Teaching Metastability in Petrology using a Guided Reading from the Primary Literature

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ABSTRACT

The primary research literature can often be a valuable supplement to undergraduate textbook and classroom activities, particularly for in-depth exploration of conceptually difficult areas of the Geosciences. It is also important for students to develop skills needed to read the literature in preparation for future employment or graduate school. I use guided readings of articles from the primary research literature as a tool to ease introductory and intermediate students into journal articles, as well as a way to teach good habits in journal reading. In Introductory Petrology, an article is assigned that describes the development of eclogite-facies assemblages in shear zones surrounded by metastable granulite-facies gneiss (Austrheim, EPSL 1987). Guiding questions step students through the observations and interpretations in the paper, and help lead them to the larger issues of metastability and polymetamorphism in metamorphic rocks. This approach is easy to implement in both introductory and advanced courses, and helps establish a good framework for subsequent in-class discussion.

INTRODUCTION

A now-common element of undergraduate science curricula is an introduction to reading the peer-reviewed primary literature. There are a number of compelling reasons for having undergraduates read journal articles in addition to standard texts, an important one being that those students who continue in science will need to be comfortable with consulting primary sources. Reading scientific papers from the literature also brings students closer to the goals and process of scientific research, which is important to students preparing for careers in science (e.g., Janick-Buckner, 1997) and to non-science majors (e.g., Pall, 2000). The expectation of clear scientific prose from students also necessitates a solid familiarity with scientific writing, including primary sources (Moore, 1994). In particular, Geoscience students need a familiarity with the primary literature, because ca. 70% of prospective graduate students in the Geosciences select graduate institutions based on their future advisor and probable research (compare to 30% in Chemistry; Golde and Dore, 2001).

There are a number of possible approaches for exposing students to journal articles. Many times students will have to navigate the primary literature for the first time in the context of a term paper assignment. Although the term paper project itself may be highly structured (with an approved project, outline, annotated bibliography, etc.), the actual foray into the literature is often unique to the student and their research topic. As a result, the student's difficulty with the selected papers is a function of the student's familiarity with the author's methodology, the sophistication of the reasoning used (e.g., Muench, 2000), the clarity of the writing, and the student's skill in reading primary sources.

Some authors suggest a more explicit introduction to the primary literature for undergraduates. The form of this introduction depends on the level of the student and the goals of the exercise, and can include interpretation of landmark papers in the discipline (e.g., Robinson, 1987; Moore, 1994; Levine 2001), group-led exploration activities (e.g., Fortner, 1999), or structured in-class discussion (e.g., Janick-Buckner, 1997). Some other interesting approaches include the comparison of papers from the primary and secondary science literatures describing the same research results (Pall, 2000), the writing of abstracts for 'decapitated' research papers (Conrad, 1991), and a 'mock-review' of a scientific paper (Mogk, 2000). Often the general guidelines for reading scientific papers given to students have a format similar to the paper itself; concentrating on objectives, methods, interpretation, and hypothesis-testing (e.g., Janick-Buckner, 1997).

In this paper I outline an approach that I have found successful in introductory and intermediate geoscience classes: a guided reading. Briefly, this method asks students to respond in writing to a number of questions unique to the journal article being read. This approach is also applicable to book chapters and some government geologic reports. The guided reading is distinct from simply assigning a series of factual questions to answer while reading the article (e.g., Nold, 1989). Instead, the questions are designed to step the student through the approach and logic used in the paper requiring progressively more sophisticated understanding and reflection on the methods, assumptions, and wider implications of the research. This method is meant to supplement other approaches used in the Geosciences to introduce undergraduates to the literature (e.g., Conrad, 1991; Mendelson, 1991; Hollocher, 1997), and is especially appropriate in situations where students are in the early stages of introduction to science or a particular geoscience sub-discipline. The goal of the guided approach is to teach good habits for reading scientific articles, and to provide an entrance-point into the article for students who have trouble knowing where to begin. A guided reading assignment is also useful to set the stage for subsequent in-class discussions or debates. If assigned beforehand the questions provide a useful base-line of knowledge that can be used by the instructor while facilitating in-class discussion.

METASTABILITY IN PETROLOGY: THE BERGEN ARCS CASE-STUDY

Metastability is a difficult concept for even advanced students to understand or appreciate, and in introductory petrology courses the topic is often given

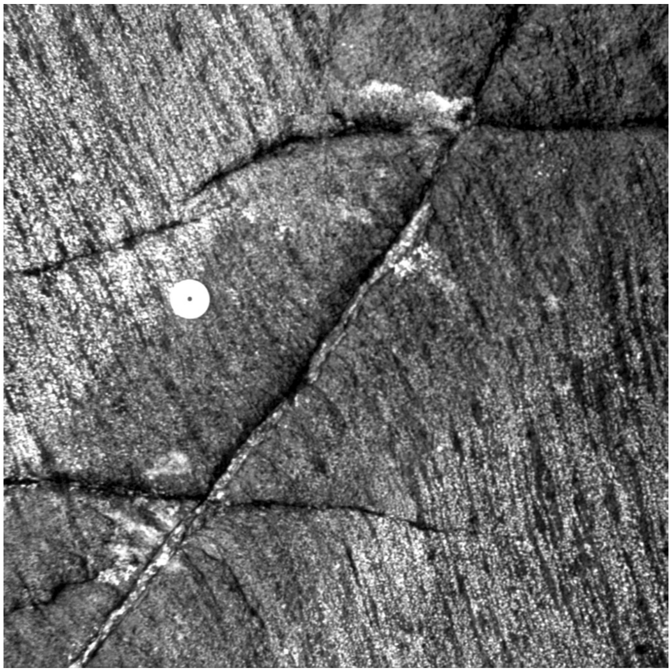

Figure 1. Granulite-facies mafic gneiss (lighter) cross-cut by an eclogite-facies shear zone (darker) on Hølsnoy, Bergen Arcs, Norway. Note that the eclogite-facies mineralogy (e.g. omphasite +garnet +kyanite +clinozoicite) extends several cm from the shear zone, illustrating the role of the shear zone as a fluid conduit. Metastable granulite-facies assemblages (e.g. plagioclase +diopside +garnet +orthopyroxene) persist through Caledonian eclogite-facies metamorphism. A surprising insight for students is that during the Caledonian the granulite was metastable through eclogite-facies conditions, but today at the outcrop *both* the granulite and the eclogite are metastable.

short shrift. Analyzing metastability as part of a class discussion can result in a provocative dialog in which many of the hidden assumptions of petrology and geochemistry are discovered by students. The ultimate goal of the Bergen Arcs exercise, outlined below, is to create a more sophisticated and nuanced view of igneous and metamorphic processes. In-depth analysis of journal articles can have many complimentary goals (c.f., Muench, 2000); in this exercise the primary goal is an understanding of some of the geological implications of metastability through a guided reading of Austrheim (1987).

Geological Context - The geology of the Bergen Arcs and the island of Hølsnoy (western Norway) is described in papers by Håkon Austrheim and coworkers (Austrheim, 1998). The aspects of the geology summarized here are provided as context of the exercise. Igneous rocks of Hølsnoy experienced granulite-facies metamorphism during the Proterozoic. Later eclogite-facies metamorphism related to Caledonian orogenesis is only sporadically exhibited on Hølsnoy, being mainly confined to Caledonian shear zones. Fluid infiltration along shear zones allowed metastable granulite-facies assemblages (e.g., plagioclase +diopside +garnet ±orthopyoxene in metabasites) to react and form eclogite-facies assemblages (e.g., omphasite +garnet +kyanite +clinozoicite), while many un-infiltrated granulites do not record the eclogite-facies event (Figure 1). This process results in a series of field localities that show the progressive eclogitization, where eclogite-facies rocks cross-cut and eventually envelope granulite-facies rocks. Polymetamorphism of this terrane is readily apparent in the field owing to the original anhydrous nature of the granulite-facies rocks, promoting their resistance to reaction during the second metamorphic event.

Guided Reading Outline - The first part of this two-part exercise is the guided reading of Austrheim (1987). Some of the students enrolled in Petrology at Colgate University have never read a geology article before (~40% have read two or less), although some have read articles in other science classes. The exercise (Table 1) is one of eight problem sets assigned in the course, and is the only one that involves the primary literature. As an introduction to the exercise I emphasize that success in understanding a scientific paper is only possible through multiple iterations of reading, taking notes, and reflecting on the material.

Class Discussion - The written answers to the guided reading are collected on the day of the in-class discussion. The discussion is supplemented by a PowerPoint slideshow of field localities on Hølsnoy, arranged as a virtual field trip to illustrate progressive eclogitization. This slide show and accompanying notes are available for downloading (http://departments.colgate.edu/geology/faculty/peck.htm). During the in-class discussion I also use the demonstration of metastability described by Erné (2000). For this demonstration water is boiled in a clean ~500 ml Pyrex measuring cup in a microwave oven. When the cup is removed the water is still >100C for a few seconds, but metastably resists boiling. During this short window of time sand can be dropped into the water, causing rapid boiling (the sand providing nucleation surfaces). This demonstration is a vivid and understandable illustration of kinetic controls on reactions and metastability, although some discussion is necessary to make the connection to the geological example.

The student answers to the guided reading, photographs of the field area, and the metastability demonstration all serve to facilitate class discussion of the paper and its implications. Some of the larger issues that have emerged in the three years I have used this exercise include: the relationship between tectonics and metamorphism, polymetamorphism, overstepping and driving forces of reactions, the meaning of facies, how petrology is done in the field, and the origin of fluids in the crust. An important issue that I try to highlight is the special circumstance of the metastability in this case-study, in that dry granulite-facies rocks can be especially resistant to reaction during polymetamorphism. The discussion is also valuable as a misconception/ preconception check, for example regarding differences between uniform and deviatoric stress. One of the more interesting and provocative topics discussed is how metastability is *necessary* to interpret metamorphic history (i.e., we live in the zeolite facies, but examine metastable rocks from other facies all the time). The discussion also is useful for exploring some commonly held tacit assumptions about

Fluid Controlled Metamorphism: A Cautionary Tale
Questions and Rationale

Question 1.
Use the AGI Glossary of Geology or Winter (2001) to look up 'shear zone'. What is important about the shear zones in this study?

As a first-order goal I want to teach good habits for reading scientific papers. Shear zones have not been discussed in detail in the course yet, so the onus is on the student to learn something about them in order to understand the paper.

Question 2.
Imagine that you were walking around on the outcrop portrayed in Figure 7c. If you looked only at the rocks in the upper left of the figure, what assemblage and metamorphic conditions would you report for the rocks? If you looked only at the rocks in the lower right of the figure, what metamorphic conditions would you infer? Using the features of the outcrop, what is the *relative age* of the two metamorphic assemblages?

The sketch map shows eclogite-facies shear zones cross-cutting gneissosity of granulite-facies mafic gneiss. The focus on cross-cutting relations is to explicitly tie petrologic concepts to 'basic geology' from introductory courses.

Question 3.
On the P-T diagram (attached) draw the position of the *quantitative* estimates of pressure and temperature of both granulite and eclogite facies assemblages. During what geologic period did these two metamorphic events occur? (You may have to look up the ages of the mountain building events mentioned in the paper).

This question serves two purposes: a preview look at quantitative geothermobarometry and to reinforce good habits for approaching papers (looking up relevant geologic events, etc.).

Question 4.
How is metastability relevant to this paper? Winter's (2001) section 5.1 has a nice discussion of this concept. During the Caledonian, what rock(s) were metastable?

This points the students in the right direction for understanding the thrust of the paper, and tries to start them linking the idea of metastability to the actual rocks discussed in the paper. This intermediary step is important because the application of abstract concepts to rocks in the field or laboratory is central to what geologists do, but is often a difficult conceptual hurdle for geology students.

Question 5.
How does Austrheim propose that eclogite has formed in these rocks? What is his evidence?

Asking students to explain the logic of the paper.

Question 6.
Why do you think I named this problem set "a cautionary tale"? Think about what sorts of issues you need to keep in mind while interpreting metamorphic rocks.

I end with this open-ended question because it allows students to unload the things they have been thinking about while wrestling with this paper. Students who haven't been thinking about the wider implications of the paper sometimes feel put-upon by this question, but can come up with good ideas with some encouragement.

Table 1. Guided reading questions for use with Austrheim (1987). Italics are explanatory text.

metamorphism (e.g., do rocks always record the peak of metamorphism, or the last metamorphic event?). The Bergen Arcs exercise could easily be expanded by supplementary readings in the same or subsequent courses, and could explore the role of fluids during metamorphism (Jamtveit et al., 1990; van Wyck et al., 1995; Boundy et al., 1997), co-metamorphism of other bulk compositions (Boundy et al., 2002), and pseudotachylytes and seismicity during metamorphism (Austreheim and Boundy, 1994).

OTHER APPLICATIONS

Introductory Geology: Guided reading as entrée to the primary literature - I have used guided readings to introduce the scientific literature in a 70-student Physical Geology course (Colgate University's Geology 105, Megageology). This course combines traditional physical geology topics with introductory planetary geology and astronomy material. The goal of the assignment was to have students apply their knowledge of higher-level concepts learned in class (e.g., r- and s-process nucleosynthesis, remnant magnetism, interaction between seismic waves and the solid Earth) to a relatively recent research article (e.g., Nicolussi et al., 1997; Zhao et al., 1997; Connerney et al., 1999). The articles were selected from Science or Nature for a clear presentation of methods used and problem to be addressed, and to have a direct connection to lecture material (c.f., Janick-Buckner, 1997). I selected short articles in part to make the assignment feel more tractable for students who had never read scientific primary sources before, and asked only three to five guiding questions. In this case the guiding questions acted as a structured introduction on how to approach the paper and which concepts and arguments need close attention.

Senior-level Seminar: Guided reading for assessment - While teaching a senior-level seminar on isotope geology (Colgate University's Geology 411, Isotopes in the Earth Sciences), I used a guided reading assignment as an assessment tool. A major component of the course consisted of weekly readings and discussion of isotope geology research articles (the 'journal-club' component of the seminar). In addition to an end-of-semester project, I also wanted to assess the students' knowledge and skill in reading the primary literature. In the format of take-home exams (a final and a mid-term), I asked a series of seven guiding questions for a medium-length research article. In this case the questions did not step the students through the basic arguments of the paper as in introductory courses, but instead focused on the details of techniques, hidden assumptions, analysis of isotope data, and appropriateness of conclusions. Students were asked to analyze the article in depth, and were directed to examine cited papers and make supplementary calculations or graphs. The take-home exam was checked out for a limited time (i.e., 48 hours) to encourage students to plan their library time efficiently and to focus their efforts.

ASSESSMENT AND DISCUSSION

The guided reading approach was assessed by subsequent classroom performance, course evaluations written at the end of the semester, follow-up conversations with students, and a questionnaire administered in January 2004. Approximately 50% of former Petrology students returned the questionnaires, which asked them to respond to questions about the effectiveness of the guiding questions, textbook reading, PowerPoint slideshow, and boiling water demo, as well as questions related to overall understanding of the articles.

The majority of students ranked equally the guided reading and slideshow as being the most helpful for understanding the Austrheim (1987) article. I think this result may unduly highlight the slideshow, as it acts as a capstone to the exercise and students may be underestimating the understanding gained through reading the article and instead focusing on the 'coming together' of the concepts at the end. In general there was a correlation between all of the 'effectiveness questions', in that students who thought any of the elements were effective also found the other methods to be quite effective, too. This result is highlighted by student comments from the questionnaire such as, "I think it is essential of having [sic] a multifaceted exercise where different kinds of learning (reading, visual) are used" and "If the students are encouraged to complete the worksheet by themselves at first, then review it in an in-class discussion (with the added visuals of a demonstration or Powerpoint), the exercise is more worthwhile than a simple worksheet that is graded individually and returned with little review." In general the students appear to have appreciated the mutually reinforcing approaches, as well as the implicit admission that scientific articles are hard to read, and take some time and thought to understand. A student corroborates this thought, "I think that the class exercises etc. made for a good way to ease people into…reading [primary sources] while gaining a basic understanding of a concept."

After the Bergen Arcs exercise, students tend to have a fairly sophisticated understanding of metastability. The combination of reading, writing, field slides, and demonstration all mutually reinforce the goals of the exercise. However, there are sometimes unintended consequences of the exercise; some students erroneously associate the eclogite facies solely with shear zones, and occasionally students will randomly cite metastability to explain metamorphic assemblages or fabrics for which they have no other explanation.

In the introductory setting, guided readings allowed me to assign a research article to a relatively large class, and to have a common standard for grading. Many non-science majors commented on their sense of accomplishment from working through a scientific paper. The exercise also reinforced lecture material that is often difficult to understand from textbook reading or lecture alone. The written responses by the students varied widely in sophistication and understanding of the material, and correlated moderately well with grades on in-class exams.

For the take-home exam in the senior-level class the guided questions were surprisingly effective in engaging the students in the assigned papers. Although one student jokingly referred to the 48-hour take-home exam as "finding out that you have a term paper due in two days", end-of-class evaluations and discussions with students characterized the experience as "demanding but effective." This was consistent with my assessment on student performance on these exams.

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