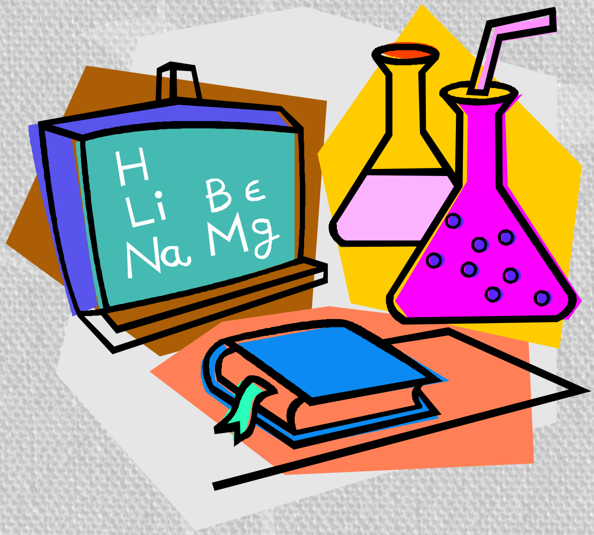
REFLECTING ON SCIENCE:

Using the primary literature to engage students in upper-level science courses

Necessary Skills for Scientists

1. Ability to think critically and independently
   - Research projects
   - HW assignments/ In-class activities
   - Lab exercises

2. Ability to understand and communicate science
   - Scientific writing is very difficult to understand
     - Technical and tedious
     - Lots of unfamiliar jargon
     - Dull and uninteresting (to some!)



Teaching Mineralogy, Petrology, and Geochemistry in the 21st Century

- August 7 – 10, 2011
- University of Minnesota
- Attended by 70 Geology faculty from across the country

- Format
  - Pre-workshop activity review
  - Daily group sessions
  - Small group break-out sessions
  - Share fairs (poster sessions)

Reading the Literature Assignments

- Short, guided readings that emphasize and apply concepts learned during lecture

- Goals
  1. To give students an understanding of how course content is applied in current research
  2. To introduce students to reading the primary literature using (hopefully) interesting and easily readable papers
  3. To improve students' ability to comprehend scientific papers and to express their understanding in a written and oral format
  4. To incorporate more discussion into a content-heavy lecture course and to encourage students to participate in classroom discussions

Format

- Articles are from the journals *Geology* or *Elements*
  - Typically 4-6 pages in length
- PDFs of journal articles and questions are posted on Reggienet at least two weeks prior to due date
- Answers to questions are due via Reggient two hours before class on discussion day
- Responses are used by instructor to guide the discussion, which varies from ~20 minutes to the entire 50 minutes class period

Assessment

50 Pts. **Outstanding performance.** Student demonstrates solid conceptual understanding and insight and is able to make extensions or apply the knowledge to other situations. Assignment demonstrates a deep level of reflection and thought. Material is well written, conveys coherent thoughts, and utilizes proper grammar, correct spelling, and appropriate terminology.

40 Pts. **Good performance.** Student demonstrates good understanding and mastery of content. Assignment is of good quality but not exceptional, demonstrating an acceptable level of reflection and thought. Material is well written, fairly easy to read, and utilizes proper grammar, correct spelling, and appropriate terminology.

30 Pts. **Adequate performance.** Student demonstrates minimally adequate understanding and mastery of content but has difficulty extending or applying knowledge to other situations. Assignment is adequate but shows minimal thought and reflection. Material demonstrates adequate writing skills, but may contain several grammatical, spelling, or terminology errors.

20 Pts **Unacceptable performance.** Student demonstrates poor understanding and mastery of content. Writing indicates little thought and reflection, or is of poor quality, making it difficult to read or understand.

0 Pts Assignment is not turned in.

Example Responses

What is the primary question the authors are trying to address?

50/50 The Primary question the authors are trying to address is how MTB's enter new habitats after being absent for long periods of time, and how they interact with that new environment. The control of this experiment was the most recent glaciation in Norway, choosing lakes in a variety of different regions in the country. They would then analyze the varves in lake sediment deposits to find out when the MTBs first arrived after the recent glaciation, and when they were abundant.

40/50 To better understand MTB's ability to withstand the many changing environments that have taken place over time, this article focuses on MTB's ability to colonize and recolonize in new and old habitats. So the question would be how did MTBs recolonize the 5 lakes of Scandinavia, with an emphasis on the close time proximity with which they occurred?

30/50 In this paper, the author's are trying to find out how 4 freshwater lakes were colonized at the same time around 10,000 years ago. The lakes aren't very close to each other either.

20/50 How did MTBs colonize and recolonize around the world?

Pasteris, J.; Wopenka, B.; Valsami-Jones, E. Bone and Tooth Mineralization: Why Apatite? (2008) *Elements*, 4, 97-104.

1. What are the basic chemical and structural difference between bone and tooth enamel, and how does the mineral:collagen ratio control the properties of these materials?

2. What kind of role does nucleation play in the mineralization of apatite in bones?

3. How does apatite seem to defy Pauling's rules, particularly the Principle of Parsimony?

4. Why is it so difficult to synthetic substitutes for bone?

5. Summarize the authors' argument as to why apatite is the primary mineral used in biomineralization of bones and teeth.

6. What terms did you not understand?

7. What concepts were hard to grasp?

Bone and Tooth Mineralization: Why Apatite?

Skull of a modern horse

Jill D. Pasteris[1], Brigitte Wopenka[1], and Eugenia Valsami-Jones[2]

DOI: 10.2113/gselements.4.2.97

Through evolution, vertebrates have "chosen" the calcium phosphate mineral apatite to mineralize their teeth and bones. This article describes the key characteristics of apatite in biological mineralization and explores how the apatite structure allows biology to control mineral composition and functionality. Through the synthesis and testing of calcium phosphates for biomaterials applications, we have gained further understanding of how sensitive the chemical and physical properties of apatite are to its growth conditions.

Keywords: apatite, bone, phosphate, biomineralization, biomaterials

WHY APATITE?

Most mineralogists and geochemists are aware that the mineral component of bones and teeth is a biologically produced analog of hydroxylapatite, $Ca_5(PO_4)_3OH$. But why is the biomineral not, for example, calcite? Clearly, the biomineral must possess the physical properties required for the functionality of the tissue, such as structural support (bones) and mechanical grinding (teeth). Bone, however, is also a chemical reservoir for phosphorus, which is a life-essential element. Phosphorus is present in a large array of biomolecules; for example, it occurs in DNA, RNA, collagen, and other proteins. It is also a major component in, and indeed is essential to the formation of, *ATP*. [Note: All words and acronyms in italics are defined in the accompanying glossary.] *Apatite* in bone stores 80 wt% of the body's phosphorus, as well as 99 wt% of its Ca and 50 wt% of its Mg (Skinner 2005; Glimcher 2006). But apatite is much more than a simple reservoir of elements: it can deliver those elements on demand.

BIOAPATITE AND EXAMPLES OF BIOMINERALIZATION

Biomineralized materials such as bones and teeth are composites of an inorganic (mineral) component, which is typically nanocrystalline, and an organic component, predominantly protein. The term "biomineral," e.g. bioapatite, refers only to the inorganic component of the composite. Among the remarkable aspects of bioapatite are the widely ranging properties and compositions it expresses in bone, dentin, enamel, and pathologic precipitates ("calcifications"); in altered form in fossilized teeth and bones; and in phosphorites, which are large sedimentary deposits dominated by phosphate materials, including fossil bones and teeth.

The chemical–structural differences between bone and tooth enamel highlight the biological adaptability of vertebrate animals, which is mirrored by the crystal-chemical versatility of the mineral apatite. Bone consists of about 45–70 wt% mineral, 10 wt% water, and the remainder collagen plus a small proportion of non-collagenous proteins (Rogers and Zioupos 1999; Skinner 2005; Fig. 1). The mineral:collagen ratio not only differs among animals, among bones in the same animal, and over time in the same animal, but it also exerts a major control on the material properties of bone, such as its toughness, ultimate strength, and stiffness. A higher mineral:collagen ratio typically yields stronger, but more brittle, bones (Rogers and Zioupos 1999; Currey 2004; Currey et al. 2004). For example, bone from the leg of a cow has a relatively high concentration of mineral (for support), whereas bone from the antler of a deer has a relatively high concentration of collagen (for flexibility). Dentin has characteristics similar to those of bone, but enamel is strikingly different, especially in its total lack of collagen and its 96 wt% mineral content (Fig. 1). Thus, enamel is much more *ceramic*-like and brittle than dentin or bone.

Bone is a composite material (Fig. 2a–h), whose two major components are microfibrils of collagen and crystallites of bioapatite. These are well organized into arrays, even at the nanometer scale (Fig. 2f). Note that the mineral:collagen ratio of the entire bone is established at this nanoscale level. These microfibril–bioapatite units, in turn, are bundled into larger organized fibrils, which are grouped into even larger mineralized fibers. In other words, bone, like many other biomineralized materials, exhibits a hierarchical structure that is well organized at several spatial scales (Weiner and Wagner 1998; Glimcher 2006).

In bone formation, during both primary development and repair, collagen is laid down first and apatite mineralization follows. But the story does not end here. Bone mineralization is a dynamic process. In the process of bone turnover (i.e. remodeling), which replaces essentially our entire skeleton every 5–10 years (depending on age, diet, and health), the collagen–mineral composite initially laid down by *osteoblast* cells is constantly reworked, i.e. *osteoclast* cells cause it to dissolve, so that osteoblasts subsequently can deposit new bone material (Figs. 2b, c). Moreover, bones that bear weight may increase in diameter through a feedback mechanism involving these same osteoclasts and osteoblasts. Osteoclasts also can be deployed to release necessary calcium or phosphate to the body fluid for use elsewhere (Glimcher 2006; Boskey 2007).

1 Department of Earth and Planetary Sciences and the Center for Materials Innovation, Washington University, Campus Box 1169, St. Louis, MO 63130-4899, USA
E-mail: pasteris@levee.wustl.edu; bwopenka@levee.wustl.edu

2 Department of Mineralogy, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK
E-mail: e.valsami-jones@nhm.ac.uk

Student Reaction - Year 1

1. Students saw the readings as extra work instead of as an additional learning opportunity
   - They felt that the RTLs took away from time that was better spent lecturing
2. Students were overwhelmed by the frequency of readings
   - Every week (with the exception of test weeks)
   - Lots of effort required - students could not keep up
3. Students felt that the weight of each RTL in their overall grade did not represent the effort required
   - 1% for each RTL , 10% total
   - No motivation or energy to do well

Changes After Year 1

1. Reduced the number of RTLs to six and made each assignment worth 2% of the final grade (12% total)
   - Can allocate more time for each discussion
2. Focused more of my attention on highlighting the connection between the lecture material and the readings
   - Changed the order or readings
   - Discuss why each article is important and how it applies to concepts covered in class

Students Responses to Changes

1. Changes have resulted in a significant improvement in student performance
   - During the 2011-2012 academic year, one-third of the students failed to regularly turn in their assignments
   - Now it is rare for even a single student to miss an assignment
2. Student responses to questions have also improved significantly
   - Students are taking the assignment more seriously
3. Participation in discussions has also improved
   - Room for improvement

Bonneville, S.; Smiths, M.; Brown, A.; Harrington, J.; Leake, J.; Brydson, R.; Benning, L. Plant-driven fungal weathering: Early stages of mineral alteration on the nanometer scale (2009) *Geology*, 37, 615-618.

1. What is the purpose of this study?

2. The authors used several different techniques (e.g. FIB, TEM, STEM-EDS, STXM) to image and analyze the weathered biotite lamellae. Research one of these techniques, and describe how it works and why it is useful in geology.

3. What structural and compositional changes did the authors' observe with increasing hypha-lamellae exposure time (from lamellae1 to lamellae 3)? Be specific.

4. What are the authors' overall conclusions about plant-driven fungal weathering of rocks?

5. Do you think this type of plant-driven weathering would be prominent in the Bloomington-Normal area? Why or why not?

6. What terms did you not understand?

7. What concepts were hard to grasp?

Plant-driven fungal weathering: Early stages of mineral alteration at the nanometer scale

Steeve Bonneville[1*], Mark M. Smits[2], Andrew Brown[3], John Harrington[3], Jonathan R. Leake[2], Rik Brydson[3], and Liane G. Benning[1]
[1]Earth and Biosphere Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[2]Department of Animal and Plant Sciences, University of Sheffield, Western Bank, Sheffield S10 2TN, UK
[3]Leeds Electron Microscopy and Spectroscopy Centre, Institute for Materials Research, University of Leeds, Leeds LS2 9JT, UK

ABSTRACT

Plant-driven fungal weathering is a major pathway of soil formation, yet the precise mechanism by which mycorrhiza alter minerals is poorly understood. Here we report the first direct in situ observations of the effects of a soil fungus on the surface of a mineral over which it grew in a controlled experiment. An ectomycorrhizal fungus was grown in symbiosis with a tree seedling so that individual hyphae expanded across the surface of a biotite flake over a period of three months. Ultramicroscopic and spectroscopic analysis of the fungus-biotite interfaces revealed intimate fungal-mineral attachment, biomechanical forcing, altered interlayer spacings, substantial depletion of potassium (~50 nm depth), oxidation of the biotite Fe(II), and the formation of vermiculite and clusters of Fe(III) oxides. Our study demonstrates the biomechanical-chemical alteration interplay at the fungus-biotite interface at the nanometer scale. Specifically, the weathering process is initiated by physical distortion of the lattice structure of biotite within 1 µm of the attached fungal hypha. Only subsequently does the distorted volume become chemically altered through dissolution and oxidation reactions that lead to mineral neoformation.

INTRODUCTION

Many rocks at the Earth's surface were formed originally at high temperature and pressure in a reducing environment. Tectonic forces have now exposed them to the slow but inevitable action of oxygenated solutions that trigger chemical reactions and physical alterations, resulting in the formation of secondary mineral phases, such as clays, that are more stable at Earth's surface conditions. Resistant primary and secondary minerals are redistributed to form sediments and soils upon which the entire terrestrial biosphere depends. Rock weathering through dissolution reactions also affects the chemical compositions of ground water, river and lake water, and ultimately oceans (Banfield and Nealson, 1997). Therefore, weathering leads to a major geochemical fractionation near the Earth's surface. Over geological time, such processes have contributed to shape the compositions of the mantle, crust, hydrosphere, and atmosphere (Berner, 2004).

While rock weathering was classically thought of as an inorganic process, it is now recognized that plants, and especially forests, accelerate weathering rates by a factor of 4 to 10 compared to geologically similar, nonvegetated areas (Moulton et al., 2000). More than 80% of plant roots form symbiotic associations (mycorrhiza) with soil fungi, and in boreal and temperate regions, as much as 90% of the woody tree root tips are covered by ectomycorrhizal fungal sheaths (as much as 600 km of fungal mycelium per kg of soil) (Ek, 1997; Read and Perez-Moreno, 2003). Thus, virtually all nutrients taken up by trees pass through these fungi, and in return, the fungi receive 20%–30% of the carbon fixed during photosynthesis by the host plants (Högberg and Högberg, 2002). Therefore, the fungi play a key role in the mineralogical modification that characterizes weathering, removing, for example, K, P, Ca, Mg, and Fe, and providing carbon that becomes fixed into soil carbonate minerals (Balogh-Brunstad et al., 2008). This link between biological mineral weathering and photosynthesis may have played a crucial role in the Earth's climate history (Beerling and Berner, 2005). Kennedy et al. (2006) suggested that the expansion of soil biota and especially fungi during the Late Proterozoic helped create conditions suitable for animal life. Indeed, molecular clock evidence suggests that fungi appeared on land ca. 700 Ma ago (Heckman et al., 2001) and the earliest fossil record of mycorrhiza dates from 400 Ma ago (Remy et al., 1994). The acceleration of weathering kinetics due to the action of soil fungi increased the formation of clay minerals, which efficiently bind organic matter, and hence this process favored carbon burial in soils and in continental margins. This increased carbon sequestration coupled to photosynthesis may have triggered the rise in atmospheric oxygen levels in the Late Proterozoic that allowed the development of large terrestrial eukaryotic organisms (Derry, 2006).

Hitherto, mineral weathering by mycorrhizal fungi was postulated to rely primarily on the ability of fungi to exude organic ligands and protons and thus alter soil solution composition (Adeyemi and Gadd, 2005; Gadd, 2007; Kraemer, 2004; Wallander and Wickman, 1999). However, most mycorrhizal fungi grow in unsaturated soils and are intolerant of waterlogging. Their mycelial networks strongly attach to mineral surfaces, and therefore weathering processes are likely to be initiated and to proceed directly at the mineral-fungi interface. This interface therefore, may play a far greater role in initiating and controlling the weathering rates than previously thought. We report here, for the first time, in situ observations at the nanometer scale of the early stages of weathering of biotite by an ectomycorrhizal fungus, *Paxillus involutus*, grown under axenic and controlled temperature, humidity, and photoperiod conditions in symbiosis with a boreal pine tree, *Pinus sylvestris* (Fig. 1A; see also the GSA Data Repository[1]). This approach recreates the essential symbiotic relationship between the tree and the mycorrhizal fungus under the typical unsaturated conditions found in soils, while excluding all other potential weathering pathways (i.e., soil pore water and other soil microorganisms).

METHODS

Pinus sylvestris (Scots pine) and *Paxillus involutus* (ectomycorrhizal fungi) were first grown separately on cellophane-covered agar plates under aseptic conditions for four weeks. Seedlings of *Pinus sylvestris* were then aseptically transferred onto *Paxillus involutus* cultivated plates. After 10 weeks of growth, roots of *Pinus sylvestris* were well colonized and had developed a symbiotic relationship with the fungi, *Paxillus involutus*, as evidenced by the formation of characteristic short "T" shape roots entangled in dense hyphal networks. Both tree and fungi were then trans-

*E-mail: s.bonneville@see.leeds.ac.uk.

[1]GSA Data Repository item 2009144, (1) methods for cultivation, ion milling, TEM analysis and chemical composition of biotite and growth medium; (2) observations of hypha by Environmental SEM at various hydration states; and (3) raw data of STEM-EDS of lamella 3, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.