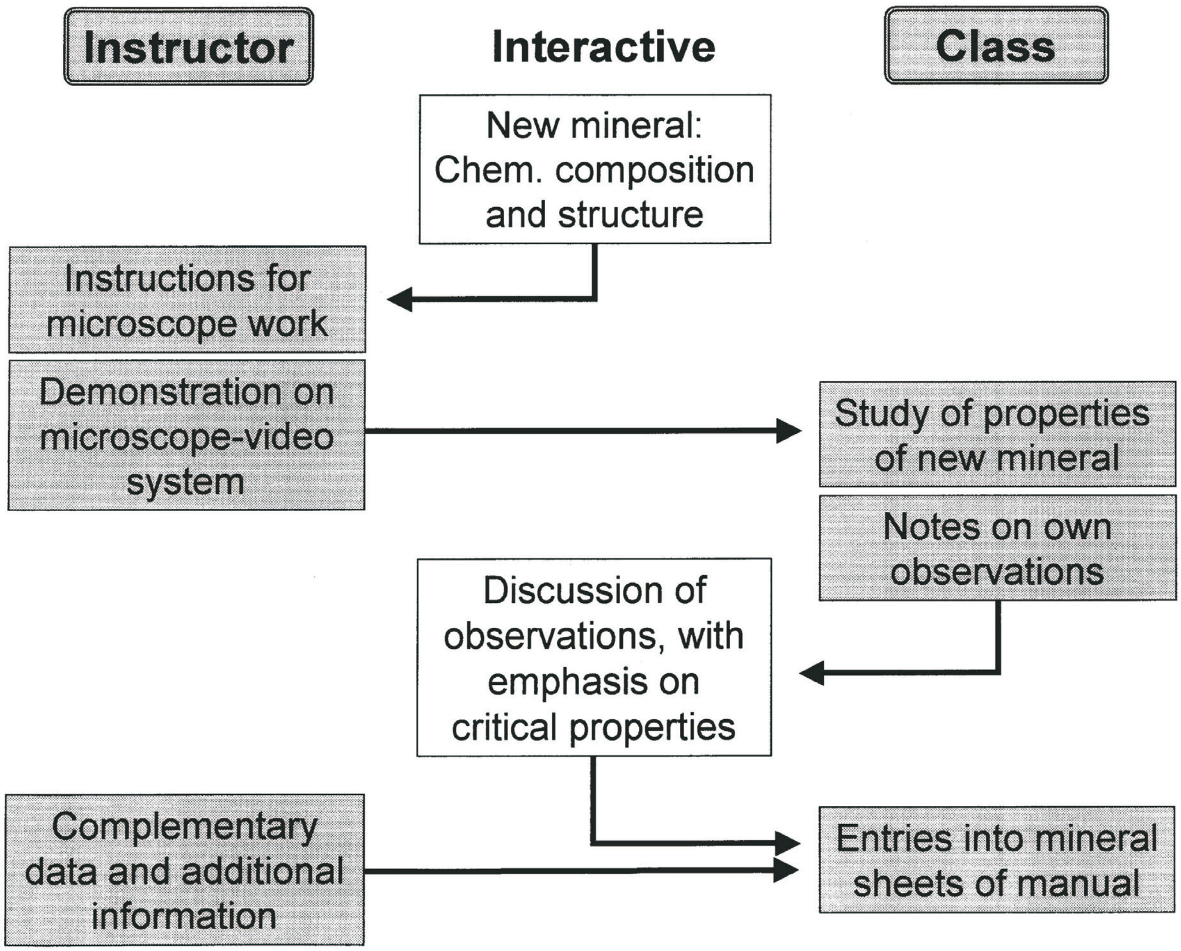

Figure 2. Routine procedure for introducing a new mineral in the microscope laboratory.

the start? A workable solution that I have tested over some years now is a laboratory manual into which data are entered as the course advances. The one I designed for optical mineralogy classes consists of a methodical part and a systematic part. The systematic part comprises a set of mineral sheets (one page for each mineral or mineral group), as in Figure 1. Only the mineral name is printed on top, and a figure is included. The rest of the sheet has to be filled in by the student as the course proceeds. To encourage a methodical approach, the sheets are subdivided into blocks: general information at the top (mineral name, chemical formula, crystal system), properties that are primarily (though not exclusively) examined in orthoscopic mode and plane-polarized light, properties that are observed in orthoscopic mode with polarizers crossed, and properties that are observed in conoscopic mode. Additional information of importance is added in the last block. If appropriate, graphs (for example for variation of properties in solid solution series) are added on the backside.

The methodical part on microscopic mineral analysis lists and explains the different features that are important for optical mineral characterization and identification. The theoretical background of mineral optics as covered by lectures is not included. The handbook is intended for use at the microscope; hence, the emphasis is on practical aspects. The sections of the methodical part essentially follow the subdivision on the mineral sheets:

- General aspects: Mineral composition, crystal symmetry, and optics
- Orthoscopic mode / plane-polarized light: relief and refractive indices, form, cleavage, color
- Orthoscopic mode / crossed polarizers: birefringence, sign of elongation, extinction, twinning
- Conoscopic mode: optic character and optic sign, optic axial angle
- Additional information: retrogression - alteration - decomposition, occurrence

In special "What-to-do" sections, the operations carried out at the microscope are explained step by step. This is to help students refresh their memory if necessary, and let them develop confidence with the technical operation of the microscope (which in turn helps to avoid unnecessary damage to microscopes).

PRACTICAL SESSIONS

Before the start of the main systematic section of the mineralogy practicals, there is a general introductory session on relief and refractive index, isotropy and anisotropy. This exercise is done with single- and multi-mineral grain mounts (e.g., quartz, garnet, fluorite, rutile) and a range of liquids with different refractive indices. All other practicals are dedicated to specific minerals, starting with quartz. In principle, the course follows the standard mineral classification of H. Strunz "backwards", from framework silicates to orthosilicates and then to non-silicates. By doing this, the most abundant minerals are taught early in the course (quartz, feldspars, micas, pyroxenes). This has the distinct advantage that, within a few weeks, students examining thin sections can recognize most of the minerals associated with any new mineral introduced and therefore see the mineral in its natural context. The only minor disadvantage with such an approach is that the first hours will be spent on framework silicates that are very similar in many respects (colorless, low relief, low birefringence).

The various optical and morphological properties are introduced successively, whenever a suitable mineral is next on the list. Starting with quartz, relief, form, birefringence, optic character and sign are given special consideration. With the introduction of feldspars, extinction, twinning, cleavage, alteration and decomposition are added. Once the course has advanced to the mica group, all the principal properties have been discussed using real mineral examples, and a more general routine can be followed from there.

New minerals are introduced as follows (Figure 2): First, mineral composition and crystal system are discussed (which would commonly be a refresher of previous mineralogy lectures). Then the class is given explicit instructions which mineral properties to examine with the microscope. Emphasis is generally placed on critical mineral data. It is too time-consuming and simply unnecessary to go through the entire set of properties for each mineral.

Examples of the mineral are shown on the demo-microscope-video system and if appropriate, hints are provided how to find the mineral in the thin sections. Then students are left to work on their own for some time to make notes on their observations (no entries into the manual at that stage). Discussions between students are encouraged as part of the co-operative learning effort. Support at the microscopes is generally provided throughout the practicals. Commonly, thin sections from a range of different samples are supplied.

After a specified time, the results obtained by the students are discussed, and the correct properties are then entered into the manual's mineral sheets, taking into consideration the full range of variations to ensure a general applicability of the data. The easiest way for the instructor is to either use reproductions of the mineral sheets for an overhead projector, or to use a data projector. Less critical data as well as information on occurrence and breakdown products are provided by the instructor to complete the data set, but there is no necessity to include properties that are normally not checked during routine petrography. Once the sheet is completed, every student has an identical data set in his or her manual.

At the end of the course, the manual is complete. It is further used for practical assignments and thin section-based exams. Students keep the manual after the course and use it in other modules if they continue in earth sciences. As it is ring-bound, more minerals can be added at any time. A mineral sheet template for photocopying is included in the original manual.

The above outlined system of teaching minerals at the polarized-light microscope has a substantial interactive component between teacher and class; it provides a very good control for the teacher on the progress and level of understanding of the class and of individual students. The condensed course format does require a relatively concentrated effort on all sides, and, without additional exercise, the necessary level of experience and confidence at the microscope may not be reached. Hence, students are encouraged to use the microscope lab outside formal course hours as much as possible. As the final assessment in practical skills before the exams, each student is given a different thin section on which a complete optical-mineralogical analysis has to be performed.

COMPUTER-AIDED LEARNING PACKAGES

What we will see in the future is increasing support from computer resources. Presently available computer-aided learning (CAL) packages include the optical mineralogy module of the UKESCC software package (Emley et al., 1998) and the digital microscope of Palmer et al. (1999). We will also see an increasing amount of photomicrographs being made available through the internet or as compilations on CD. These resources are welcome for demonstration purposes in the labs and provide important learning resources for students outside actual course hours.

There is indeed a large potential in CAL to support optical mineralogy teaching, both on the theoretical side and on the practical side. One standard line to follow is repetition of lecture material in an interactive way. The particular advantage of computers in mineralogy and petrography, however, lies in 2-D and 3-D graphical visualization of structures, optic phenomena and concepts, as well as in animated graphics. Even though all of this can be used for classroom demonstrations once teaching practice has advanced to using a data projector, it is important for students to be able to revisit such sections on their own. 3-D concepts in particular are typical problems where students can have a very different levels of comprehension.

One of the technical challenges of optical mineralogy software is the simulation of the polarized-light microscope. This also incorporates the question whether we could teach optical mineralogy without the real microscope. While the "microscope simulator" is a valuable tool for clarifying practice-related procedures, it is unlikely to ever replace the reality of examining rock thin sections and minerals with the optical microscope. Polarized-light microscopy is a typical hands-on subject, and there is no need to change that. Just as a geologist cannot acquire and test the essential skills in geological mapping without physically going into the field, microscopy can neither be taught nor learned without using a microscope. Real progress in teaching this topic lies in the sensible combination of the strengths of CAL tools with the advantages of personal teaching (such as flexibility and direct interaction with students), printed course materials, and hands-on exercises using real equipment and real samples.

FINAL COMMENTS

The students' response to the course and the teaching concept has been positive, as is evident from course evaluation questionnaires. Perhaps surprisingly positive, considering that mineral optics and systematic mineralogy are commonly not at the top of the list of students' favorite courses. The prime target of the course restructuring has always been to meet the objectives in an effective way. Not surprisingly, the workload in the course is perceived as relatively high. Class assessment and examinations yield positive results, with pass rates between 80 and 100%. The "home-made" lab manual is generally very well received by the students. As it is produced once a year, it can be continuously updated and modified by the instructor.

A positive aspect of offering a relatively compact optical mineralogy course is that students who are still uncertain about the final route of their studies may rather try a short option than opt for a multi-semester sequence of modules. Some may then find the subject attractive enough to include mineralogy in one form or another in their further studies. The integration of mineralogy courses into programs other than mainstream earth science would certainly help to attract students and promote mineral science in general.

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REFERENCES

Bloss, F.D., 1961, An Introduction to the Methods of Optical Crystallography, Holt, Rinehart and Winston, New York, 294 p.

Bloss, F.D., 1999, Optical Crystallography, Mineralogical Society of America, Washington, D.C., 239 p.

Deer, W.A., Howie, R.A. and Zussman, J., 1992, An Introduction to the Rock-Forming Minerals (2nd edition), Longman, London, 696 p.

Ehlers, E.G., 1987, Optical Mineralogy, Vol. 2. Mineral Descriptions, Blackwell Scientific Publ., Palo Alto, 286 p.

Emley, D.W., Rowbotham, G. and Lees, G.J., 1998, Optical Mineralogy (Version 2), UK Earth Science Courseware Consortium, University of Manchester.

Gribble, C.D. and Hall, A.J., 1992, Optical Mineralogy: Principles and Practice, UCL Press, London, 320 p.

Gunter, M.E., 2004, The polarized light microscope: Should we teach the use of a 19th century instrument in the 21st century?, Journal of Geoscience Education v. 52, p. 34-44.

MacKenzie, W.S. and Adams, A.E., 1994, A Colour Atlas of Rocks and Minerals in Thin Section, Manson Publ., 192 p.

Means, W.D., 1989, Synkinematic microscopy of transparent polycrystals, Journal of Structural Geology, v. 11, p. 163-174.

Nesse, W.D., 1991, Introduction to Optical Mineralogy (2nd ed.), Oxford University Press, New York, 335 p.

Nesse, W.D., 2000, Introduction to Mineralogy, Oxford University Press, New York, 442 p.

Palmer, D.C., Tindle, A.G. and Crompton, S., 1999, Digital Microscope, CD S260 Geology Block 2, The Open University, Milton Keynes.

Panozzo Heilbronner, R. and Pauli, C., 1993, Integrated spatial and orientation analysis of quartz c-axes by computer-aided microscopy, Journal of Structural Geology, v. 15, p. 369-382.

Perkins, D., and Henke, K.R., 2000, Minerals in Thin Section. Prentice Hall, Upper Saddle River, 125 p.

Phillips, W.R., and Griffen, D.T., 1981, Optical Mineralogy. The Nonopaque Minerals. W.H. Freeman, San Francisco. 677 p.

Stoddard, E.W., 1997, Minerals and Light, in: Brady, J.B., Mogk, D.W. & Perkins, D. (eds.), Teaching Mineralogy, Mineralogical Society of America, Washington, D.C., p. 291-296.

Tröger, W.E., Bambauer, H.U., Taborszky, F. and Trochim, H.D., 1979, Optical Determination of Rock-Forming Minerals, Part 1: Determinative Tables, Schweizerbart, Stuttgart, 188 p.

Wahlstrom, E.E., 1979, Optical Crystallography (5th ed.), John Wiley & Sons, New York, 488 p.

Zimmermann, H.D., 1997, Experiments in Crystal Optics, in: Brady, J.B., Mogk, D.W. & Perkins, D. (eds.), Teaching Mineralogy, Mineralogical Society of America, Washington, D.C., p. 297-308.