Building the Quantitative Skills of Students in Geoscience Courses

R. Heather Macdonald*
Department of Geology
College of William and Mary
PO Box 8795
Williamsburg, Virginia 23187
rhmacd@wm.edu

LeeAnn Srogi*
Department of Geology and Astronomy
West Chester University
750 Church Street
West Chester, Pennsylvania 19383
esrogi@wcupa.edu

Glenn Blair Stracher*
Department of Geology
East Georgia College
Swainsboro, Georgia 30401
stracher@ega.peachnet.edu

*Co-editors of the papers in this issue

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As the geosciences continue to become more quantitative, geoscience educators need to consider a variety of issues regarding the development of quantitative skills required for geoscience courses at all levels of the curriculum. What quantitative skills are important in this curriculum? How can we integrate quantitative tasks into courses to illuminate students' understanding of geoscience, as well as to enhance their quantitative skills? What are the constraints imposed by different formats and levels of courses and by different student populations? How can we make students feel more comfortable about approaching problems quantitatively so they will be more likely to employ quantitative solutions when solving problems in the future? How can mathematicians and geoscientists work together to develop the mathematical skills of students? How can we develop assignments in which students acquire and manipulate real data and work on real problems? If we accept that "the ability to use numbers and equations to describe situations and answer questions…is a fundamental tool… needed by citizens, scientists and teachers for the future" (Manduca, 1999), then we need to develop ways to most effectively build the quantitative skills of all students.

The importance of this subject prompted us to arrange forums where ideas could be shared and issues discussed. Glenn Stracher organized a symposium, *Activities for Enhancing the Quantitative Skills of Earth Science Students*, at the March 1998 meeting of the Southeastern Section of the Geological Society of America, which included eleven presentations. Several papers based on the talks at this meeting were published in a special edition of *Mathematical Geology* (Stracher, 2000). Heather Macdonald, Cathryn Manduca, Randall Richardson, and LeeAnn Srogi organized a Project Kaleidoscope workshop, *Building the Quantitative Skills of Non-Majors and Majors in Earth and Planetary Science Courses*, that was held at the College of William and Mary in January 1999. The workshop agenda and session descriptions are available at http://www.pkal.org/curricul/eandp/willmary/agenda.html. Heather Macdonald, LeeAnn Srogi, and Glenn Stracher convened a topical session, Building the Quantitative *Skills of Non-Majors and Majors in Geoscience Courses*, that included 29 presentations at the 1999 Geological Society of America national meeting. This issue of the *Journal of Geoscience Education* includes many of the papers presented at the 1999 GSA meeting, some of which were first presented at the Project Kaleidoscope workshop, and one paper by an author who attended the PKAL workshop. The papers provide an opportunity for readers to learn about various teaching strategies, assignments, and conceptual approaches used to build the quantitative skills of students in geoscience courses.

Introductory geoscience courses are particularly useful because they provide an important pathway for a large number of non-science majors to develop the quantitative skills they need to be effective citizens, for future K-12 teachers to learn about effective methods of integrating mathematics and science in the classroom, and for geoscience majors to begin to develop the quantitative skills necessary for their major and for future work. Introductory courses that address real-world problems using quantitative methods are valuable to all students regardless of their future major or career. However, many geoscience courses at the entry level are primarily non-quantitative for a variety of reasons. Faculty may have little experience in effectively incorporating quantitative exercises into entry-level courses. Introductory geoscience textbooks generally do little to enhance quantitative skills. Shea (1990) found that more than half of the introductory geology textbooks he examined had little or no mathematical content. Even when mathematical equations were included, almost no sample problems were worked out and explained, and most textbooks did not include any end-of-chapter questions that used equations given in the text. Many students do not feel confident about their ability to use mathematics to solve problems or to make well-informed decisions, and many faculty are frustrated with the ability of their students to do quantitative work. Some faculty attribute this to poor preparation in mathematics at the K-12 level.

Eleven of the seventeen papers in this special issue discuss quantitative skills in introductory-level courses, which is not surprising given university and national mandates to improve science and mathematics education for all students. These papers encompass a variety of strategies to address some of the special challenges of working with students in introductory courses – how to motivate students, how to enhance their understanding of fundamental concepts, and how to provide effective opportunities for students to practice and improve their quantitative skills. Many of the activities and ideas in these papers could be adapted for use in middle- or high-school earth-science or geology courses.

Overview of Papers on Quantitative Skills

The seventeen papers in this issue reflect some of the diverse ways in which geoscience educators are incorporating quantitative activities and problems into their courses and into the curriculum at this point in time. The papers are organized by curricular level and the approach used to build quantitative skills. The first nine papers describe approaches in entry-level geoscience courses, including the incorporation of quantitative material into lectures and problem sets (Bailey; Shosa and others; Dupré and Evans), laboratory activities (Carlson; Nelson and Corbett; Herrstrom; Stracher and Shea), quantitative reasoning and logic problems (Guertin), and activities culminating in a mock trial (Bair). Activities and problem sets used in upper-level courses are described next (Hall-Wallace; Kenyon), followed by three papers that describe multi-week research projects in courses for majors (Keller and others, Roberts) and an entry-level course (Furman and Merritt). Upper-level majors courses that focus exclusively on quantitative skills are next (Vacher; Lutz and Srogi). The final paper (Macdonald and Bailey) describes an approach to infusing quantitative skills throughout the geoscience curriculum.

Some of the papers present a conceptual framework for quantitative-skills development that can be helpful in planning a curriculum or a course. Keller and others construct a table based on the components of traditional research methodology (for example, hypothesis development and data collection) to identify and implement a "repertoire" of quantitative skills within a single course. Kenyon designs sequential problem sets that develop quantitative skills incrementally and that help the instructor identify specific tasks or skills that students find difficult. Macdonald and Bailey describe how a department can construct a matrix to identify important skills and concepts and to ensure that these are implemented in courses at all levels of the curriculum. These three frameworks are not mutually exclusive and could be used in combination.

One of the key challenges in teaching entry-level courses is motivating students to learn and use quantitative skills. In the first paper, Bailey emphasizes the importance of selecting topics that are interesting to students. Examples by other authors include important regional issues, such as the flooding of local rivers (Dupré and Evans), and issues that have been widely publicized in the media, such as climate change (Furman and Merritt) and contaminated ground water in Woburn, Massachusetts (Bair). Another way to engage students' interest is to use the results of quantitative work as a theme uniting different topics throughout the course. This approach is taken by Carlson and by Nelson and Corbett, who show how the property of density can first be measured and then applied to a variety of important geological processes. Other papers describe how students enjoy and value the hands-on use of technology, whether contemporary Global Positioning Systems (Herrstrom) or more traditional methods such as the geologic compass (Stracher and Shea). Macdonald and Bailey state the importance of implementing consistent and comparable quantitative work in all entry-level courses so students do not have any non-quantitative options (at least in the geosciences). Bailey's paper emphasizes that incorporating mathematics into lectures every week helps to send the message that quantification is a natural – and inescapable – part of any science course.

The format of a particular entry-level course may influence the approach used to build quantitative skills. All four papers that discuss large lecture sections of introductory geology (Bailey; Shosa and others; Dupré and Evans; Guertin) use very similar approaches involving some in-class instruction and problem sets as homework assignments. Bailey, who teaches a course without a required laboratory component, chooses to devote a significant proportion of class time to quantitative-skills development. As an alternative, Shosa and others describe self-contained problem sets that can be completed by students independent of lecture or laboratory, with help from the instructor and teaching assistants if needed. Direct experimentation and data collection by students tend to be carried out in smaller classes, typically in a laboratory format (Carlson; Nelson and Corbett; Herrstrom; Stracher and Shea). It is interesting that the two examples of complex, multi-week investigations (Bair; Furman and Merritt) are both courses with small enrollments that focus on a specific topic rather than survey a discipline.

What quantitative skills are considered important by the geoscience community? Some would argue that the answer to this question is different for courses at different levels of the curriculum or for students who are geoscience majors or non-majors. Algebra and graphing are the two skills included in almost every paper of this issue. A few authors include the development of spatial skills and geographic literacy as an important aspect of quantitative skills (Herrstrom; Stracher and Shea; Furman and Merritt). Calculus is recognized as important in some upper-level courses for majors. Several authors discuss the importance of having students express quantitative understanding verbally, either informally or in more structured formats. Thus, Dupré and Evans present a table of the skills and concepts needed by students for their introductory geology course. Macdonald and Bailey present a list of quantitative skills, concepts, and topics that their department felt should be incorporated throughout the entire curriculum, albeit at different levels of depth or complexity in different courses.

Both Bailey and Hall-Wallace describe the importance of developing students' abilities to express physical phenomena in mathematical terms. The papers by Carlson and by Nelson and Corbett show how students can move from measuring numerical values of individual quantities (mass and length), to developing functions that describe properties of increasing complexity (volume, density, and porosity). Carlson's more lengthy treatment is an essentially constructivist approach that provides sustained support for the students' development of a deep understanding of the density of different materials. The ability to express physical phenomena in mathematical terms can have enormous predictive power, as demonstrated by the discussions of flooding (Dupré and Evans) and plate motions (Hall-Wallace).

Problem solving using mathematics is interpreted in a variety of ways in the papers comprising this issue. It can be as straightforward as using trigonometry to show whether a traverse made by GPS or a Brunton compass is closed (Herrstrom; Stracher and Shea). A more complex example described by Furman and Merritt is the use of spreadsheet functions and statistics to evaluate climate change in Africa. The problem-based approach advocated by Bair, Keller and others, and Furman and Merritt is structured by the instructor to a great extent. Roberts uses a problem-solving approach in an upper-level majors course in which the students are almost entirely responsible for the structure of the project, from selection of the problem to evaluation of the results. Her paper highlights the growth of the students' conceptual understanding as they conduct the project. Guertin, in a novel approach at the introductory level, has students solve logic problems and emphasizes that the development of logical reasoning is essential to quantitative problem-solving as well as critical thinking in general. In the upper-level courses devoted to building quantitative skills described by Vacher and by Lutz and Srogi, geoscience problems are used to illustrate the application of a variety of mathematical skills and concepts; a few examples are given in each paper.

As we incorporate more mathematics into the geoscience curriculum and ask students to become more engaged in active problem-solving, we need to provide additional support structures for the students. In part, the support can simply mean access to additional help from instructors or teaching assistants (Bailey; Shosa and others; Guertin), or logistical support for using technology (Herrstrom; Furman and Merritt). Kenyon's use of problem sets that build skills incrementally is a different kind of support structure in which the task itself provides direct information to the instructor about which students need help with specific skills or concepts. The papers by Roberts and by Vacher describe very different courses, but both authors discuss the very subtle and fluid kinds of support that instructors provide when students determine the content and direction of a course. Finally, Lutz and Srogi describe how the need to provide both academic and departmental support for geoscience majors taking calculus led to the development of a geoscience course designed to "shadow" the calculus course.

Quantitative-Skill Development in Perspective

We recognize that quantification in geoscience courses is not a new issue, and we provide some historical background and look to the future. The National Association of Geoscience Teachers (NAGT) and the *Journal of Geoscience Education* (*JGE*) have addressed the issue of quantification in geology in various ways in the past few decades. As far back as 1965, an article in *JGE* called for greater utilization of mathematics in geology courses (GEO-Study Mathematics Panel, 1965), and the NAGT – Eastern Section had a meeting about *Quantification in Geology*. Two years later, a special issue of *JGE* (1967, v. 15, n. 6) included thirteen problems designed to "stimulate the introduction of problem-oriented approaches in beginning- and intermediate-level geology courses." Most of these problems were quantitative, as noted in an editorial by James Shea (1988). In that editorial, Shea encouraged readers to share quantitative problems by submitting papers for publication in *JGE*, and since then, *JGE* has published numerous papers addressing quantification or mathematics in geoscience. In addition to articles describing specific activities or courses, several authors have written on-going columns for *JGE*. Don Triplehorn wrote "On the Back of an Envelope: A Column Devoted to Encouraging Calculation in Geology" from 1994 to 1995, and Len Vacher continues the tradition with his column "Computational Geology" (1998 to present). Marion Wampler's column about misconceptions in geology textbooks, which began in 1996, commonly pertains to quantitative issues.

There are probably many reasons why interest in building the quantitative skills of students is increasing. Mathematics plays a larger role in modern geoscience, although some subdisciplines of geoscience have always been quantitative (for example, engineering geology). The emphasis in the geosciences has shifted to fields that require more quantitative methods, such as plate-tectonic theory and analysis of ground-water and contaminant flow. The advent of high-speed computers has enabled the application of sophisticated mathematical methods to complex geological systems. At the same time, educational reform efforts have moved geoscience courses towards more quantification. The *National Science Education Standards* (NRC, 1996) called for the coordination of science programs and mathematics education, given that "science requires the use of mathematics in the collection and treatment of data." One of the recommendations made in *Shaping the Future of Earth Science Education* (Ireton and others, 1996) was to integrate and incorporate quantitative reasoning across the curriculum. Many of the activities, problems, and investigations used to engage students more actively in learning are those in which mathematics plays an important role.

The papers in this issue represent a snapshot, to some extent, of where the geoscience-education community is at this point in time. The quote below eloquently describes the conceptual struggles faced by a thoughtful educator trying to write a paper (for this issue) about experiences building students' quantitative skills:

> In what I did write I set out to make two related points: 1) That students commonly go astray in solving problems that involve physical quantities because they fail to visualize the quantities involved, focusing instead only on the numbers in a computation, and 2) that students probably do that [focus on the numbers] because much of their earlier training in math and science involves plugging

numbers into relationships that have already been worked out for them as sample problems. I suspect that students generally aren't good at "word problems" because they haven't been given much opportunity to work out the kinds of relationships they need for solving such problems. As I was writing anecdotes about how my students have gone astray, I came to realize that perhaps I have been expecting too much of them in the way of working out the relationships they need to solve problems. …I realized that I should have been teaching them how to derive relationships, not just expecting them to do it. And I realized that if I am going to complain about the effect of too much rote computation – not enough problems that require thoughtful responses – in earlier schooling, I'd better become familiar with the educational literature on the matter.

As we face the challenges of building students' quantitative skills – those so well stated in this quote as well as others – all members of the K-16 geoscience community need to work together toward our common goals. We have much to learn from each other, as well as from colleagues in mathematics, physics, and chemistry. For example, the national standards for mathematics education developed by the National Council of Teachers of Mathematics for K-12 classrooms (NCTM, 2000) and the standards for college mathematics before calculus developed by the American Mathematical Association of Two-Year Colleges (AMATYC, 1995) can help science educators think through issues related to the development of quantitative skills. Two-year colleges enroll approximately 45% of all US undergraduates (American Association of Community Colleges, 1997), and many future elementary- and middle-school teachers take most of their college science and mathematics courses at two-year colleges (NSF, 1998). Thus, an important aspect of quantitative-skills development in entry-level courses is the critical role played by two-year colleges in the science and mathematics education of undergraduate students.

A national endeavor to build students' quantitative skills will require a concerted effort by the K-16 geoscience community. Individual instructors can help by incorporating activities that build students' quantitative skills in the context of meaningful geoscience problems and concepts. Ideas may come from this compilation, along with the papers in *Mathematical Geology* (Stracher, 2000) and the abstracts from the 1998 GSA-SE meeting and the 1999 GSA national meeting. Instructors can also help by adopting textbooks with more mathematics for the courses they teach, by recommending greater use of mathematics in introductory textbooks when serving as reviewers, and by supplementing mathematics-impoverished texts with additional activities that boost quantitative skills at appropriate levels. We hope that the papers in this issue encourage and stimulate faculty to consider using a more quantitative problem-solving approach in all their courses, particularly in entry-level courses, and to share their experiences widely with the community.

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