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[link http://serc.carleton.edu/NAGTWorkshops/coursedesign/goalsdb/12058.html ‘Mineralogy’] is often the “gateway” course to the geoscience major. As such, it plays an important role in the geoscience curriculum by setting professional standards and expectations in the training of young geoscientists. The [file 6175 ‘learning outcomes’] of my Mineralogy course are closely aligned with the methods that geoscientists use in their professional careers: I do expect my students to master a certain amount of scientific content related to minerals, their composition and structure, the context of minerals in interpreting geologic setting, processes and history, the centrality of mineralogic principles in addressing geoscience research questions and applications to society. But in addition, a major learning outcome of my Mineralogy class is the [link http://serc.carleton.edu/NAGTWorkshops/earlycareer/research/habitsofmind.html ‘scientific habits of the mind’] that help to prepare students for a career in geoscience. Beyond content knowledge, my goal is to help students: a) develop technical skills (e.g. mineral identification, use of the petrographic microscope, XRD), b) develop related transferable skills (e.g. communication, quantitative, and interpersonal), c) make connections between our Science, and their personal professional goals, or with societal issues by engaging aspects of the affective domain such as curiosity and motivations to learn; and d) gain exposure to geologic “ways of knowing” so that they can be reflective (metacognitive) of not only what we know, but also how we know and to be able to formulate strategies to learn in new domains of knowledge. The students’ learning outcomes in my course are focused on mastery of geologic content, skills, and ways of knowing; my personal course outcomes are students who are prepared to be contributing Scientists.

The design of my mineralogy course uses a historical approach that emulates the evolution and advances of the science over the past 300 years or more. This is a kind of disciplinary “ontology recapitulates phylogeny”: the stages of development of Mineralogy as a science, must be reproduced by the students so that they can understand the underlying reasoning and full context of what is known and how we have come to this state of current understanding. (And I would posit that this is true also for other disciplines in the geosciences and beyond). A history of mineralogy has been written by Hazen (1984; and this is required reading by my students). Initially, Mineralogy was largely a descriptive science until the mid 1800’s, with two camps of practitioners who advocated use of physical properties of minerals (e.g. Mohs, Wegner) v. crystallographic characterization (e.g. Steno, 1600’s) as the basis for mineral identification. In both cases, description was the primary geoscience method. (And consequently, the science of Mineralogy has labored under a general perception that it is predominantly a descriptive science, that looks for increasingly arcane and rare specimens, and should be relegated to museum status along with its samples). James Dwight Dana was able to integrate these into the coherent classification scheme that is universally used today. This answered the primary question of **“what”** minerals are.

The more interesting question of “**why**” do minerals exhibit their unique compositional and physical properties could not be addressed until the advent of atomic theory (e.g. the Bohr model of the atom) and an understanding of the nature of chemical bonds (Linus Pauling, 1954 Nobel Prize for Chemistry). These theoretical considerations led to deeper explorations of crystallography, crystal chemistry, and crystal structures. An understanding of the relative strength and direction of chemical bonds provided the basis for explanations of the physical properties of minerals such as cleavage, hardness, melting point and ductility.

But “**how**” do we know, what is the evidence? Technology is really the answer, that allow for **precise and reproducible measurements of natural phenomena**. Carangeot applied a contact goniometer (mid 18th century) to confirm Steno’s “law of constancy of interfacial angles”, and Wollaston developed the reflecting goniometer (mid 18th Century). At about the same time, Cronstedt and colleagues used blow pipe methods to do rudimentary chemical analyses (which by the way led to discovery of 84 elements of the Periodic Table first described as a major or trace component of minerals). A huge leap in technology was realized in the application of the petrographic microscope to the identification of minerals and analysis of textures in rocks (Nicols and Sorby, mid 19th Century). It was really the discovery of X-rays and their application to determination of crystal structures (that resulted in the award of the 1915 Nobel Prize in Physics to the father-son Bragg team) that opened up a revolution in analysis of the structure and composition of minerals. This confirmed the supposition that there were indeed atomic scale building blocks (unit cells; first proposed by Steno) that were organized in definite proportions and with ordered atomic arrangements that we recognize as minerals. The atomic scale ordering is reflected in the mesoscopic crystal forms we can hold in our hand. After X-ray diffraction, other technologies emerged in the 20th century to further characterize the morphology, composition (elemental, isotopic), structure, and other physical properties of minerals: scanning electron microscopy, electron probe microanalyzer, mass spectrometry, Mossbauer spectroscopy, and recently atomic force microscopies. These are the tools that allow us to **test** materials, and the theories that control their properties and occurrences.

Finally, “**who**” should care about mineralogic research? Geoscientists, colleagues in other science and technology disciplines (chemistry, physics, biology, engineering), and citizens. Minerals are the monitors of geologic process and history: the story of Earth is recorded in the composition, structure, and natural associations and occurrences of minerals in the Earth system. Minerals are the result of natural experiments conducted over geologic time, and as a result often reveal fundamental principles about how the universe works. And, minerals have been used since the dawn of civilization to support the material needs of society.

So, the evolution of the science of mineralogy includes the early description of minerals, theory that explains their properties, experimental and analytical methods that tests and confirms our theoretical understanding, and ultimately, this information becomes relevant and useful to the progress of society and to sustain human society. Enough of my homage to Mineralogy.

So how does this apply to Teaching GeoMethods?

In the first half of my Mineralogy course, the focus is on determinative mineralogy and hand sample identification. But as L.C. Graton famously stated: “*The purpose of classification is not to enunciate certain and final truths, but rather, to be used as stepping stones towards greater understanding.*” This early training is really an exercise in guided **observation** and **description**:

* Helping the students know what to look for amidst the complex variations encountered in natural samples (e.g. recognizing multiple varieties of quartz; knowing to avoid alteration).
* Prioritizing evidence (what properties are diagnostic, what is permissible or exclusive)?
* Measurements (aspect ratio, interfacial or cleavage angles);
* The beginnings of synthetic and analytical reasoning (using multiple lines of evidence to formulate an internally consistent interpretation; interpreting mineral occurrences in the context of larger geologic settings); and
* Clarity and precision of descriptions and appropriate use of scientific terminology as an essential component of communicating scientific knowledge.

A basic knowledge of mesoscopic properties of minerals provides the foundation for investigations of the more abstract, **theoretical considerations** of crystallography, crystal chemistry, structure. Geomethods used in these instructional units include:

* Spatial reasoning, particularly with respect to the 3-dimensional atomic “architecture” of mineral structures (e.g. “I-beam” chains of Si-tetrahedra in pyroxenes and amphiboles; stacked sheets of micas);
* Quantitative reasoning in crystallography (set theory as the basis of point groups; Miller indices as vector representations; trigonometric relations);
* Modeling: physical, analog models are used to represent mineral structures (ball-and-stick models); computer-based visualization models are used for dynamic demonstrations of crystal structures.

Analysis of mineral properties requires **analytical thinking**. Students must understand fundamental principles of the analytical technique, procedures related to sample selection, sample preparation, instrumental parameters, standardization, data acquisition, replication, data reduction, and data representation. Students need to be trained to be “critical producers and consumers of data”. These principles are applicable to instruction and use of techniques such as optical mineralogy, X-ray diffraction, SEM/EDS techniques; all of which are easily accessible in an introductory Mineralogy class.

A final, in-class research project is designed to pair Mineralogy students with faculty or graduate student mentors. Each mentor provides materials to be analyzed to address a mineralogic question related to their own research. Topics explored have ranged from composition of dinosaur bones and eggs to salts related to saline seep occurrences, composition of fault gouge, clay mineralogy in off-shore turbidites, ore mineralogy of a poly-phase precious mineral deposit….Students must write a short research proposal with methods that will be used to characterize their specific Earth materials. They then conduct appropriate experiments to characterize morphology, texture, composition and structure of their materials. This is a first critical exposure **to integrative problem-solving** (using multiple independent lines of evidence to solve a mineralogic problem).

So, in summary, students in a mineralogy course can develop through the same stages of discovery that the discipline of Mineralogy followed over almost three centuries: 1) an early emphasis on description of mesoscopic physical properties that led to a universally accepted classification scheme; 2) codification of the principles and theory of crystallography and crystal chemistry that explains and confirms the reasons for the expression of these physical properties; 3) technology-assisted analysis of materials (petrographic microscope, XRD, SEM/EDS) to test hypotheses about their occurrences and properties; and 4) applications to questions of Scientific or societal consequence, using problem-solving strategies that integrate multiple lines of evidence.

A final note, this historical approach to teaching mineralogy not only introduces a scaffolded sequence of geomethods used by practicing geoscientists, but also ascribes to the tenets of successful teaching in the sciences as articulated in Science for All Americans (AAAS, 1989): Start with questions about Nature, and Work from the concrete to the abstract.

AAAS, 1989, Project 2061, Science for All Americans, AAAS: Washington DC.

Robert M. Hazen **1984,** Mineralogy: A Historical Review, Journal of Geological Education v 32, p288-298.