

# A Strategy for Teaching an Effective Undergraduate Mineralogy Course

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## ABSTRACT

An effective undergraduate mineralogy course provides students with a familiarity and understanding of minerals that is necessary for studying the Earth. This paper describes our strategy for integrating the disparate topics covered in a mineralogy course and for presenting them in a way that facilitates an understanding of mineralogy that enables students to apply it in subsequent courses and research. Our strategy is to organize the course into a well-integrated sequence of lectures, demonstrations and laboratory exercises that unfolds the material logically and at a pace that is responsive to the students' needs. The course begins with six weeks on crystal chemistry, then five weeks covering analytical methods for characterizing minerals and ends with five weeks on the silicates. This order facilitates a progression of learning from the basic concepts to the more advanced and allows us to reinforce the concepts of crystal chemistry during the final section on the silicates. Optical mineralogy is almost entirely taught in the lab and is aided by use of a mineral identification chart developed to help students learn to identify minerals in thin section. Student performance is assessed through one technical paper and presentation as well as homework, essay exams and lab practicals.

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## INTRODUCTION

An effective course in mineralogy is essential for students to develop an understanding of the Earth. Most undergraduate geology programs in the U.S. include only one course in mineralogy or have consolidated mineralogy and petrology into a single course. Therefore, a well thought out strategy for enabling students to develop their understanding of the chemical and physical behavior of minerals is essential. The course material should be presented in a logical order and at an appropriate level and pace with the novice student in mind. Mineralogy should become one of the courses that students look forward to taking. Our goal is for each student to develop a sufficient understanding of minerals to effectively use and integrate it into other course work and in solving Earth-related problems.

Our undergraduate mineralogy course covers crystal chemistry, crystallography, descriptive mineralogy, mineral identification, and analytical methods including X-ray diffraction and electron microprobe analysis. Most mineralogy students have little background (usually one semester of chemistry and possibly one semester of physics) to tackle these often abstract topics. However, our students are quite excited and hopeful at the prospect of learning as much as possible about minerals. This optimism in the face of what is perceived as a difficult course speaks to how

much geology students like rocks and minerals. We make every effort to nurture that initial optimism by (1) starting with a familiar topic, (2) presenting information in a logical sequence and at an appropriate pace, (3) working to make each class period a dynamic presentation, and (4) providing encouragement throughout the semester. The danger in letting their initial optimism dissipate is that students can become demoralized enough to negatively affect their learning and thus their ability to apply mineralogy in other classes.

Teaching an effective mineralogy course requires a viable strategy for presenting the course material in a logical, well-integrated fashion. Although there is no unique logical order for presenting materials in mineralogy, we suggest that some ways are more effective than others. For example, a common, but often unproductive way is to start the course with a detailed discussion of crystallography. This traditional approach is used by many textbooks (e.g., Nesse, 2000). However, because symmetry is an abstract and unfamiliar subject requiring lots of new terminology, most students initially have difficulty understanding its relevance. Starting with such an abstract topic is likely to frustrate already nervous students which tends to erode their confidence. In the preface of the 22<sup>nd</sup> Edition of the *Manual of Mineral Science*, Cornelis Klein (2002) explains that, while participating in the 1996 Mineralogical Society of America workshop on Teaching Mineralogy at Smith College, he learned "that students are more comfortable if the course begins with chemical and crystallochemical subject matter, instead of crystallography." He goes on to say, "Last year, the first time in a long teaching career in mineralogy, I myself began the course with subject matter in chemistry and followed with crystallographic concepts. It worked well." Klein (2002) reorganized the 22<sup>nd</sup> Edition placing the chapters on crystal chemistry and physical properties at the beginning, ahead of those discussing crystallography.

This paper describes the undergraduate mineralogy class we have developed and currently teach that has been effective for encouraging and enabling students to understand mineralogy. Although the Mineralogical Society of America's monograph on Teaching Mineralogy (Brady et al., 1997) and numerous articles published in the *Journal of Geoscience Education* contain well-developed exercises and strategies for teaching specific topics in mineralogy, there are few recent publications addressing the overall course design. We are not suggesting that there is only one way to teach an effective course but rather, that the focus must be on facilitating students to understand and think rationally about minerals so they can interpret and predict their physical and chemical behaviors. We developed our course while team teaching mineralogy at Purdue

Week	Lecture Subject	Lab Exercise	Minerals in Lab
1	Course introduction Chemistry 1897-1927	No lab	
2	Atomic structure & the periodic table Chemical bonding & bond energy curves	Physical properties	Native elements
3	Intro to solids and Pauling's rules Radius ratios(r/R) & coordination numbers	Close packed structures and lattices	Sulfides
4	r/R ranges and ionic substitution Physical properties of the non-silicates	Non-silicate structures	Oxides and hydroxides
5	Intro to the morphology of crystals Point symmetry & Miller indices	Point symmetry and structural classification of minerals	Halides, fluorides and carbonates
6	Stereographic projection & forms Intro to internal symmetry & lattices	Point symmetry (cont.)	Sulfates, phosphates, borates, and other "ates"
7	<b>Lecture Test</b> Space groups & 14 Bravais lattices	Review for Lab midterm	
8	Crystal structure representations Intro to light theory & interference effects	<b>Lab Midterm</b>	
9	Intro to X-ray diffraction X-ray vs. Microprobe analysis	Powder X-ray diffraction	Tectosilicates
10	Interpreting microprobe data Introductions to Indicatrix theory	Analysis of X-ray data	Phyllosilicates
11	<b>Lecture Test</b> Intro to silicates	Intro to optics and the polarizing microscope	Inosilicates and cyclosilicates
12	Framework silicates & phase diagrams Sheet silicates	Uniaxial theory & thin section mineral ID	Sorosilicates and orthosilicates
13	Chain silicates Bowtie and ring silicates	Optical theory (cont.) & thin section mineral ID	Thin section minerals: quartz, K-feldspar, plagioclase, biotite, muscovite, hornblende, chlorite, augite, olivine, garnet, zircon, apatite
14	Island silicates Color in silicates	Phase diagrams and the structure of the Earth	
15	Structure of the Earth Economic mineral deposits	Review for the final	
16	Economic mineral deposits (cont.) Student Presentations	<b>Lab Final</b>	
<b>Cumulative Lecture Final</b>			

**Table 1. Outline of topics covered in Mineralogy at IUPUI, fall semester 2002.**

University, and have taught it over the past few years at our respective universities. The course is based on 2.5 hours of lecture and 3 hours of lab per week, our classes vary in size from 8-30 students per 16 week semester.

## **MINERALOGY: PART 1**

Our course begins with a selective review of chemistry because most of the students have had a chemistry course and are familiar with the basic ideas and language (Table 1). However, we assume that one course in chemistry is insufficient to provide the level of understanding students need for learning crystal chemistry. We review modern theory of atomic structure and establish its relation to the periodic table, explain valence, review periodic trends including electronegativity (EN) and ionic radii, and define bond character with respect to the EN's of the bonded atoms. Then we relate bond character to physical properties.

Many of the students are amazed to find that the periodic table is quite useful for rationalizing chemical behavior. They are also surprised to hear that they are required to bring a periodic table to both the lecture and laboratory for the remainder of the course. Students do not routinely bring their textbooks to class and lab meetings but need a periodic table at both. In the first laboratory session the chemical classification of minerals is introduced along with an exercise on describing the physical properties of minerals.

Next we discuss potential energy and stability, first using objects in the room with gravity as the potential field. Potential energy, as the driving force for spontaneous events, is one of the major themes running throughout the course. A fist sized rock facilitates a vivid demonstration of stability, instability and the associated change in potential energy when moved from a position on the floor and perched on a high shelf. After some discussion about the relative stability of objects with respect

to their height above the floor, we discuss the atomic structure of solids, by asking what controls the arrangement of atoms that constitutes a stable mineral. Usually this requires several leading questions and selected demonstrations of various stacking arrangements of spherical objects for students to understand that filling space efficiently is an important requirement of stability.

At this point we present the concept of equilibrium bond length by plotting the potential energy of two atoms versus the distance between their centers to demonstrate that the equilibrium bond length represents the minimum potential energy. We ask the students how they think the size of atoms might be derived from observed bond lengths. This is easily accomplished for homo-metallic and homo-covalent bonds by dividing the bond length by two, but ionic radii are problematic in that there is no unambiguous way to divide the bond. Therefore, our lectures focus on determining and defining ionic radii, explaining that the tabulated ionic radii are used for predicting equilibrium bond lengths but are not the actual radii of ions.

Linus Pauling developed a set of rules to predict the minimum potential energy structure for a mineral, i.e., the stable structure (Pauling, 1960). We introduce Pauling's Rules by paraphrasing them as follows: (1) fill space as efficiently as possible without stretching bonds; (2) maintain local charge balance; (3) keep highly charged cations separated; and (4) keep the structure simple. This lecture coincides with a laboratory exercise on the close packing of spheres, which serves to motivate an investigation of metal structures followed by ionic solids. Evaluating close-packing arrangements of spheres requires an introduction to lattices, the unit cell and their relation to a periodic structure. We start by using two-dimensional lattices to create periodic patterns which can easily be drawn on the board to help students visualize these concepts. An example of such an exercise uses M.C. Escher patterns to illustrate lattices (Buseck, 1997). Periodic patterns can be easily obtained by students (e.g., gift-wrapping paper or wall paper). We also use these examples in lecture and laboratory sessions.

For all of the laboratory exercises, the students are required to work in groups of three or four. This allows the instructor to efficiently assist all the students and facilitates cooperative learning among students as they work together to understand and complete the exercise. Similar strategies of cooperative learning are discussed by Srogi and Baloch (1997). For the close-packing exercise, each group of students constructs various close-packed structures using Styrofoam spheres and calculates the percent fill for each. Because metals primarily fill space as efficiently as possible, by finding the highest percent fill packing arrangements of spheres, students can predict probable stable metal structures. However, predicting stable ionic structures is more complex. While making close-packed structures, our students also locate, describe and name the voids between the spheres. In metal alloys, impurities often reside in the voids and for many non-silicate structures the anions are closest-packed with cations occupying the voids.

We posit to the students that by assuming the anions are large and close packed (like the atoms in a metal) and by using tabulated ionic radii, it is possible to predict which void a cation fits into without stretching bonds.

This leads naturally to a discussion of the radius ratio of a cation to its coordinating anions. Calculating the ideal radius ratios for voids with various coordination numbers helps students comprehend radius ratio ranges and begin to understand the limits on ionic substitutions. Because these concepts are essential for understanding crystal chemistry, we spend several lectures on radius ratios and their application to ionic substitution and solid solution. Pauling's Rules are then stated verbatim and discussed with the students, who are now equipped to understand them. We explain that covalent solids do not strictly follow Pauling's rules because they require special geometries to facilitate overlapping of shared atomic orbitals. Hydrogen bonds and van der Waals forces are also discussed.

Next, the structures of the common non-silicate minerals are presented using three-dimensional ball-and-stick models, structure drawings and computer programs that display crystal structures (CrystalMaker, 2003; XtalDraw, 2003). We assist the students in relating these structures to the close packing arrangements of spheres they constructed in the laboratory. These visualization tools are invaluable for understanding the crystal chemistry of the non-silicates and silicates, including the relationship between the number of shared anions between adjacent cation polyhedra and the separation of highly charged cations. Discussing the crystal chemistry of the non-silicates provides a natural context for recently learned concepts such as close packing, bond character, radius-ratio constraints on coordination number (CN), solid solution, and Pauling's Rules. At this point, the manner in which crystal structure and chemistry control the physical properties of the non-silicates is now well within reach of the students and is discussed using many mineral pair examples (e.g. halite *vs.* galena to illustrate the effects of chemical differences).

Now we begin a two-week laboratory exercise on point symmetry. The structural classification of minerals is justified by relating the shape of a mineral's unit cell to its crystal morphology. To adequately describe crystal morphology requires an understanding of point symmetry and Miller indices. Using simple two and three dimensional examples illustrating symmetry about a plane, a line and a point we explain the point symmetry operators and their function. The students work in their small groups to find all the symmetry possessed by each block in a carefully selected set of 15 block models of crystals. Our primary objectives in teaching point symmetry are for students to understand (1) that the point symmetry generates the equivalent faces that constitute a form, and (2) that the point symmetry places constraints on a mineral's physical properties.

The naming of crystal faces, forms and lattice planes requires students to understand Miller indices. We explain that the Miller index (hkl) assigned to a crystal plane can be understood in two ways: (1) that h, k and l represent the integer ratios of the reciprocals of a crystal face's intercepts with the crystallographic axes; and (2) that (hkl) specifies the set of lattice planes cutting the a-axis into h parts, the b-axis into k parts, and the c-axis into l parts. The latter explanation is very useful for determining d-spacing of a particular set of lattice planes. We also explain that the Miller index not only provides a label for a particular plane but allows one to

visualize the orientation of that (hkl) plane relative to the crystal axes.

We differ in our opinion of the effectiveness using stereographic projections of point symmetry for explaining symmetry operations and the generation of forms. Although stereographic projection is a powerful method for manipulating and visualizing three-dimensional objects, considerable lecture time is required for students to use the method successfully. Stereographic projection is used in the mineralogy course at IUPUI, however, at Purdue it is taught in structural geology.

Space groups are discussed to introduce students to the Bravais lattice types and to demonstrate that space group symmetry generates the symmetrically equivalent atom positions in the unit cell from the fractional coordinates of the unique atoms. We introduce the Bravais lattices using three-dimensional ball-and-stick models. The space group symmetry operators are described and space group notations explained. To demonstrate the utility of space symmetry we instruct the students in the use of crystallographic software designed to display and manipulate crystal structure drawings (XtalDraw, a PC program written by Bob Downs; and CrystalMaker, a Macintosh program created by David Palmer). Each student learns to operate the software and uses it to make a structure drawing of their adopted mineral for a research paper they are required to write (described later). We expect the students to understand that these programs use the space group symmetry to generate the equivalent atoms from the specified fractional coordinates of the unique atom positions and then use the unit cell dimensions to plot the atoms in a single unit cell. Several adjacent unit cells are then placed together to complete the structure drawing. Most of the students enjoy making structure drawings and report that it really helps them visualize the structures. Students often spend part of their non-class time making crystal drawings of various minerals utilizing the available software. We also use these programs during lecture to project and manipulate crystal structures on a screen. Part 1 of our course usually takes about six weeks to complete.

## **MINERALOGY: PART 2**

The second part of the course is dedicated to analytical methods including powder X-ray diffraction, electron microprobe analysis and optical microscopy. The objective is for students to become familiar with some of the common methods used to identify and quantitatively analyze minerals and learn to interpret the data. We begin by discussing the basic properties of visible light: energy, velocity, wavelength, frequency, index of refraction, interference, polarization, refraction and absorption. These are demonstrated to the students using simple examples such as the apparent bending of a pencil as it enters a glass of water, the rainbow created by light passing through a glass prism, blocking surface glare by Polaroid paper, Newton's rings formed between two glass slides, and the colors diffracted from a compact disk.

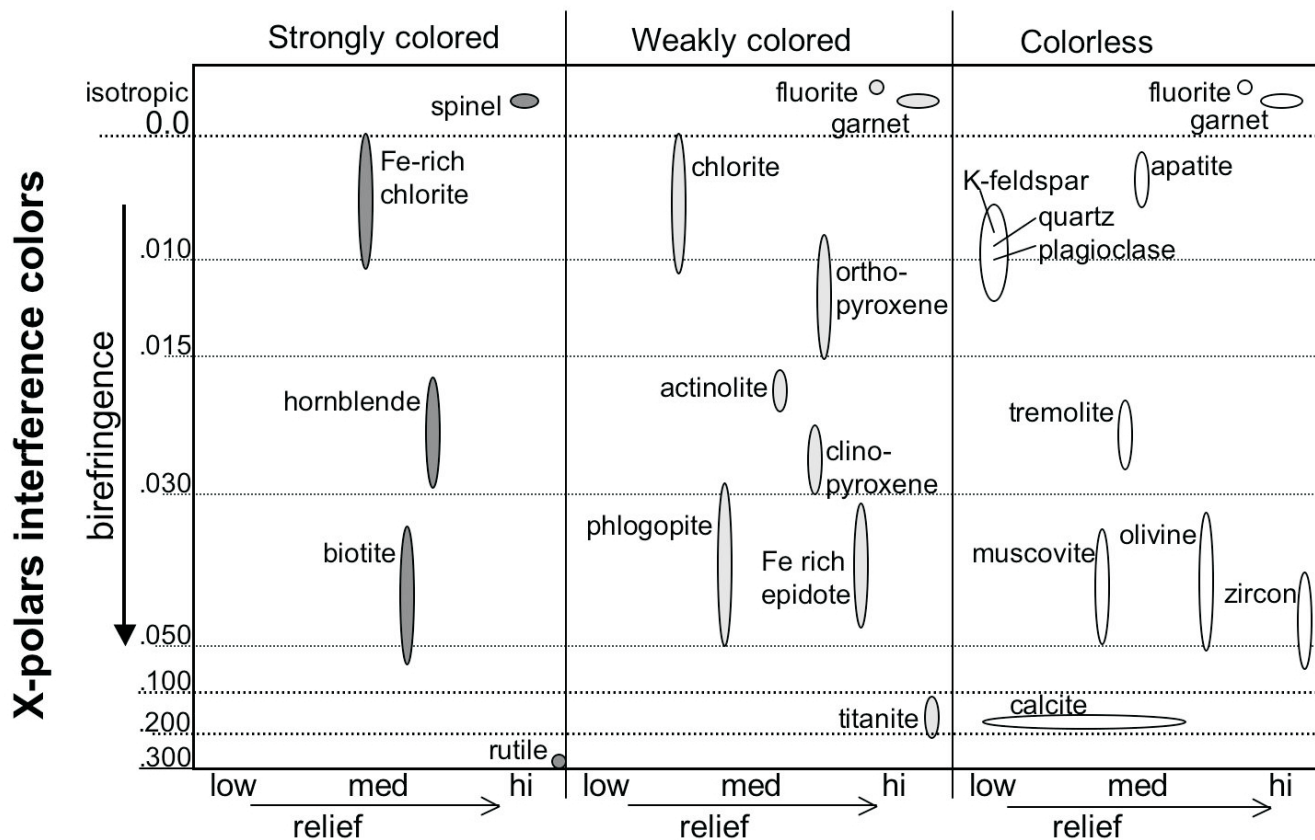
We use the electromagnetic spectrum to explain that X-rays are electromagnetic radiation at a higher energy and shorter wavelength than visible light. Examples of

visible light diffraction (like the colors diffracted from the surface of a compact disk or from a precious opal) help the students understand interference effects. The students accept that if visible light and X-rays are both electromagnetic radiation then X-rays should also show interference effects. However, the distance between the scatterers in a periodic array must be similar to the wavelength of the incident radiation for diffraction to occur. In 1912, Von Laue guessed correctly that the periodicity in minerals is the appropriate size to diffract X-rays (Bragg, 1949). Shortly thereafter, Bragg derived a simplified expression describing the in-phase scattering of X-rays from a set of lattice planes (Bragg, 1949). This explanation helps students appreciate the historical significance of X-ray diffraction. We require the students (using simple geometry and some trigonometry) to show how the Bragg constraint yields in-phase scatter, which helps them to better understand X-ray diffraction (Klein, 2002; Chapter 7).

In the laboratory each student collects and interprets powder X-ray diffraction data using an automated diffractometer (Siemens d5000 at IUPUI, Scintag-X2 at Purdue). The students prepare their mineral samples, assist in running the machine and analyze their results. They learn how to calculate d-spacing from observed 2-theta values, index the patterns, calculate unit cell dimensions and use various search match routines to identify unknowns. The students have been told to assume that the X-ray tube produces monochromatic X-rays to facilitate use of the Bragg equation. At this point we lecture about the generation of X-rays in an X-ray tube as a transition to explaining how the chemistry of a solid can be analyzed using an electron microprobe. We explain that in both cases electrons are accelerated into a target at sufficient energy to produce X-rays by two mechanisms: (1) by the deceleration of the incoming electrons producing white radiation; and (2) by the excitation of atoms in the target by the loss of an inner shell electron and the emission of characteristic X-radiation as those atoms relax. In an X-ray tube electrons impact a single-element, metal target producing characteristic X-rays of that metal in addition to white radiation. For diffraction experiments this X-radiation is filtered by some means allowing only K-alpha X-rays to pass.

X-ray diffraction is then contrasted with electron microprobe analysis where electrons are also accelerated into a target, but now the sample being chemically analyzed is the target. We explain that the atoms of the various elements in the sample are excited by incoming electrons and each element radiates its unique characteristic X-rays. These X-rays are detected and analyzed by determining the element(s) that produce each observed characteristic X-ray peak. A standard of known chemistry must be used to calibrate the exact proportion of each element in the sample. Comparing the function of characteristic X-rays in X-ray diffraction with their function in microprobe analysis helps students better understand both methods. Additionally, we explain why many microprobe analyses are reported as weight percent oxides and demonstrate how to recalculate weight percent oxide into a chemical formula. To emphasize the utility of X-ray diffraction and microprobe data, the students are asked to calculate the density of a particular mineral sample given X-ray diffraction and microprobe data. We also have the

## Color in plane-polarized light



**Figure 1. An identification chart for minerals in thin section on which the common igneous minerals are plotted and, with the exception of quartz and feldspar, show no overlap. The optical data are from Heinrich (1965).**

students calculate the density of granite and basalt from their specified modal compositions, mineral formulae and cell data, and explain how the results relate to the subduction of oceanic crust under continental crust.

Optical mineralogy is almost entirely covered in the laboratory, with the exception of one or two lectures on optical theory. In the first optics laboratory exercise students learn to operate a petrographic microscope and draw sketches of interesting thin sections both in plane-polarized light and under crossed polars. By encouraging them to explore each slide as if they were flying over some unknown landscape in a small plane, we hope to instill a sense of adventure and discovery in microscopy. Starting optics with a fun, inquiry-based exercise has been highly effective in motivating students; most of our students are fascinated by interference colors, thoroughly enjoy looking at thin sections and are eager to learn more optical theory. We use the optical indicatrix and its relation to the symmetry of a mineral to explain how light interacts with anisotropic minerals to produce interference colors (see Nesse, 2002). We

present optical theory in 15-30 minute lectures during the remaining optical laboratory sessions which allow students to observe the optical phenomena being discussed. It also breaks the presentation of optical theory into smaller, more digestible pieces.

Students are required to become proficient at identifying 10-12 common rock-forming minerals in thin section. Using an identification chart (Figure 1) developed by R. J. Swope helps students develop a sound strategy for identifying minerals in thin section. Common igneous minerals plot on this chart with almost no overlap, except for quartz and feldspar, which are easily differentiated by cleavage, twinning and alteration. We use two versions of the chart; first a blank version of the chart is used by the students to plot each of the unknown minerals in a thin section by its observed optical properties. After plotting the unknowns, students are given the complete chart (Figure 1) to identify the unknown minerals. The students are strongly encouraged to augment their complete chart by sketching the habit and cleavage of each mineral next to

its plotted position and by neatly adding optical data (i.e. optical sign, 2V, extinction angles and color). Students also use their augmented chart for other laboratory exercises and on identification tests. Usually there is insufficient time to cover the details of the biaxial minerals, but we feel this is acceptable because (1) the students are saturated with optical theory by the end, and (2) most students take a subsequent petrology course where they can further develop their optical skills while looking at thin sections of rocks. Part 2 of our mineralogy course takes approximately 5 weeks to complete.

### **MINERALOGY: PART 3**

In the final part of our course we talk in detail about the silicates: their crystal chemistry, physical properties and occurrence, while in lab we emphasize the identification of silicates in hand specimen and thin section. Throughout our discussion of the silicates we integrate new topics such as: phase diagrams, Gibbs free energy, phase changes, polymorphism, exsolution, color, crystal growth, and twinning. We try to make a bridge to petrology by discussing the structure of the Earth and economic mineral deposits. In presenting the economic importance of minerals we not only point out the industrial potential of minerals but also discuss their environmental applications. In this part of the course, our intent is to have students use the concepts developed previously to more fully understand the silicates and, hopefully, to motivate the study of rocks.

We begin with an overview of the silicate classification and explain how increasing polymerization of the tetrahedra generally leads to higher Si:O ratios because fewer oxygens are required. We prefer to work through the silicate groups from the most polymerized to the least, beginning with the SiO<sub>2</sub> polymorphs. Conveniently the stability of these polymorphs can be represented on a one-component pressure (P), temperature (T) phase diagram. The structure of each polymorph and the various phase transformations are explained along with the environments where the SiO<sub>2</sub> polymorphs occur. Gibbs free energy is introduced using the details of the SiO<sub>2</sub> phase diagram as an example. Feldspars provide a good example for examining two-component phase diagrams plotted in composition (X)-T space (at a fixed P). We describe the feldspar structure and its relation to cleavage, crystal forms, twinning, and cation ordering. Binary X-T phase diagrams provide a basis for discussing solid solution, exsolution and ordering. Other tectosilicates, feldspathoids and zeolites, are also discussed.

The structures of the phyllosilicates are quickly grasped by students. The phyllosilicates also introduce students to structures with more diverse cation sites accommodating greater chemical variation than quartz and feldspar. The classification of phyllosilicates, based on their stacking patterns, is separated into dioctahedral and trioctahedral groups. This distinction facilitates better understanding of the chemistry of muscovite and biotite. We also explain how layer charges are controlled by various substitutions to enable students to understand the chemistry and physical properties of the clay minerals.

The structures of the inosilicates are not that dissimilar to that of mica. Once the students grasp the I-beam structure, a projection of the composite structure along the I-beam direction clearly illustrates how the I-beams are stacked together and connected by cations in 6-8 coordinate sites. We compare the structures of pyroxene and amphibole rationalizing their crystal chemistries and physical properties. A firm understanding of these two major rock-forming mineral groups is essential to the subsequent study of petrology. Pyroxenoids illustrate the variations in single chain construction. Additionally, we examine cyclosilicate structures of beryl and tourmaline. While discussing tourmaline, we explain polar structures and how they give rise to piezo- and pyroelectricity.

The soro- and nesosilicates, with little or no tetrahedral polymerization, demonstrate that the physical properties may not depend on the tetrahedral arrangement, but rather on some other structural unit, often edge-sharing octahedral chains. We focus on epidote, olivine, garnet, and the Al<sub>2</sub>OSiO<sub>4</sub> polymorphs. After presenting their structures, discussing their physical properties and crystal chemistries including phase diagrams, we give a lecture on the causes of color in minerals. The lecture on color, which is based on a paper by Nassau (1978), provides an excellent opportunity to learn about the behavior of transition elements in minerals. Finally we discuss the structure of the Earth and economic mineral deposits as a way to integrate what has been learned about minerals and relate it to a broader context.

We reserve the last lecture period for student presentations. These are 3-5 minute presentations in which each student uses one or two figures to describe the structure of their adopted mineral. Although short, these presentations provide invaluable speaking experience for the students. After their initial shyness disappears, the students enjoy the presentations.

### **Laboratory, Homework and Term Paper**

The laboratory exercises are hands-on experiences designed to enable students to better understand the concepts introduced in the lecture. We run our own laboratory sections and lead all of these exercises because we feel that the laboratory portion of the course is challenging to orchestrate and essential to the success of the course. However, we welcome the assistance of a teaching assistant. Students work on laboratory exercises in small groups to facilitate cooperative learning. During a portion of each laboratory session, we help the students with their mineral identification skills. Our students are required to learn to recognize approximately 80 minerals in hand specimen and learn the formulae of 35 of these common rock-forming minerals. Mineral identification tests are given at midterm on the non-silicate minerals, and at the end of the semester on silicates. The students are required to keep a notebook containing their laboratory notes and mineral descriptions that they are permitted to use during the mineral identification tests. They also learn basic optical theory, become proficient at operating a petrographic microscope and identifying 10-12 minerals in thin section. Additionally, we demonstrate various other mineral properties such as fluorescence and magnetic susceptibility.

We usually give about five homework assignments, which are designed as a review and application of the lecture material. We try to make the assignments sufficiently involved to challenge the students but short enough not to discourage them from completing the exercises and we encourage students to come to our office for help on their home work. The first homework reinforces the importance of inorganic chemistry in mineral science, focusing on the relationship between electronic configuration, electronegativity (EN) and chemical bonding, and between ionic size, radius ratio ( $r_C/r_A$ ), coordination number (CN), close packing, and ionic solids. The second homework promotes an understanding of crystal structure, symmetry and the structural controls on physical properties. It requires students to use software to draw crystal structures to identify symmetry elements, find cleavage planes, and extract unit cell parameters. The third homework is an extension of a laboratory session during which the students collect X-ray diffraction patterns of two minerals with similar structures (e.g., galena and halite). For this homework, the students use the diffraction patterns to calculate the d-spacing and determine the Miller Index for each diffraction peak, determine the unit cell dimensions, and finally explain the difference between the two X-ray patterns. The fourth homework, which deals with simple phase diagrams, Gibbs free energy and relative stabilities of minerals, is designed to enhance the understanding of the importance of the three key variables (P,T,X) on mineral stability. The final homework assignment is an exercise illustrating how substitution mechanisms affect both the chemical and physical properties of a mineral group (e.g., olivine group); this homework forces our students to integrate several topics they have previously learned.

An important part of our mineralogy course is a research paper, as originally discussed by Smyth and Swope (1993). Each student adopts a mineral for the duration of the course and writes a research paper about that mineral which includes: physical properties, crystal structure, chemical composition, X-ray diffraction pattern, optical properties, occurrences, and industrial, environmental or decorative uses. At the beginning of the course, each student receives a hand specimen of their adopted mineral which they use for various determinative tests, including X-ray powder diffraction and electron microprobe analysis. We assist small groups of students in the collection of X-ray diffraction and microprobe data on their samples. Although time consuming, this approach gives each student several hours of experience running modern analytical equipment. In many cases, it is only through these tests that the students can unambiguously verify the identity of their adopted mineral. Typically, our students are very excited about this laboratory experience. The results of all determinative tests are tabulated and discussed by the students in their paper. An essential part of this semester project is the use of the library, and our students are required to attend a session on how to find and access scientific information. This training session is taught by professional librarians at our institutions, and illustrates how computer technology and the Internet can be utilized to search for scientific information. The term paper forces students to apply many of the concepts they have learned and organize a wide array of information into a single, well-written paper.

## ASSESSMENT

To assess how well the students learn the course material, we consider a combination of criteria. The most accurate evaluation seems to come from our daily interactions with students during the lecture and in the laboratory. Listening to the student's responses to our in-class questions, encouraging students to ask questions, talking with students individually or in small groups help us obtain a reliable indication of how well the students are keeping up with the course material. Looking at the quality of their homework may or may not be indicative of what a student is learning; homework is probably a better indication to students of whether their understanding of the material meets our expectations. However, when students come to our offices for help this provides an ideal opportunity to ask them about their progress.

We try to construct our tests so that students can demonstrate their level of comprehension. Our tests consist of essays and questions with short answers, with some problem-solving questions interspersed. Each essay question requires students to explain a concept in detail (e.g., describe how atomic structure can be used to explain the form and utility of the periodic table). We also use tests to help assess our teaching; consistently poor answers on a particular question indicate that we did not explain that specific topic very well or that the question was not worded clearly. The comprehensive final exam provides the best test results for evaluating the students. Although the students consistently score slightly lower on the final exam, overall their test answers clearly demonstrate their understanding of the course material.

The student research papers provide us with direct evidence of their ability to understand referenced mineralogical information, to use technical language correctly, and to organize and clearly present the information pertaining to their mineral. The rubric used to assess the quality of the paper includes: accuracy of content, organization, clarity, proper referencing and appropriate use of figures and tables.

We consistently receive excellent student evaluations for our mineralogy course. The written comments indicate that students enjoyed taking the course and learned a lot. Typically, they also indicate that they appreciate our effort to present the material in an interesting and understandable manner. Both of us have taught the petrology course that is the sequel to mineralogy, and have observed first hand that our students retain much of what they learned in mineralogy and are able to apply this knowledge to the study of rocks. Many of our former students have worked with us on undergraduate research projects, and we can attest to these students' ability to use their mineralogical training effectively in their research. The results of various assessments and more informal observations indicate that most our students enjoy mineralogy while acquiring an understanding of minerals and developing skills which they apply to their subsequent studies of the Earth.

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