

# Teaching Mineralogy from the Core to the Crust

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## ABSTRACT

Mineralogy is commonly the first difficult geology course that a student major encounters. To provide a solid foundation and context for learning mineralogy, and, in an effort to enhance retention of information and facilitate learning, the 'typical' sequence in our mineralogy course is restructured using the whole Earth as a reference framework. This method provides a context in which to teach the materials that comprise our Planet. Beginning with the Earth's core, simple native elements are introduced, followed by minerals with increasing complexity as discussion moves outward to the Earth's crust. Key theoretical concepts are seamlessly interwoven into discussions of various portions of the Earth, rather than being considered initially in a separate section. This flexible framework allows individual courses to be tailored to the needs of the department while maintaining a strong tie to geology and establishing links to societally-relevant issues.

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## INTRODUCTION

Mineralogy is typically the first core curriculum course encountered in a major's program for Geology after an introductory course. Thus, mineralogy represents a significant leap, not only in the kind of information to be learned, but in the detail accompanying that information. In recent years, discussions have focused on the manner in which this course should be taught and what material should be covered (e.g. Hawthorne, 1993; 1996; Teaching Mineralogy workshop, see Brady, et al., 1997; 2002 IMA symposium). Approaches range from course content emphasis on crystallography and material sciences to that of 'traditional' systematic mineralogy. Generally, the systematic mineralogic approach directly ties to the petrologic environment exemplifying how minerals can be used to interpret Earth's processes. A continuum of emphases and approaches between these end-members exists. In most instances, mineralogy courses attempt to strike a balance, tailored to, for example, the departmental focus and needs, length of class, degree of difficulty, and the instructor's interests.

In an effort to provide a mechanism for better student retention of mineralogic information, while maintaining a strong tie to geology, the typical sequence of crystallography, crystal chemistry and systematic mineralogy was reorganized at Louisiana State University (LSU) using Planet Earth as the reference framework. Using this approach, many crystallographic concepts are woven into discussion of earth materials, and mineralogic products are directly related to the geologic processes of formation. This contrasts with a course discussing most of the theoretical basis (e.g. polymorphic transformations) prior to mineral discussions (e.g. aluminum silicates). Reorganizing the mineralogy course in this way maintains the necessary petrologic focus in the LSU Geology and Geophysics Department. This style of organization also provides consistency in our geologic curriculum by teaching a solid Earth foundation with references back to the basics

of introductory geology, while preparing students for future geology courses with a strong field emphasis. Because minerals form the foundation of our Planet, they are fundamental to many areas of the earth sciences and to allied sciences such as material science, chemistry, physics and environmental science. This approach, however, may not be as useful for those students from allied disciplines whose needs do not rely on an Earth framework. This paper discusses the course organization, highlights and details selected topics, and includes some of the recognized benefits and drawbacks using this approach.

## COURSE ORGANIZATION - CORE TO CRUST

At the outset of this sophomore (2<sup>nd</sup> year) mineralogy course, it is important to establish several basic concepts of mineralogy prior to discussions of mineral systematics (in whatever sequence). Class begins with a brief review of the physical properties of minerals to provide a linkage back to physical geology and chemistry, and to set the stage for linking microscopic aspects to macroscopic and observable properties of minerals. Color is covered in a separate lecture because it is easily viewed as a diagnostic property, although often incorrectly. Fundamentals of crystallography and theoretical aspects such as, how and why bonds form and how that relates to mineral properties, what types of polyhedra exist, how these are combined to form minerals, and Pauling's Rules, provide a basis (traditional) for examining the resulting minerals. Symmetry and symmetry operations follow and provide fundamentals as to how elements and ions are organized into minerals. Symmetry is also easily visualized by students and a quick look around the room provides endless examples (e.g. symmetry of chairs, people, erasers, chalk boards, tables, room arrangement, etc.). During the laboratory portion, students do a mineralogic exercise in which they generate their own classification scheme (Mogk, 1997). They quickly realize that classification is difficult. Hence, the students soon appreciate the value of organizing minerals by symmetry and crystallographic axes. Additional mineralogic concepts, such as polymorphic transitions, twinning, and solid solution, can be covered later during discussions of systematic mineralogy when these concepts relate to specific minerals. A brief overview of the Earth's chemical makeup is provided, and discussed in more detail with respect to the Earth's major seismic and chemical divisions.

The approximate concentric divisions of the Earth form a useful outline for examining several mineralogic and structural concepts. The Earth can be divided into three distinct portions; the core, the mantle and the crust; each zone containing distinct minerals, structures, and assemblages. The introduction of systematic mineralogy follows Earth's structure, and is organized from the core outward to the crust (Figure 1), from more simple to more complex mineralogy. Because boundaries of the Earth are broadly based on seismic discontinuities, a linkage back to physical geology and the Earth's structure is made as well as a link to how we know what we can't see in the deep Earth. Explaining that knowledge

Region (km)		Mineralogy Covered
crust	1	Other Silicates (tectosilicates, phyllosilicates, etc) + Non-Silicates
	0	
mantle	4	Olivine, Pyroxene, Amphiboles, Diamonds, Garnet
	1	
	0	Spinel, Garnet (majorite), Oxides, polymorphic transitions: ol→sp→per, pyx→gt→ilm
	6	
7	Perovskite, Oxides (Magnesio-Wustite, Ilmenite, Rutile, Stishovite structures)	
0		
core	0	Native Elements (Liquid Iron + Ni + S)
	5	
	0	Native Elements (Solid Iron + Ni)

**Figure 1. Reference framework for teaching mineralogy as a function of the Earth's divisions.**

based on direct observational science and measurement of the upper portions of the Earth must be allied with experimental data and theoretical studies for understanding deeper portions of the Earth, demonstrates the limits to field-based acquisition of data and the power of combining multiple techniques and lines of evidence to understand a single problem (e.g. the mineralogic makeup of the Earth). While debate and substantial research on these boundaries remains, boundaries can be broadly related to regions of specific and distinct mineral phases (e.g. Navrotsky, 1994, p. 302). Discussion of compositional versus structural changes in minerals as a function of their general Earth position commences in lecture.

## EARTH'S CORE

The Earth's inner core provides an intuitive introduction to mineral systematics using native elements e.g. Fe, S, C. These simple chemical compounds also demonstrate relatively easy-to-visualize packing arrangements and mineral structures; isometric Fe (with hexagonal closest packing) and the kinked rings of orthorhombic sulfur (e.g. Klein, 2002). One current hypothesis on the core being a 'single crystal' can intrigue students with the processes of mineral growth and crystallization (e.g. Bergman, 1998; Wenk et al., 2000; Garcia, 2002). It also provides a critical-thinking question as to how such a large (1200 km) single crystal could form. In addition, hand samples of meteorites are introduced here as the extraterrestrial, natural analog to core material.

Discussion of the liquid outer core provides another opportunity to reinforce the definition of a mineral (e.g.

Nickel, 1995), taught prior to the study of systematic mineralogy. Students recall that shear waves do not travel through liquid, hence the outer core is liquid; this leads back to the definition of a mineral and why the outer core is not composed of minerals. The outer core's chemistry is, instead, reviewed in terms of its bulk composition rather than mineralogy, with appropriate reference made to a mineral's definition.

## EARTH'S MANTLE

Moving outward in the Earth, the mantle provides a marvelous backdrop for increasingly complicated compositional and structural variations in minerals. The mantle, mineralogy and structure, is discussed in terms of three distinct divisions: the upper mantle, transition zone and the lower mantle. Linkage here can also be directed toward deducing mineralogy based on limited direct evidence derived from the upper mantle (e.g. mantle xenoliths). As discussions move deeper into the mantle, mineralogic makeup must be deduced from other, often more ambiguous, theoretical and experimental methods.

Olivine, pyroxene and amphiboles are covered in the section on the upper mantle. Olivine provides a ready entry point for discussion of end-members, solid solution, chemical zoning and T-X diagrams, as well as ordering related to cation size and sharing of polyhedral elements (Ca, Mg in M2 - regular vs. M1- distorted; Klein, 2002). Commensurate with the change in mineralogy in the divisions of the mantle are the structural transformations that occur. Entering the transition zone, phase transformations, polymorphs, density increases, packing and other mineral behavior can be logically placed in context and related to the geologic processes or variables causing such behavior (e.g. pressure and temperature). For example, tracing the phase transformations and evolution of olivine to spinel then perovskite + MgO from the upper to the lower mantle provides a basis for inquiries such as: (1) why structural transformations are important (e.g. mantle convection and properties, regions of earthquake generation) (2) how they occur (e.g. packing arrangements, reconstructive transformations) and (3) why they occur (e.g. stability fields for minerals). Separating polymorphic transformations from chemical changes (e.g. spinel to perovskite +MgO) is a key issue during this portion of the course. Pyroxene transformations to garnet and ilmenite structures are included here, but discussed separately. Pyroxenes also serve to introduce exsolution processes, and if time permits, geothermobarometry using co-existing clino- and ortho-pyroxenes.

For the exotic and fun in minerals, a more lengthy discussion of diamonds is incorporated together with various diamond indicator minerals, e.g. pyrope, chromian diopside. Aspects of diamond formation such as isotopic arguments for derivation of carbon from mantle or subducted surface material, supersonic transport to the surface, transporting medium, age of formation and inclusion history, demonstrate that Earth's signature is also contained in gem materials (e.g. Ward, 1993; Harlow, 1998). Because diamonds may be 3 billion years old, the antiquity of diamonds reminds students of the vastness of geologic time and that their jewelry may be extremely old! Diamond stability

conditions afford an introduction to the concept of metastability in minerals. The high energy required to convert diamonds to graphite assures that diamonds are forever, at least during our lifetimes. Popular lecture topics can include gem materials as guides to the earth's evolution or their utility as important technological materials because of their remarkable properties (e.g. substrates for circuitry, windows for space craft; e.g. Collins, 1998).

In lieu of samples, lower mantle mineralogy must be inferred from results of high pressure experimental data together with theoretical calculations. Students are often amazed to learn that we can now go into the lab and attain deep mantle conditions in high pressure, high temperature experiments (e.g. Hemley and Mao, 2002). Here, students can also be introduced to the most abundant Earth material, perovskite, and its structure (e.g. Putnis, 1992, p. 138). There are numerous experimental studies of perovskite and its analogs from which to draw more information (e.g. Akaogi et al, 2002; see also references in Navrotsky, 1995). Extremes of pressure in the lower mantle together with the stishovite structure reinforce the concepts of coordination number (e.g. the unusual coordination number of six in Si), its dependence on external forces (in this case, pressure), and, hence, its deviation from the coordination number predicted by Pauling's Rules (i.e. radius ratio arguments). The experimental approach, utilized in the case of stishovite, shows the mineralogy student a mechanism to test hypotheses; synthesis of the material, location of pressure - temperature conditions in nature commensurate with formation, and discovery in nature (e.g. predicting/theorizing a mineral prior to discovery; another example is jimthompsonite)! This reinforces concepts of using the scientific method for understanding Earth's materials.

In this section, students examine minerals that display distinct crystal forms e.g. octahedra, dodecahedra, cubes. Because these morphological forms are characteristic of several mantle minerals (e.g. spinels, diamonds, garnets), students wonder what these forms are called, and their curiosity drives them to (more willingly) study parameters, forms and Miller Indices. Although this may seem out-of-place, a succinct description of forms in relation to the observed faces and morphology serves as a critical diagnostic tool. This empowers the students! Students fascinated with morphology wonder how to describe it, will learn the useful concepts and the corresponding complicated nomenclature more readily than when introduced at the outset of the course with symmetry. Combining hands-on mineralogy with theoretical concepts interconnects the importance of products, processes and the language of mineral sciences.

## EXAMPLES OF LABORATORY EXERCISES DURING THIS SECTION

At this point in the course, calculation of stoichiometric mineral formulae are introduced. Having become acquainted with triangular plots for mineral compositions and relationships in earlier labs, students calculate stoichiometric compositions of an orthopyroxene and a clinopyroxene and plot their compositions on the pyroxene quadrilateral of Lindsley (1983). They become

researchers and determine the temperature at which the rock formed. This provides an illustration of why we need mineral chemistry and normalization schemes, what we can decipher from mineral compositions, and how it relates to conditions of formation. Students also tour the LSU electron microprobe lab and watch as minerals are imaged and analyzed. Ideally, it is best to have a two-pyroxene bearing rock for analysis. Students can then use the data collected in the lab for calculation. This exercise is reinforced in a subsequent course on igneous and metamorphic petrology in which students individually analyze their own 'pet rock' samples.

Mineral specimens discussed in lecture are identified in lab. Several of the mineral samples have excellent crystal forms including a variety of spinels (red to black), garnets (dodecahedra, trapezohedra, and combinations) and tiny diamonds (octahedra and cubes). These help form the basis for the Miller Indices lab, and are used together with traditional wooden blocks to exemplify forms discussed previously.

## EARTH'S CRUST

Moving outward to the crust, minerals are broadly related to the geologic environment in which they form. This section varies in length and complexity depending on the number of minerals one wishes to cover. At this point, silicates and non-silicates omitted previously are considered (for details on specific minerals see <http://geol.lsu.edu/dutrow/miny> ). The crust serves as a foundation to explore the complexity and variety of minerals.

Because of the ubiquity and the importance of the quartz and feldspar mineral groups as rock-forming materials, this section of the course begins with tectosilicates (as opposed to the non-silicate groups). During these discussions, complicated mineral structures are deemphasized while their common occurrence is highlighted. Reconstructive polymorphic transitions have already been introduced during the progression of olivine to high pressure conditions in the mantle but are reviewed during study of the SiO<sub>2</sub> system and displacive transformations are now added. The value of experimental work, developing hypotheses and hypothesis testing, is related to the discovery of stishovite. The unique conditions required to transform and preserve coesite provide evidence that careful observation produces remarkable new insights on Earth's processes (e.g. Chopin, 1987). Radius ratio, solid solution, exsolution, and coupled substitution concepts are reinforced during study of the feldspar compositional series (e.g. Very limited substitution of K for Ca; complete Na-Ca at high temperatures; limited Na-K with a miscibility gap and exsolution). Order-disorder transformations follow when covering the K-feldspar polymorphs. In addition, the K-feldspar polymorphs allow a discussion of intracrystalline ordering as it relates to cooling times of geologic phenomena.

Zeolites are one exception to deemphasizing structures and their structures are described in detail. Zeolites provide a foundation for a discussion of the importance of minerals as technological materials - from molecular sieves to adsorbants for cat litter and radionuclides (hazardous waste disposal). Experimental mineralogy also fits here, with the synthesis of zeolites

containing specific properties for industrial use (e.g. Kerr, 1989). Aspects of quartz can also be discussed as high tech materials.

The remaining silicates are presented in order of decreasing numbers of bridging oxygens; from phyllosilicates to nesosilicates. Phyllosilicates are divided into clay minerals important in sedimentary environments and the micas, important in metamorphic and silica-rich igneous environments. Phyllosilicate structures are related back to X-ray diffraction by using d-spacings to determine the stacking arrangement. Inosilicates, not covered previously, are primarily non-quad varieties for both single and double-chains (e.g. jadeite, glaucophane) and discussed with respect to igneous or metamorphic environments. Once phyllosilicates and inosilicates are covered, a lecture on environmental mineralogy can be inserted.

The 'asbestos' controversy provides a timely, societally-relevant and applicable issue with which to discuss the importance of mineral scientists to public policy. Germane to this issue is the intertwined nature of physical properties, mineral structures, and mineral compositions with respect to nomenclature of complex minerals that have large degrees of chemical variability (amphiboles), as they relate to a regulatory environment. Added to this, is the specter of making public policy and rules in a landscape where lawmakers have little understanding of mineralogic concepts (see Wildavsky, 1995). Critical thinking exercises incorporating mineralogy can easily be incorporated at this point. For example, what happens when the asbestiform silicate that causes mesothelioma is named 'winchite' such as that at Libby, Montana, USA (e.g. Wylie and Verkouteren, 2000), when that amphibole name does not appear in the regulations? Where does this mineral fall in the regulatory scheme of 'asbestos' in the U.S.A when asbestos is defined by six different minerals in two different silicate classes (phyllosilicates and inosilicates), all apparently assumed to share the same properties? An abundance of information related to 'asbestos' is available via the internet for both regulations and mineralogy (see also Guthrie and Mossman, 1993; Wildavsky, 1995).

Linking jade to the current trends in nanomaterials brings to the forefront that natural materials can often be the basis for new, important, engineered materials. Alternatively, natural materials may hold keys to the properties sought in such engineered materials. Another such material is ulexite, the natural optical fiber. Students remark that seeing this mineral makes the entire course worthwhile.

Cyclosilicates, sorosilicates, and nesosilicates follow. Relatively few of these minerals are selected, and done so primarily based on their utility as petrogenetic indicator minerals or as representatives of key concepts previously addressed (e.g. Al-silicates as reconstructive polymorphs; cordierite; tourmaline and their striations representing many prism faces {hk i0}). Other minerals such as zircon and cordierite retain geologically useful information and are encountered in future courses. Crystallographic concepts of twinning are woven into discussion when staurolite crystals are examined. Staurolite also provides the basis for explaining epitaxial growth and pseudomorphs. Students see specimens with kyanite epitaxially growing on staurolite and pseudomorphs of muscovite after staurolite. There are

continuous linkages of macroscopic and observable properties relative to their microscopic makeup.

For the non-silicates, key minerals are selected from oxides, sulfates, carbonates, phosphates, etc. Focus here is on minerals that are key to environmental conditions. Carbonates, sulfates and phosphates can be introduced in light of differing fluid compositions in oxygen-rich environments, and the importance of bond strength during dissolution of radicals. Halite, one the few minerals in Louisiana, is considered in light of its industrial and economic importance; providing the only substrate for soil that satisfies the needs of growing Tabasco peppers (on salt domes) and as a buoyant material forming structural features (domes) that trap oil and gas. Fluorite is tied back to causes of color in minerals and offers an excellent example of when color cannot be used as a diagnostic property. Corundum, requiring silica deficient conditions, is another excellent example of color in minerals and its cause. One can purchase an entire color spectrum of gem corundum, from white to dark blue, covering crystal field transitions to molecular orbital transitions for this demonstration.

This course concludes with topics related to ore deposits and the economic importance of minerals to our everyday life (e.g. copper wiring for electricity, gold for currency). This section encompasses the sulfide group and the remaining native elements (e.g. gold, silver, lead, etc). Because many sulfides are easy to identify based simply on their color, rocks with several minerals can be used to assess conditions of mineral formation. Using slabs of sedimentary rocks cut by veins of several copper-bearing phases and other sulfides, students can identify the minerals and hence chemical composition, work out cross-cutting relationships and determine the change in fluid composition as the veining progressed. This exercise ties back to principles learned in introductory geology, those of cross-cutting relationships and the relative timing of events. Typically these principles are performed on the outcrop scale, but these principles can also be useful at the microscopic scale (this lab is on-line: [http://serc.carleton.edu/NAGTWorkshops/petrology/teaching\\_examples/935.html](http://serc.carleton.edu/NAGTWorkshops/petrology/teaching_examples/935.html)). Concerns of a sustainable world in the face of limited non-renewable resources may enter into discussion here as another societally-relevant issue. Students can easily identify needs of materials with aluminum beer cans or titanium mountain bikes.

## EXAMPLE LAB EXERCISES ASSOCIATED WITH MINERALS OF THE CRUST

The crust around us encompasses the complexity and variety of minerals. These materials hold the key to new technologies, new interpretations about our Earth, new insights into matter. These features are emphasized in lab.

In addition to identification of crustal minerals, building on previous principles is continuously incorporated into laboratory exercises. For example, to reinforce concepts of triangular diagrams, solid solution variability and the petrogenetic utility of minerals, students plot tourmaline compositions from a low grade metamorphic rock (Henry and Dutrow, 1992) on the tourmaline provenance diagram (Henry and Guidotti, 1985). Students then determine the source rocks for the detrital tourmaline and, hence, the provenance of the metamorphic rock. X-ray diffraction of household materials also works well for study of the non-silicates

and for utilizing analytical methods (Dutrow, 1997). A more advanced aspect, relating to identification of the copper-bearing minerals in slabs, is to have students determine general fluid compositions based on activity-activity diagrams such as those found in Bowers et al. (1984) or to determine the replacement conditions required for pseudomorphing of aragonite by native copper (marvelous pseudomorphs of copper after aragonite are from Bolivia, complete with reentrant angles and cyclical twinning). This linkage to geochemistry sets the stage for future courses.

## DISCUSSION

Structuring a mineralogy course from the core to the crust provides a flexible framework for incorporation of concepts and key elements of mineralogy into the foundation set by the Earth. This repackaging serves several purposes; it: (1) places minerals in the context of Earth; (2) reinforces prior knowledge about the Earth's structure; (3) provides a basis for future courses in petrology, geochemistry, etc., if these courses are constructed around a plate tectonics theme; (4) places physical behavior of minerals in context of processes; (5) puts products in the context of processes and (6) improves critical thinking skills at the beginning of a student's geologic career. More or less detail can be added as time permits; emphasis can differ depending on the specific requirements of the course and the instructor's area of interest and speciality. Laboratory exercises continue to play an important role in reinforcing material, by active learning and group activity.

At LSU, mineralogy consists of (a mere) two hours of lecture accompanied by three hours of lab (which is split into two sessions of 1.5 hrs each) per week for 15 weeks. Consequently, this mineralogy course seems to be 'bare bones'. In the scheme of our curriculum, we strive for consistency so that objectives and aspects of each course are reinforced in future courses. This framework provides a vital link to the subsequent courses.

During the past seven years, undergraduate students majoring in chemistry, physics, and environmental science, graduate students from chemistry and natural science, and working scientists from oil and chemical companies, have taken this course in addition to geology majors. Most of these students find the geologic nomenclature difficult, but comment that they understand much more about the Earth and its role in the sciences while learning mineralogy. Graduate students from chemistry remark that they actually learn inorganic chemistry.

## SELECTED BENEFITS

For geology students, this course structure provides a strong link to the Earth and its processes. Theoretical concepts can be placed in the context of the processes of formation and appear to be more readily retained. Students become engaged in the study of the Earth rather than only seeing isolated minerals in a box. In addition, this method reinforces the importance and fundamental role minerals play in composing our Planet, their use in a multitude of ways and our reliance on them.

Based on discussions with professors instructing subsequent courses, this framework appears to be a more

effective method for teaching students mineralogy and having them retain information. And, if teaching evaluations can be used as an indicator of student acceptance (or enjoyment), students appear to appreciate this approach because my teaching evaluations improved markedly (1+ points on a 10 point scale). Of course, students have only had the course presented in this way.

Several universities in the U.S.A. have combined a number of mineralogy/petrology courses into a single course. Although the framework presented here is designed for a standalone course, this approach to teaching mineralogy could be seamlessly incorporated into a combined mineralogy/petrology course, with the over arching theme of the Earth's structure. Using this methodology, consistency is also apparent. Concepts are reiterated and a 'whole Earth systems' approach can be implemented such that each course is part of a whole, rather than viewed as an isolated, disconnected, and non-interacting portion of the geologic curricula.

Any mineralogic book will suffice for this framework, the challenge is keeping the students at the correct place in the book. I use Klein's Manual of Mineral Science (2002) together with much supporting information. For a more complete description of daily material, see: <http://geol.lsu.edu/dutrow/mingy/> for one possible syllabus.

## SELECTED DRAWBACKS

Based on seven years of teaching this course as presented here, a few drawbacks have yet to be overcome. Perhaps the most significant problem is that there are currently no textbooks that follow this approach. Consequently, this requires students to skip around the book while reading material. For most of us, that is not a problem. However, for sophomore students, the criticism of the lack of a book to sequentially follow occurs year after year. Regardless of putting page numbers for reading on their printed syllabus, web syllabus, and on the board for each class, there appears to be difficulty or discomfort skipping around in the book.

An additional problem is maintaining the distinction between structure-types, found in the mantle, and the minerals that contain the same structure at the surface. Making this distinction is important for understanding structures and mineral assemblages. With this course continually evolving, these perturbations will hopefully be overcome.

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## REFERENCES

- Akaogi, M., Tanaka, A., and Ito, E., 2002, Garnet-ilmenite-perovskite transitions in the system  $Mg_4Si_4O_{12}$ - $Mg_3Al_2Si_3O_{12}$  at high pressures and high temperatures: phase equilibria, calorimetry and implications for mantle structure, *Physics of the Earth and Planetary Interiors*, v. 132, p. 303-324.
- Bergman, M.I., 1998, Estimates of the Earth's inner core grain size, *Geophysical Research Letters*, v. 25, p. 1593-1596.
- Bowers, T.S., Jackson, K.J., and Helgeson, H.C., 1984, Equilibrium Activity Diagrams, for Coexisting Minerals and Aqueous Solutions at Pressures and Temperatures to 5kb and 1000oC, Springer-Verlag, New York, 397 p.
- Brady, J. B., Mogk, D.W., and Perkins, D. III, (Editors), 1997, *Teaching Mineralogy*, Mineralogical Society of America, Washington, D.C., 406 p.
- Chopin, C., 1987, Very-high-pressure metamorphism in the western Alps - Implication for subduction of continental crust, *Philosophical Transactions of the Royal Society of London*, v. 321, p. 183-197.
- Collins, A.T., 1998. *Diamonds in Modern Technology: Synthesis and Applications*, in *The Nature of Diamonds*, G. Harlow, Editor. Cambridge University Press, p. 255-272.
- Dutrow, B., 1997, Better living through minerals: X-ray diffraction of household products, in *Teaching Mineralogy*, J.B. Brady, D.W. Mogk, and D. Perkins, III. (Editors), p. 349-360. Mineralogical Society of America, Washington D.C.
- Garcia R., 2002, Seismological and mineralogical constraints on the inner core fabric, *Geophysical Research Letters*, v. 29.
- Guthrie, G.D., Jr. and Mossman, B. (Editors), 1993, *Health Effects of Mineral Dusts*, *Reviews in Mineralogy*, v. 28, Mineralogical Society of America, Washington, D.C.
- Harlow, G.E. (Editor), 1998, *The Nature of Diamonds*, Cambridge, U.K. Cambridge University Press, 278 p.
- Hawthorne, F.C., 1993, Minerals, mineralogy and mineralogists: past, present and future, *Canadian Mineralogist*, v. 31, p. 253-296.
- Hemley, R.J. and Mao, H.K., 2002. New windows on earth and planetary interiors, *Mineralogical Magazine*, v. 66, p. 791-811.
- Henry, D.J., and Dutrow, B.L., 1992, Tourmaline in a low grade clastic metasedimentary rock: an example of the petrogenetic potential of tourmaline, *Contributions to Mineralogy and Petrology*, v. 112, p. 203-218.
- Henry, D.J., and Guidotti, C.V., 1985, Tourmaline as a petrogenetic indicator mineral: an example from the staurolite-grade metapelites of NW Maine, *American Mineralogist*, v. 70, p. 1-15.
- Kerr, G.T., 1989, Synthetic Zeolites, *Scientific American*, v. 261, p. 100-105.
- Klein, C., 2002, *Manual of Mineral Science*, New York, John Wiley & Sons, Inc., 642 p.
- Lindsley, D.H., 1983, Pyroxene thermometry, *American Mineralogist*, v. 68, p. 477-493.
- Mogk, D. W., 1997, Mineral Classification - What's in a Name?, in *Teaching Mineralogy*, J.B. Brady, D.W. Mogk, and D. Perkins, III. (Editors), Mineralogical Society of America. P. 37-42. Washington D.C.
- Navrotsky, A., 1994, *Physics and Chemistry of Earth Materials*, Cambridge, U.K., Cambridge University Press, 417 p.
- Nickel, E.H., 1995, The definition of a mineral, *Canadian Mineralogist* v. 33, p. 689-690.
- Putnis, A., 1992, *Introduction to Mineral Sciences*, Cambridge University Press, 457 p.
- Ward, F., 1993, *Diamonds*, Bethesda, MA, Gem Book Publishers, 64 p.
- Wenk, H.R., Baumgardner, J.R., Lebensohn, R.A., and Tome, C.N., 2000, A convection model to explain anisotropy of the inner core, *Journal of Geophysical Research*, v. 105. p. 5663-5677.
- Wildavsky, A., 1995, No runs, no hits, all errors: The asbestos and alar scares: in *But is it true? A citizen's guide to environmental health and safety issues.*, Cambridge, MA, Harvard University Press, p. 185-222.
- Wylie A.G., and Verkouteren, J.R., 2000, Amphibole asbestos from Libby, Montana: Aspects of nomenclature, *American Mineralogist*, v. 85, p. 1540-1542.