

A Quantitative Approach to Introductory Geology Courses

Christopher McNeill Bailey
Department of Geology
College of William and Mary
Williamsburg, Virginia 23187
cmbail@wm.edu

ABSTRACT

Introductory geology courses taught from a question-based approach that effectively incorporates problem solving demonstrate to students that science is more than a collection of facts. By having students put together observations and calculations to answer questions about the Earth, the course provides opportunities for students to develop more quantitative ways of thinking. Proficiency with quantitative problem solving comes from doing in-class exercises, homework, and exams that include numerical and graphical problems requiring arithmetic, algebra, and geometry. Incorporating quantitative problem solving is hampered by student perceptions about geology courses as well as the lack of introductory geology textbooks with a quantitative focus. However, quantitative materials can be successfully incorporated into large introductory geology courses if the instructor is accessible, engaging, and positive towards students' problem-solving ability.

Keywords: Education – undergraduate; education – geoscience; miscellaneous and mathematical geology.

In the case of nearly all branches of science a great advance was made when accurate quantitative methods were used instead of more qualitative.

– H.C. Sorby, 1908

INTRODUCTION

In the past twenty years geology has become increasingly more quantitative, but many introductory courses are taught in a qualitative fashion. Introductory geology textbooks are copiously illustrated but generally lack any substantive treatment of quantitative topics (Shea, 1990; Shea, 1994). Science is more than a collection of facts; science is a way of thinking that commonly involves problem solving and numerical analysis. Geologists must therefore endeavor to teach courses that more accurately reflect the workings of our discipline. Introductory geology courses should illustrate the grandeur of the Earth, but they can also teach students the rudiments of critical and quantitative thinking.

Why teach introductory geology courses with a quantitative focus? Institutions of higher education aspire to produce graduates that are able to think for themselves and are critical consumers of information. Courses that teach students a collection of "facts" about the earth do little to develop critical-thinking and problem-solving skills. In order to enhance the

quantitative skills of students in introductory geology, I use a question-based approach that poses problems for students to solve quantitatively. I believe this approach is valuable for both non-science majors and science majors because it provides opportunities for students to better understand the way science works, to practice solving problems, and to enhance mathematical skills. In this paper, I outline my approach to teaching introductory courses with a quantitative focus and give examples of problems.

To develop a better sense of student perceptions in my introductory course, I survey the class during the latter part of the semester. Over the past few years, I have given students a three- to five-question in-class survey. Typically 85- to 90 percent of the students are in attendance when the survey is completed. A majority of the students in my introductory geology course feel it involves more mathematics and problem solving than they expected (Figure 1A). Furthermore, nearly 50 percent of students dislike math and problem solving (Figure 1B). I suspect that the attitude of William and Mary students is probably similar to that of most undergraduates taking introductory geology courses. In order to make introductory geology courses more quantitative, we must overcome student expectations that geology is a non-quantitative subject and work with an audience that generally brings a dislike for quantitative thinking.

The numerical problems I use in my introductory geology course require students to do arithmetic, algebra, geometry, and some trigonometry. At William and Mary, many students have taken calculus (Figure 1C) and have significantly more training in mathematics than is needed to solve problems in introductory geology. However, many of these students have never used mathematics outside the math classroom and are uncomfortable with their problem-solving ability. The level of mathematics that most students bring to college (at least algebra?) is sufficient to solve problems in introductory geology. At many institutions students may not have taken calculus or trigonometry, but they can do arithmetic and algebra and apply these skills to earth-science problems. The instructor must encourage students by illustrating how the math that they already know can be used in new ways to solve real-world problems.

A QUESTION-BASED APPROACH TO TEACHING QUANTITATIVE MATERIAL

Background

At William and Mary, introductory geology courses typically have 100 to 150 students. Over half of these students are freshman and sophomores, most of whom are taking geology to satisfy a science requirement

A Quantitative Approach to Introductory Geology Courses

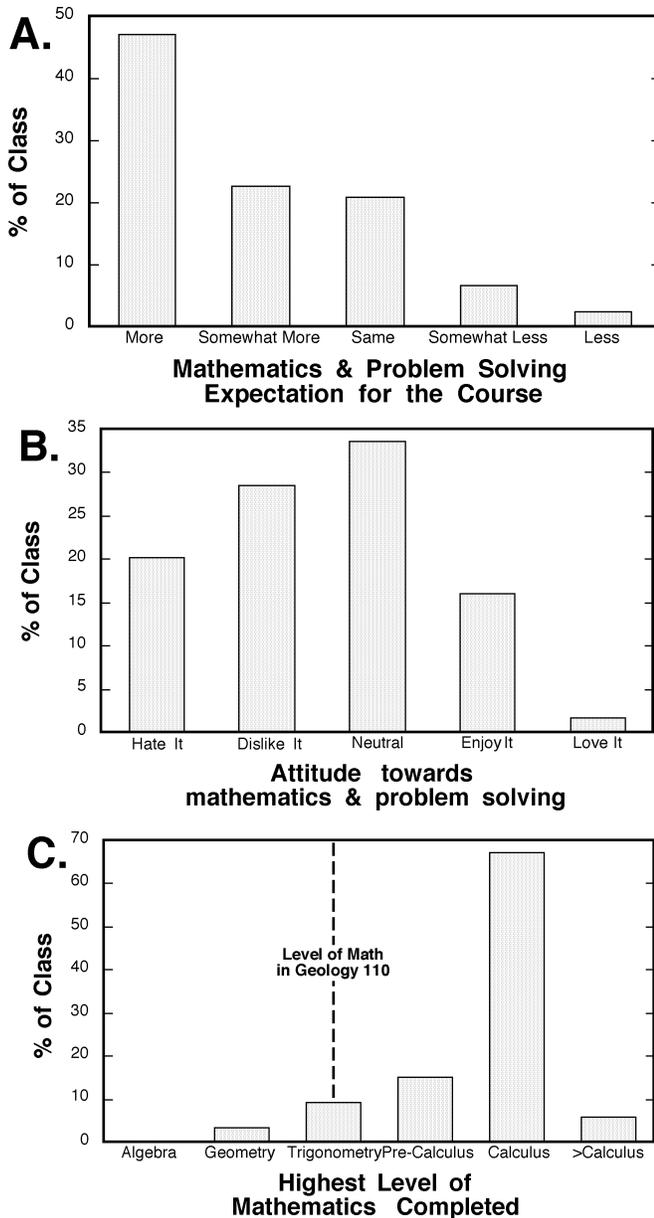


Figure 1. Geology 110, College of William and Mary, spring 2000, n = 119. A) Student expectations of mathematics and problem solving. B) Student attitudes toward mathematics and problem solving in general. C) Highest level of mathematics completed by students.

and do not plan to take any more science courses. Ten to fifteen percent of the students are also enrolled in the education program and plan careers as teachers. Although very few students taking introductory geology plan on becoming geology majors, typically 10 to 20 students will pursue further study in geology after completing the course. The course is taught in a large lecture hall with chalkboards and a large screen for slides, transparencies, and computer presentations.

The First Day

I use a question-based approach in the introductory courses. I pose questions about the Earth and work with the class to answer those questions. The

Level of Mathematics Used in Geo 110	Interrelated Topics
Arithmetic	Observation vs. Interpretation
Algebra	Correlation vs. Causation
Geometry	Orders of Magnitude and Scale
Trigonometry	Units and Dimensionless Numbers Graph Construction and Interpretation

Table 1.

question-based approach enables me to bring many quantitative topics into the class (Table 1). Many of these questions are simple but need to be answered and understood before more complex topics can be developed. At the start of the first class period I put a question to the class:

What best approximates the shape of the Earth: a Frisbee, a grapefruit, or a beach ball?

I ask this question before handing out the syllabus or discussing the logistics of the course because I want to set an inquiry-based tone for the class. Invariably, nobody picks the Frisbee as the best model for the shape of the Earth. I then ask:

Why is the Frisbee a poor model for the shape of the Earth?

A chorus of students will respond that the Earth is most certainly not flat like the Frisbee but spherical (or round) like the grapefruit and beach ball. To that I respond:

Prove the Earth is not flat; prove the Earth is spherical.

I ask students to work in small groups, talk about the question for a few minutes, and write down observations that prove the Earth is spherical. A surprisingly large number of students cannot explain how they know that the Earth is spherical or provide any observations that might prove the Earth is spherical. To these students, the spherical Earth is a fact and nothing more. However, other students bring forward observations such as the shadow of the Earth on the Moon during a lunar eclipse and ships disappearing over the horizon as they sail out to sea. I attempt to reinforce this by showing slides of a lunar eclipse and ships at sea. With relatively simple observations, the class can provide convincing evidence that the Earth is spherical and that the flat Earth model (Frisbee) is incorrect.

What is the size (radius) of the Earth?

To answer this question, I use the historical example of Eratosthenes, the ancient Greek librarian who is said to have estimated the size of the Earth in 200 BC using observations and simple geometry (Phillips, 1968; Emiliani, 1992). At Aswan, on the upper Nile in Egypt, the sun is directly overhead at noon on mid-Summer's day. In Alexandria (727 km north of Aswan) on the Mediterranean the sun is not directly overhead at noon on mid-Summer's day and shadows are cast (Figure 2). Assuming the sun's rays are parallel, not an unreasonable assumption that I address during class, the Earth's surface must be curved. Two staffs (1 meter in length) were placed vertically

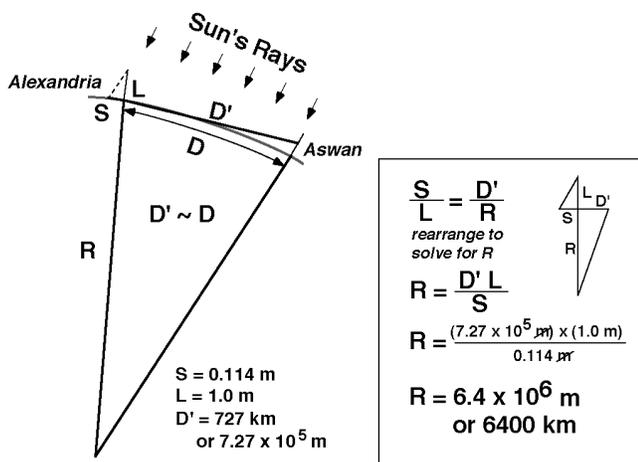


Figure 2. Illustration of the geometry and equation needed to determine radius of the Earth.

in the ground at Alexandria and Aswan at noon on June 21 (Figure 2). The staff in Alexandria casts a shadow 0.114 m in length, while there is no shadow cast in Aswan. Two similar triangles can be constructed between the staff (L) and shadow (S) in Alexandria and the distance between Alexandria and Aswan (D') and the center of the Earth (R). The ratio between sides is the same for similar triangles such that

$$S/L = D'/R \quad (1)$$

where D' is the straight-line distance (note: the angular difference between Aswan and Alexandria is small thus, $D' \sim D$). The distance to the Earth's center (radius) can be determined by rearranging the equation

$$R = D' \cdot L / S \quad (2)$$

I solve this equation at the board in a step-by-step fashion, being careful to illustrate the conversion between meters and kilometers and how units are canceled (Figure 2). The radius of the Earth is approximately 6400 km. Students could have been told this fact, but instead they went through the observations and calculations needed to make this discovery. Throughout the semester, the class will use the Earth's size as a starting point for a number of other topics, including the mass and density of the earth, the geothermal gradient, and the nature of internal layers.

The class has still not resolved whether the grapefruit or beach ball is the better model for the Earth's shape. Most students think the grapefruit is a better model because the nooks and crannies of the grapefruit may approximate the mountains and valleys on Earth, whereas the beach ball seems too smooth. To evaluate this, I have students determine the relief ratio of the Earth, grapefruit, and beach ball. The highest point on Earth is Mt. Everest at approximately 9 km above sea level and the lowest point, in the Mariana's trench, 11 km below sea level. Although Mt. Everest and the Mariana's trench are thousands of kilometers apart, the total relief on the Earth is

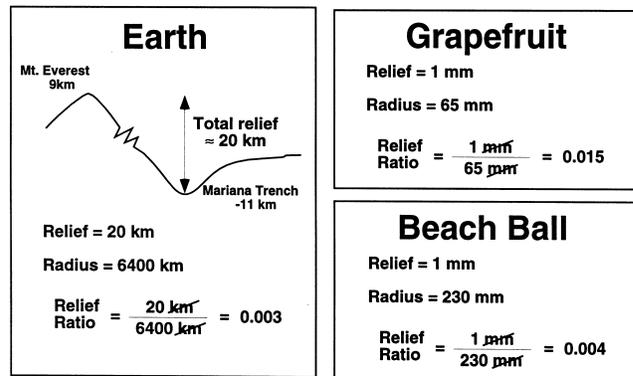


Figure 3. Relief ratio for the Earth, a grapefruit, and a beach ball.

approximately 20 km. Students make visual estimates of the radius and relief on the grapefruit and beach ball. The relief ratio of a grapefruit is approximately five times that of the Earth (if the grapefruit were the size of the earth, its Mt. Everest would be over 40 km in height), but the nearly featureless beach ball's relief ratio closely approximates that of Earth (Figure 3). The difference between relief ratios on the grapefruit and beach ball is large enough that, regardless of the relief estimated by students, the relief ratios are very different. This example also illustrates dimensionless numbers and their role in geology. I have done the shape-, size-, and relief-ratio examples in a single 50-minute class period but have also left the relief ratio for another day when there is insufficient time to adequately cover the material in one class.

Beyond the First Day

At the start of every class, I ask questions of the students. Much of my effort is devoted to lectures that are relatively traditional but focus on trying to help the class answer specific questions. It is important to pose interesting questions (questions that seem interesting to faculty may not always be interesting to college students). If students are interested in the question, they are more likely to seek out the answer, even if it requires using mathematics. Many of my questions require numerical manipulation, but many are also of a qualitative nature.

Just as athletes and musicians repeatedly practice their craft to become experts, students must practice their problem-solving and numerical-manipulation skills if they are to become proficient. I give students the opportunity to work on problem solving during almost every class period. I build five- to eight-minute intervals into the lecture and have students work alone or in small groups on a problem. After they have worked the problem in class, I go over the problem at the board or with slides and make clear the approach and correct answer to the question. I plan to post the in-class activities (problems and solutions) on a class web page in the future. In-class activities count for five percent of the course grade. I do not always grade these problems because they are intended to help students learn and practice problem solving as well as to encourage class attendance.

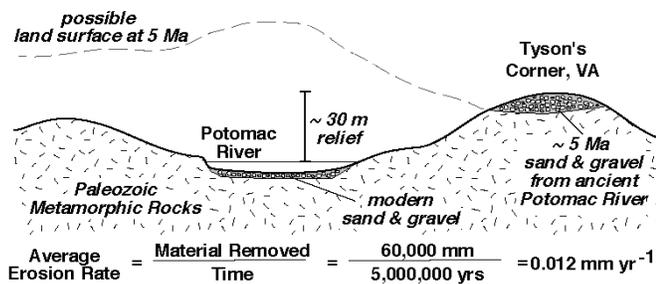


Figure 4. Schematic cross section of the northern Virginia Piedmont illustrating data needed to determine average erosion rate.

An example of an in-class problem is estimating the average erosion rate in the Piedmont. As the modern Potomac River flows across the Piedmont, it transports sand and gravel in its bed load (Figure 4). In northern Virginia, the Piedmont bedrock is composed primarily of Paleozoic metamorphic rocks; however at Tyson's Corner the hilltops are underlain by sand and gravel (Figure 4) (Froelich, 1976). These sediments are interpreted to be fluvial deposits of Miocene to Pliocene age (~ 5 Ma) (Froelich, 1976). I show maps, cross sections, and field photographs of the area. I also lecture about topographic inversion and discuss the possibility that sediments exposed at Tyson's Corner were deposited in a valley by the ancient Potomac River. The students then work in pairs to estimate the erosion rate (in mm per year) in the Piedmont using the data illustrated in Figure 4. Because the modern topography has ~30 meters of relief, it is reasonable to assume ~30 meters of relief for an ancient landscape, thus a total of ~60 meters of material has been removed. The assumption that the ancient landscape is similar to the modern is an outgrowth of the geologic concept that the present is the key to the past. However, many students are rightly suspicious about this assumption. I try to make clear that this is a reasonable starting point for our estimate and that there is an inherent uncertainty in the estimate. The average erosion rate can be estimated by dividing the amount of material removed from downcutting of the Potomac River by the age of the ancient sediments. I do not explicitly tell the students how to calculate the erosion rate; they are left to come up with that relationship in their small groups.

Based on data from northern Virginia, the average erosion rate for the Piedmont is 0.012 mm yr⁻¹ (Figure 4) (Menard, 1961; Pavich and others, 1985). An erosion rate of one hundredth of a millimeter per year seems small; however, without context, the value is meaningless. To provide a comparison, I have students determine the average erosion rate in the Himalayas using sediment-load data from the Ganges River (see Bailey, 2000) as a homework question. Erosion rates in the Himalayas (a tectonically active mountain belt) are ~1-2 mm yr⁻¹, two orders of magnitude greater than in the tectonically quiescent Piedmont. After students have completed the homework, I give a short summary that puts the erosion rates into perspective. Some other problems that students work on

Determination of the residence time of water in the atmosphere, water in a campus pond, and carbon in the atmosphere
Determination of the geothermal gradient from observational data
Determination of the velocity of seismic waves from earthquake data
Determination of lithospheric plate movement rates from seafloor magnetic anomalies
Estimation of drainage basin areas from maps
Estimation of discharge in streams and rivers
Calculation of the age of groundwater, sediments, and igneous rocks using radioisotopes
Determination of groundwater and pollution velocity through aquifers
Calculation of solar insolation on slopes
Calculation of the exponential population increases of rats and humans, and decrease in hydrocarbon resources over time

Table 2. Examples of quantitative problems used in introductory geology.

during class and on homework exercises are listed in Table 2. A few example problems with solutions are given in Bailey (2000).

Students in my introductory course complete three problem sets that are primarily quantitative (Table 2). Problem sets count towards 15 percent of the final class grade. Some of the problems in the homework exercises are similar to material covered in class, but many are not. Thus students are required to use the skills they have developed to solve problems in a different way.

I conduct weekly help/review sessions (outside the normal class time) that are well attended by students who ask many questions concerning problem solving. Students that regularly attend the sessions feel it helps their performance on the problem sets. I do not solve the problems for the students but try to help them set the problem up correctly and review material covered during class. Review sessions seem to be an efficient way to help students in large classes (100 students) because I can answer the same question once rather than numerous times. Student who are quiet and do not ask questions may have their concerns addressed by other students' questions.

My in-class examinations (two exams during the semester and a final exam) are not as quantitative as the homework exercises. Approximately 20 percent of an exam includes problem solving and numerical manipulation. Interpretation of graphical data is also a significant component (20 percent) of exams. The quantitative problems on the exams are not as complex or as difficult as homework problems. I do not ask students to memorize lengthy formulas. For example, I have used a topographic inversion-erosion rate problem similar to Figure 4 as a test problem. I try to design both numeric and graphical questions that require students to understand fundamental quantitative relationships but can be answered in the limited time of an hour-long exam.

My attitude and accessibility play a large role in how successfully quantitative material is incorporated

A Quantitative Approach to Introductory Geology Courses

into the introductory course. I want to engage students in the classroom. My lectures and in-class activities are planned out, but I want the students to feel the class has an element of spontaneity and excitement. If I am enthusiastic about the questions and problems, it rubs off on many of the students. Early in the semester, it is important to illustrate to the students that they have the ability to successfully solve problems and do the required mathematics. I strongly encourage students to attend the review sessions, come for individual discussions, and e-mail any questions they have to me. In a large class, it is difficult to know all the students, but I feel the effort made to learn names and know students demonstrates a commitment to help them succeed in the course. Students seem to work more diligently if they know I am aware and concerned about their performance.

CHALLENGES, DIFFICULTIES, AND THE EFFECTIVENESS OF THE QUESTION-BASED APPROACH

Instructors wishing to make their introductory geology class more quantitative must overcome a number of challenges. Introductory textbooks present few equations, generally provide few examples of how quantitative problems are solved, and rarely have numerical problems with end-of-chapter questions (however, see Strahler and Strahler, 1997; Rogers and Feiss, 1998). It is ironic that many introductory geology textbooks have appendices with conversion factors and simple equations, but this information is never used in the text to solve problems. As pointed out by Shea (1990), textbooks have dropped numerical treatment of subjects because students, faculty, and textbook reviewers have demanded qualitative products. Instructors can overcome the lack of quantitative material in textbooks by posting material (in-class problems, answer keys for homework exercises, and so forth) on the web as a reference for students. Preparing and posting information to the web is time-consuming, but if geologists are going to make their courses more quantitative, useful reference material must be available for students.

Student misgivings about problem solving and quantitative material are important. I have found that most students are willing to do mathematics if they see a reason for solving the problem. Environmental problems that require a quantitative solution (for example, "How long will it take a pollutant to reach the water-supply reservoir?) seem to be effective for developing student interest. It is also critical to follow up quantitative problems with a qualitative discussion that demonstrates the point of solving the problem in the first place (for example, what are the best ways to remediate a plume of pollution moving towards a water supply). Most students can do arithmetic, cancel units, and rearrange equations, but they need to be reminded of how to do it and encouraged to believe they have the skills to be successful. Some students are openly hostile to this approach and feel problem solving is inappropriate in a first-level course.

However, most students are positive about their experience, my instructor evaluations are overwhelmingly positive, and a significant number (10-20 percent) of students take more earth-science classes.

It is also important to talk with colleagues about the level of quantitative material used in the introductory geology course. At William and Mary, the faculty teaching introductory courses feel that quantitative material is important, and we are working to cover topics with the same level of rigor in each of our introductory classes. We are attempting to present a unified front to students and avoid having students resent the quantitative material in one instructor's class because another instructor does not require problem solving.

I have not completed any significant research into the effectiveness of teaching a quantitative question-based introductory course (for example, with pre-testing and post-testing). Historically, the average grade on problem sets rises throughout the semester (data from four introductory courses 1996-1999: Problem Set #1 – 77%, Problem Set #3 – 82 percent), suggesting that students are getting better at solving quantitative problems. My feeling is that students completing my introductory course leave with the ability to tackle quantitative problems and think critically about what different observations mean. Student comments on the course and instructor evaluations seem to bear this out.

CONCLUSIONS

Quantitative problem solving has a place in introductory geology courses. Teaching quantitative materials is not easy, but we have a responsibility to our science, to our institutions, and most importantly to our students to help them learn to think clearly and critically. College students have the training to do simple mathematics and will use those skills if the problems are interesting and worth solving (Table 3). Students become better with quantitative material through repeated practice in the form of in-class exercises, homework problems, and exam questions. The accessibility and attitude of the instructor is very important in successfully bring quantitative material to introductory students.

Use a question-based approach
Provide interesting and worthwhile questions and problems
Demonstrate the point of solving each problem
Solve quantitative problems in class every day
Illustrate how units are canceled, orders of magnitude manipulated, etc.
Use individual and group problem-solving activities in class
Have quantitative homework problems and exam problems
Repetition of problem solving
Positive instructor attitude
Accessibility of the instructor to students

Table 3. Keys to successfully incorporating quantitative material to introductory geology courses.

ACKNOWLEDGMENTS

I thank my graduate oral examination committee at Johns Hopkins University for helping me see the value of quantitative thinking. Heather Macdonald and Glenn Stracher organized workshops and symposia that helped me articulate why and how I teach introductory courses in a quantitative fashion. The many students who have both enjoyed and suffered through my problems are thanked for tolerating my attempts at making introductory geology more quantitative. Three anonymous reviewers are thanked for helping to significantly clarify this paper.

REFERENCES CITED

- Bailey, C.M., 2000, Rates of geologic processes: Problems for an introductory geology course: *Mathematical Geology*, v. 32, p. 152-158.
- Emiliani, C., 1992, *Planet Earth*: Cambridge, Cambridge University Press, 718 p.
- Froelich, A.J., 1976, A geologic and environmental guide to northern Fairfax County, Virginia: Geological Society of America field trip guidebook, Short Course 3, 28 p.
- Menard, H.W. Jr., 1961, Some rates of regional erosion: *Journal of Geology*, v. 69, p. 154-161.
- Pavich, M.J., Brown, L., Valette-Silver, J.N., Klein, J., and Middleton, R., 1985, ¹⁰Be analysis of a Quaternary weathering profile in the Virginia Piedmont: *Geology*, v. 13, p. 39-41.
- Phillips, O.M., 1968, *The heart of the Earth*: San Francisco, Freeman, Cooper, and Company, 236 p.
- Roger, J.J.W., and Feiss, P.G., 1998, *People and the Earth*: Cambridge, Cambridge University Press, 338 p.
- Shea, J.H., 1990, Mathematics in physical-geology textbooks: *Journal of Geological Education*, v. 38, p. 138-148.
- Shea, J.H., 1994, Mathematics (or the lack of it) in introductory-geology courses: *Geological Society of America Abstracts with Programs*, v. 26, n. 4, p. 60.
- Sorby, H.C., 1908, On the application of quantitative methods to the study of the structure and history of rocks: *Journal of the Geological Society of London*, v. 64, p. 171-232.
- Strahler, A., and Strahler, A., 1997, *Physical Geography*: New York, John Wiley and Sons Inc., 637 p.
-