DESIGN, IMPLEMENTATION, AND EVALUATION OF GIS-BASED LEARNING MATERIALS IN AN INTRODUCTORY GEOSCIENCE COURSE

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ABSTRACT

Learning with Geographic Information Systems (GIS) rather than about GIS has great potential for improving students' skills in problem solving, analysis, and spatial visualization. However, little is known about how well GIS-based learning lives up to this potential. Using classroom observations, student interviews and surveys, pre- and posttests of knowledge, and measures of spatial skills, we have begun to quantify student learning that occurred with a GIS-based module on plate tectonics and geologic hazards. We also investigated factors in the design and implementation of the materials that impacted student learning. Classroom observations were key to improving the materials so that students in an introductory geoscience course can successfully complete the activities with minimal instruction in GIS. Through field-testing, we improved the materials design to address student difficulties with learning to use a GIS, identifying basic geographic locations and features, and interpreting topography and other two- or three- dimensional representations. In a quantitative measure of knowledge, using pretests and posttests, mean scores improved 17% ($p<.001$). We also found positive correlations between students' spatial ability and performance on both the posttest and a regular course exam that covered the material in the GIS activity. We are continuing this investigation in Fall 2001 to measure changes in spatial ability due to use of GIS-based materials.

Keywords: Education – Testing and Evaluation; Education – Computer Assisted; Education – Undergraduate; Geoscience – Teaching and Curriculum; Geophysics – Solid Earth

INTRODUCTION

Instructors walking into a large introductory class with the goal of teaching students about global earth processes, geologic hazards or environmental science face a daunting task. The full richness of these topics requires knowledge of world geography, organizational and logic skills to work with large amounts of information, and the ability to visualize three-dimensional space and space-time relationships. To meet this challenge, instructors must choose instructional methods and materials carefully to maximize the learning experience. Unfortunately, too often we have little evidence that the learning goals of any particular activity are actually met.

Instruction with activities that use a Geographic Information System (GIS) has the potential to impact student learning by reinforcing concepts through discovery, and by improving problem solving, visualization and computational skills (Salinger, 1994; Barstow, 1994). Once a tool used only by professionals, now GIS is being used with students in middle through graduate school. The power of a GIS is in the tools it provides for rapid analysis and visualization of large geographic data sets. Investigations with a GIS allow students to identify physical and spatial relationships by constructing multiple representations of data in the form of maps, tables, charts, and layouts. The analytical tools allow students to quantify those relationships using database functions for sorting, database searches, simple calculations, and statistics. They can even develop new data for their own investigative research. While, the potential for learning is great, we know little about how well GIS-based investigations meet these objectives (e.g. EdGIS; NSF, 1994).

In this paper, we report on our investigations of student learning from a suite of GIS-based activities on plate tectonics and geologic hazards taught in a large introductory course for non-science majors. The design and classroom implementation of materials can affect learning. Thus, our investigation includes extensive evaluation of these factors, as well as a measure of learning impact. We will continue this investigation in Fall 2001 to measure the impact of these materials on students' spatial skills.

TEACHING WITH GIS

Most college-level instruction using GIS is taught at the advanced undergraduate or graduate level and focuses on learning the tool first and problem solving later. This instruction is provided mainly in geography departments and is meant for those who want to become GIS professionals. So, when one of the authors and several colleagues at the University of Arizona conceived the idea of having freshman learn *with* GIS rather than *about* GIS, we were met with great skepticism. Undaunted, we developed a series of learning modules that include investigations of three

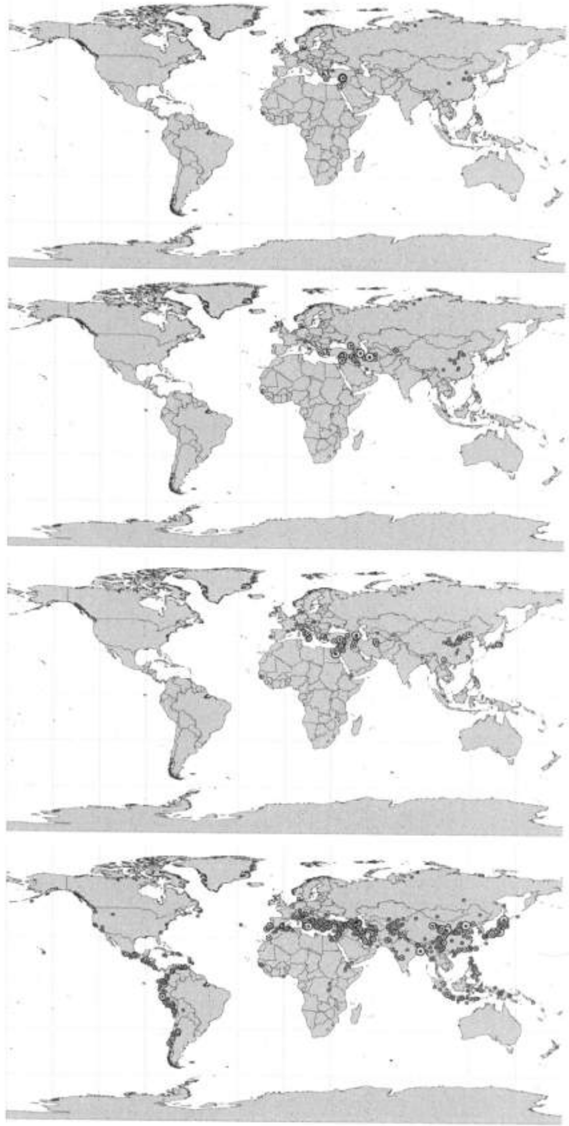


Figure 1. Distribution of deadly earthquakes since 186 BC. Students query the earthquake database to identify the location of deadly earthquakes through historic time. Patterns reflect written historic records until the 20th century when seismic networks became the primary mode of recording events. A) Earthquakes from 186 BC to 499 AD are restricted to China and the Mediterranean region; b) Earthquakes from 500 AD to 999 AD show an increase in number and distribution in Europe and Asia; c) Earthquakes from 1000 AD to 1499 AD; d) Earthquakes from 1500 AD to 2000 AD show great expansion and increase in number due to spread of cultures with written language and the development of the seismometer.

topics frequently addressed in earth systems science courses: plate tectonics and related geologic hazards, tropical cyclones, and water resources (Hall-Wallace et al., 2003). The investigations begin at the global scale and progress to regional and local scale studies. The global scale investigation develops the scientific and social framework for the local scale case study by introducing the fundamental science concepts and driving forces behind a particular Earth process. Regional and local scale studies typically focus on a smaller area and deal with issues and problems of interest to many communities. The content and form of the inquiry progresses from guided to open-ended as students build their knowledge and reasoning skills. Threaded throughout each module are animations and other two and three-dimensional visualizations to enhance student learning.

Our unit on earthquake hazards is a typical investigation. Students query records of the deadly earthquakes occurring since 186 BC to look for spatial and temporal patterns. The temporal patterns show the diffusion of cultures using written language through time, demonstrated by the 'first recorded' occurrence of a deadly earthquake in South America in the 1600's (Figure 1). Students also use queries, statistical tools and graphing skills to compare the frequency of deadly earthquakes to the number of deaths per quake. From this they discover that the number of deadly earthquakes is increasing but the average number of deaths is decreasing (Figure 2). Finally, after examining five major earthquakes that had significant human or economic impact (1976 China, 1994 Northridge, 1995 Kobe, 2000 Turkey, 2000 Taiwan), students assess each country's seismic risk based on gross national product (GNP), population density and seismic hazard. This assessment shows how population density and GNP impact the number of deaths associated with an earthquake. In completing this unit, students have explored a wide variety of subject matter and have discovered the power of a GIS for spatial and temporal data analysis. This typically inspires them to pursue their own questions and creates a desire to learn more about the tool.

Activity development follows the learning cycle model (Karplus and Thier, 1967; Lawson, 1988; Lawson et. al., 1989), which promotes student inquiry and exploration as a process of learning science. The learning cycle divides the learning process into stages that build upon one another. In the first stage, students are engaged in a process that draws out their prior understanding of the topic and promotes natural curiosity and exploration. Students make observations of the data, begin to formulate questions and may draw initial conclusions about the relationships observed. The visual and analytical tools of a GIS are excellent for this type of inquiry. In the second stage, students are introduced more formally to the science concepts of the

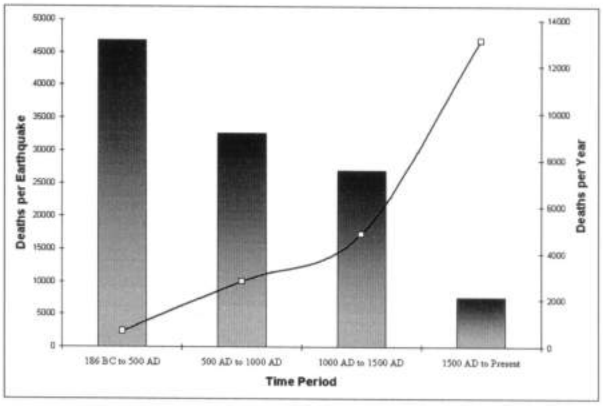


Figure 2. Graphing data is an integral part of the activities. To explore trends in historic earthquakes, students graph the number of earthquakes in a specified interval along with the number of deaths per earthquake in the same interval.

lesson. This is done through reading and discussions but, it could also be done in a lecture format. In the final stage, the students use their knowledge of the data and science concepts to test ideas more thoroughly and explore new processes or questions.

Evaluation of Materials Design - Formative evaluation of the materials included classroom observations, informal student interviews, and pre-/post-tests of content knowledge. Implementation and evaluation of the materials was conducted each semester from spring 1999 through fall 2000. Pilot testing (spring 1999 and fall 1999) focused on evaluation of the design and implementation of the materials. Field-testing (spring 2000 and fall 2000) focused on evaluating student learning. Except where noted, all evaluations were conducted in Geologic Hazards and Society (GHS), a large enrollment introductory geoscience course for non-science majors. Due to a change in university policy, laboratory-based instruction for non-science majors taking introductory level courses has been eliminated. To incorporate more inquiry in the GHS, the instructor assigned our learning modules on plate tectonics, geologic hazards and tropical cyclones as homework. The GIS software and data needed for the assignments were available to the students in an open-access university computer lab. Students had the option of attending one of several help sessions. A five-minute introduction to GIS was provided at the beginning of each session after which the instructor, several teaching assistants, and one of the authors assisted students as needed.

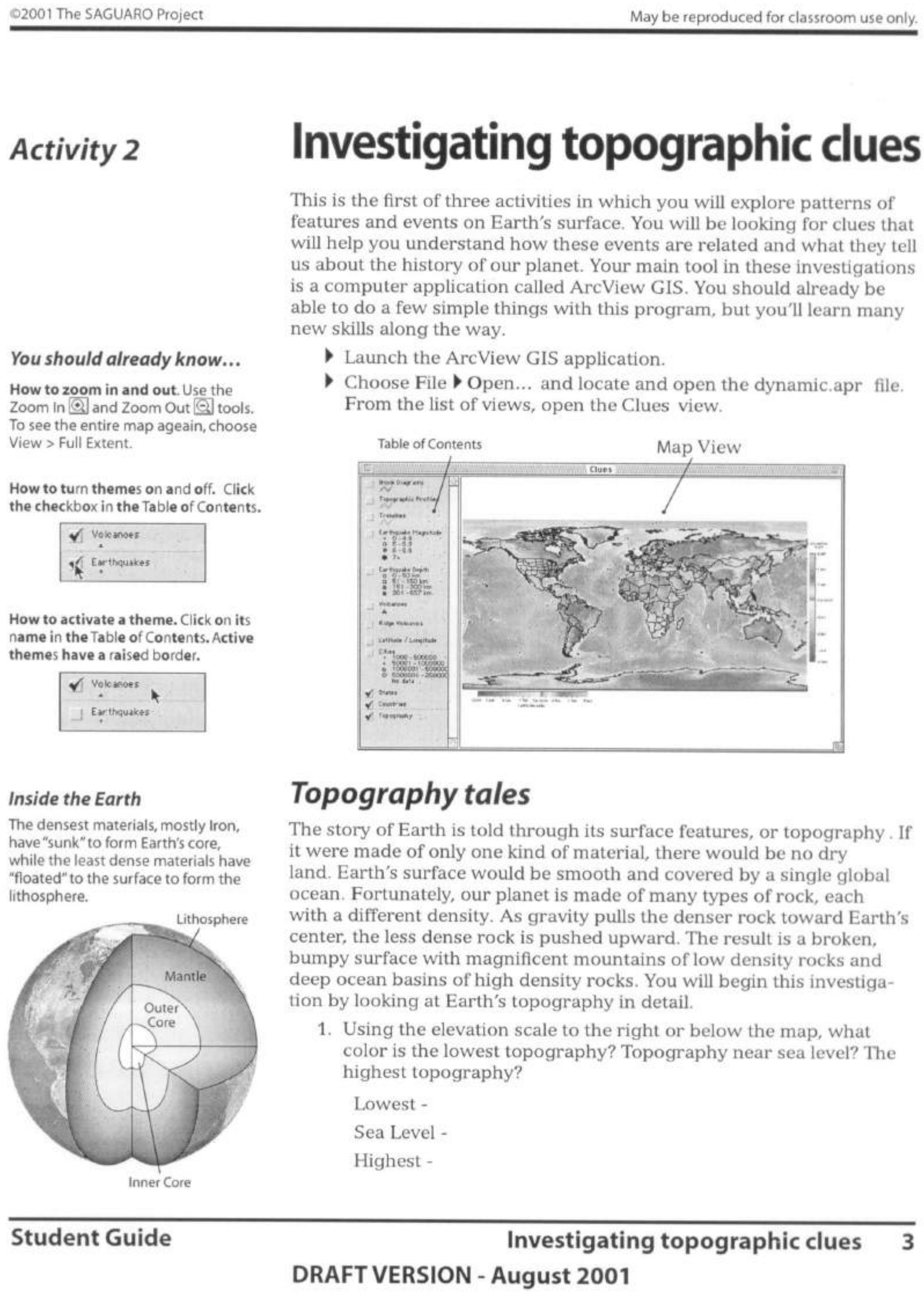
While students worked with the modules in the help sessions, we recorded all of their questions and comments about the activity. Several stages of revision were completed during the pilot-testing phase as a result of student feedback. Initially, students' questions were primarily about procedures (asking how to do different operations) and clarification (asking for help to understand the directions or the questions) but with continued refinement of the materials, students' questions are now primarily about the observations and conclusions they draw.

We encountered three types of problems in our initial materials design. Students had difficulty: (1) working with the GIS tool because of lengthy instructions or cumbersome procedures; (2) identifying basic geographic locations and features; and (3) interpreting topography and other two- or three-dimensional representations.

Initially, our materials required the student to learn more about the tool than was necessary to accomplish the learning goal. This often frustrated students and slowed their progress in discovering relationships in the data. For example, we had students modify the map legend (e.g. display earthquakes with different symbols for different magnitudes) on several occasions rather than providing them an appropriate legend. Our motivation was to teach students a skill that would allow them to explore the data more freely on their own. However, this backfired for two reasons. To see patterns easily on a map (view) that has multiple data sets (often called layers) such as earthquakes, volcanoes and topography, requires careful attention to color choices. Often the legend selected by the student resulted in obscured relationships because different features were displayed with very similar colors. Also, modifying a legend properly is time consuming and distracting from the main point of the lesson. Thus, we changed our design strategy so that the student simply applies a custom legend that we provide, rather than having to create it themselves. We found that this level of interaction with the tool gave curious students adequate skills to create their own legends later.

We also learned that students' basic geography skills vary greatly and it is essential to provide adequate labels for key geographic regions addressed in the lesson. Geographic weaknesses ranged from not knowing what is meant when we refer to "regions" of the world such as "the Mediterranean region" or "southeast Asia" to not being able to locate specific countries.

We found that two- and three-dimensional visualization was particularly difficult for some students. A common misconception is that the deepest part of the ocean is located half way between the two bounding landmasses. Initially, we thought students



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Activity 2

Investigating topographic clues

This is the first of three activities in which you will explore patterns of features and events on Earth's surface. You will be looking for clues that will help you understand how these events are related and what they tell us about the history of our planet. Your main tool in these investigations is a computer application called ArcView GIS. You should already be able to do a few simple things with this program, but you'll learn many new skills along the way.

- Launch the ArcView GIS application.
- Choose File ▸ **Open...** and locate and open the dynamic.apr file. From the list of views, open the Clues view.

You should already know...

How to zoom in and out. Use the Zoom In and Zoom Out tools. To see the entire map ageain, choose View > Full Extent.

How to turn themes on and off. Click the checkbox in the Table of Contents.

How to activate a theme. Click on its name in the Table of Contents. Active themes have a raised border.

Topography tales

The story of Earth is told through its surface features, or topography . If it were made of only one kind of material, there would be no dry land. Earth's surface would be smooth and covered by a single global ocean. Fortunately, our planet is made of many types of rock, each with a different density. As gravity pulls the denser rock toward Earth's center, the less dense rock is pushed upward. The result is a broken, bumpy surface with magnificent mountains of low density rocks and deep ocean basins of high density rocks. You will begin this investigation by looking at Earth's topography in detail.

1. Using the elevation scale to the right or below the map, what color is the lowest topography? Topography near sea level? The highest topography?

   Lowest -

   Sea Level -

   Highest -

Inside the Earth

The densest materials, mostly Iron, have "sunk" to form Earth's core, while the least dense materials have "floated" to the surface to form the lithosphere.

Student Guide **Investigating topographic clues** 3

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Figure 3. Example of activity layout. The left margin is reserved for tips on how to use the GIS tools. More complex operations, such as developing a query statement are introduced with screen shots step by step instructions to guide the students the first time.

gave the wrong answer because they were not reading the map legend carefully. However, student misconceptions remained even after we had them verify their understanding of the legend for the shaded relief map before answering the question. While this reduced the number of incorrect responses, it did not eliminate them. We ultimately experienced success when we had students investigate the topography at the mid-ocean ridges and at the deep subduction zone trenches using both two-dimensional graphs of the topography and three-dimensional block diagrams before identifying the deepest part of the ocean basins.

In another instance, we introduced students to tsunamis with an animation that revealed the interaction between a tsunami wave and natural tides. The animation was especially exciting to a wide variety of scientists and the authors. However, students who were just learning about tsunamis had difficulty interpreting the animation. They could not locate the trigger event geographically even though several markers were available, and they could not figure out what was happening to sea level heights from the animation or associated graphs. In the end, we simplified the interface and incorporated questions which guided the students through the visual interpretation. With this assistance, students' really got excited and came to understand the phenomenon much better.

While the majority of our evaluation studies were done with students in Geologic Hazards and Society (GHS), we also tested the materials with advanced undergraduates majoring in geosciences, high school earth science teachers and university faculty. We observed only one significant difference in the learning styles of these groups from the students in the introductory level course. Specifically, we found that as students' knowledge of the topic investigated increased, they observed more complex relationships and drifted off task to investigate their own questions. This resulted in much greater enthusiasm for data exploration and often increased interest in learning more GIS skills. These results combined with our observations in GHS are very encouraging signs that our materials can be used broadly in the geosciences, even in classes where the faculty and students have little prior experience with a GIS.

Our final design incorporates GIS instructions as needed and has a much stronger focus on data analysis and interpretation (Figure 3). GIS tips and tricks to facilitate exploration are provided in the left margin to improve the flow of the activity. We use screen shots of maps and dialog boxes to guide the students as they progress through difficult operations the first time. Each map view also contains easily accessible names of countries, continents and oceans. To address problems with spatial visualization, we have constructed 3-D block diagrams that correspond with the 2-D topographic profiles. In future research, we intend to investigate whether this proves an effective method for addressing students' misconceptions about topography.

One measure of a module's quality is the students' ability to accurately complete it in a reasonable amount of time, without a lot of intervention by the instructor. In our field testing, students needed progressively less help with the GIS activities each time they were assigned. Over 90% of the students in GHS attended at least part of the first homework help session. Attendance dropped off to around 55% for the second homework help session and fell to less than 30% for the third homework help session. However, greater than 94% of all students turned in all of the homework assignments and the average score on each was 84-86%. Thus, we can conclude that the students achieved a moderate to high level of success in learning with GIS. Student attitudes in interviews and course evaluations indicated that they generally enjoyed the exercises especially, the dynamic nature of the maps and exploring real data.

EVALUATION OF STUDENT LEARNING

During summative evaluation, (spring 2000-fall 2000), we continued our classroom observations as a primary tool for enhancement of the materials design. Our studies also addressed the following questions:

1) Can students' content knowledge be improved through engagement in GIS-based activities?

2) Is there a relationship between spatial thinking and GIS – based learning?

In spring 2000, we developed a twenty-item multiple choice test on plate tectonics and geologic hazards that included concepts taught in both the lecture and the activities as well as some concepts taught only in the activities. Students took the pretest on the day before the first homework was assigned; they took the posttest near the end of the semester, after all of the activities were completed. In all of our studies, the pretest and posttest were identical and no feedback was given to the students on their performance. Students had approximately two weeks to complete each activity and the average student spent 1.5-2 hours on each activity. Extra credit was given for completing both the pretest and the posttest regardless of demonstrated knowledge. Item analysis was conducted on each test question to evaluate the clarity, accuracy, reliability, and difficulty level. Based on the results, we revised many of our questions and on 25% of the questions, we incorporated images that showed particular relationships emphasized in the activities.

In fall 2000, we repeated the process using the revised knowledge test. The pretest of knowledge covering plate tectonics and geologic hazards was

Question	1	2	3	4	5	6	7	8	9	10
Posttest	98.89	83.33	52.22	37.78	68.89	46.56	92.22	82.22	40.00	73.33
Pretest	90.00	56.67	18.89	38.89	60.00	47.78	65.56	48.89	64.44	5.56
Post-Pre	8.89	26.67	33.33	-1.11	8.89	-2.22	26.67	33.33	-24.44	67.78
Question	11	12	13	14	15	16	17	18	19	20
Posttest	51.11	61.11	52.22	64.44	36.67	91.11	61.11	74.44	76.67	56.67
Pretest	52.22	27.78	48.89	43..33	27.78	97.78	26.67	56.67	52.22	25.56
Post-Pre	-1.11	33.33	3.33	21.11	8.89	-6.67	34.44	17.78	24.44	31.11

Table 1: Difficulty levels for pretest and posttest scores and their percent differences

completed on the first day of the semester. The posttest was taken the day after the two units were completed, approximately 2.5 months after the pretest. Again, students were awarded several points of extra credit for completing the pretest and posttest regardless of their demonstrated knowledge. Figure 4 shows the frequency distribution of the pretest and posttest. Mean scores improved 17% and the T-test comparisons of pretest and posttest scores show that the improvement is statistically significant ($p<.001$). The time period between pretest and posttest makes it highly unlikely that maturation influenced our test results. Also, since the students were not assigned grades nor given any feedback on their pretest or posttest performance, the test/retest effects probably did not play a role either (Kubiszyn and Borich, 2000).

Item analysis and critical review of the posttest revealed that problems still remained with some test questions. The difficulty level of a test item is defined as the percentage of students selecting the correct response for that item. Difficulty levels for the posttest questions are given in Table 1. In addition, percent differences between the difficulty levels of the pretest and posttest were calculated. The negative post-pre differences indicate questions that confused students. For example, questions 3 and 9 are both somewhat difficult. On the posttest, 52% of the students selected the correct response for question 3 while 40% selected the correct response for question 9. However, question 3 is a useful question since it has a 33% positive difference from pretest to posttest. The negative difference for question 9 means that 24% of the students who selected the correct response in the pretest, chose the incorrect response during the posttest.

Based on the item analyses, six questions need to be revised or removed from the test before its next use. Two of the questions depended on images that did not reproduce clearly (#11, #20), one had multiple correct answers (#6), two had very complex stems and/or distractors (#9, #13) and one addressed material that was not emphasized in the activity or in class (#4). Question 6 asks about the primary driving force of plate tectonics. The activities stress the role of heat while the lecture stress the role of gravity, while both are valid answers. We also identified two questions that were very easy, question 1 which deals with the concept that earthquakes and volcanoes tend to be concentrated on plate boundaries, and question 16 which compares the energy release of volcanic eruptions with different Volcanic Explosivity Index.

Student performance on the posttest was also correlated with performance on a course test, Exam 2, which covered the content in the plate tectonics and geologic hazards GIS lessons as well as other topics. The correlation between the posttest and Exam 2 was .219 ($p<.05$). Two questions (#5 and #18) from Exam 2 were included on the posttest and these scores were positively correlated ($p<.05$). Students performed 9% and 14% better on question 5 and 18 respectively, when accuracy counted as on Exam 2, than when it did not count in awarding points as on the pre- and posttest.

We hypothesized that a relationship might exist between spatial thinking and GIS usage, because a geographic information system is a tool for spatial analysis. Spatial thinking can be partitioned into separate spatial abilities or aptitudes for various manipulations and perceptions of images (Ekstrom, et. al, 1976). We measured spatial thinking using two standardized tests from the *Kit of Factor Referenced Cognitive Tests* (Ekstrom, et. al., 1976). The Cubes Comparison Test measures spatial orientation, which is the ability to perceive a spatial configuration from an alternate perspective. During the test, subjects are presented with paired images of cubes (Figure 5a). They

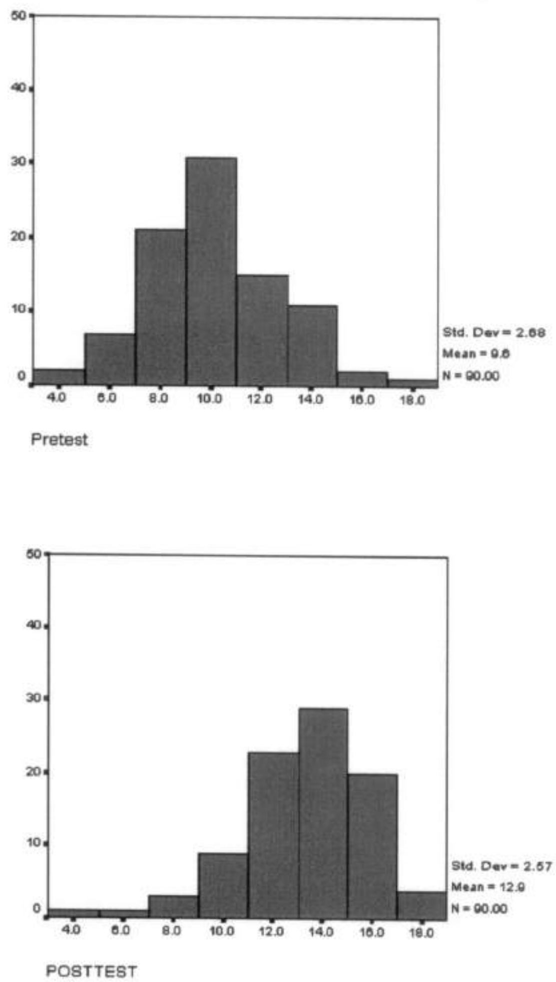

Figure 4: Frequency distribution of the (top) pretest and (bottom) posttest scores. The mean of the pretest is 9.6 and the mean of the posttest is 12.9.

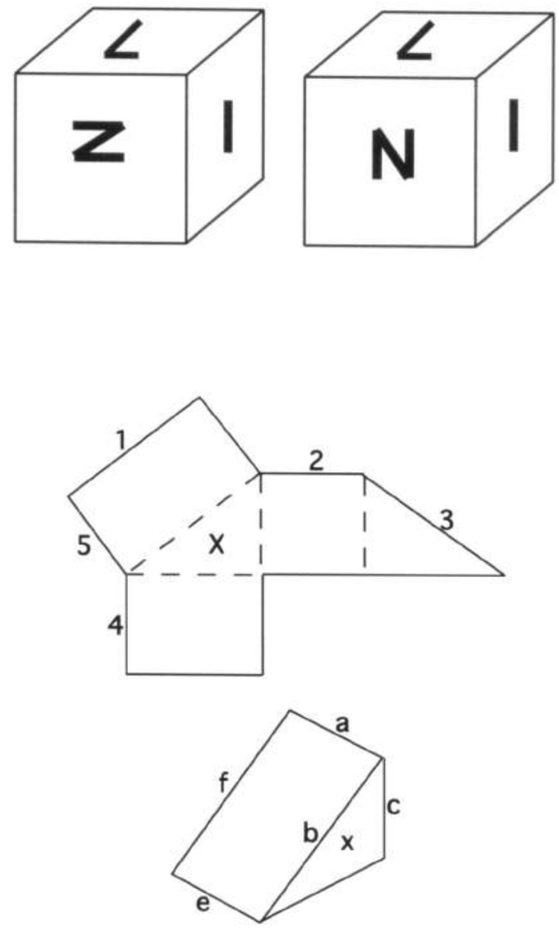

Figure 5. (Top) Sample item from the Cubes Comparison Test from the *Kit of Factor-Referenced Cognitive Tests*. (Bottom) Sample item from the Surface Development Test from the *Kit of Factor-Referenced Cognitive Tests*.

must determine if the cubes are the same or different. Analysis requires a mental rotation of the cube to make the judgment. The Surface Development Test measures spatial visualization, which is the ability to transform a mental image. In this test, subjects are presented with pairs of objects. The object on the left is an unfolded representation of the object on the right (Figure 5b). Subjects must identify corresponding edges of the folded and unfolded object. This analysis requires the subject to mentally fold the unfolded object for comparison. Scores from the Cubes Comparison and Surface Development tests were aggregated to produce an overall spatial score.

Students were given the spatial tests after they had completed both the plate tectonics and geologic hazards units. No pretest was given due to logistical problems. Thus, we can determine correlations between spatial skills and performance on the modules or in the class, but we cannot determine whether spatial skills were improved by using the modules. Figure 6 shows the frequency distribution of this spatial measure. We found correlations with the spatial score for both the posttest and Exam 2. The correlation with the posttest which contained visual aids from the GIS investigations was .310 ($p<.01$) and the correlation with Exam 2 was .211 ($p<.05$) indicating that a relationship exists between spatial ability and these measures. The magnitude of

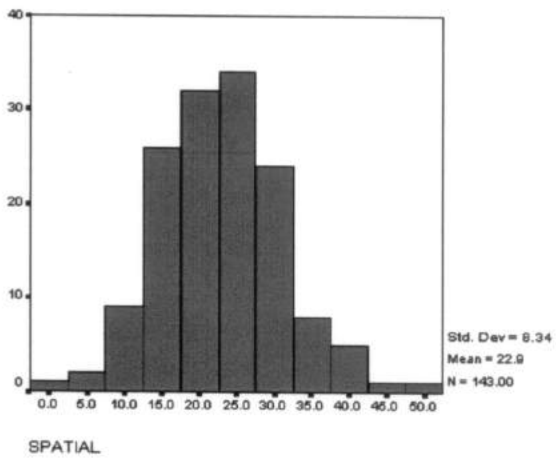

Figure 6: Frequency distribution of spatial thinking skills. Spatial skills are normally distributed (Mean=22.9; SD=8.34).

these correlations is consistent with those found by others conducting similar research. In a general chemistry class, correlations between spatial ability and class exams were .20, .17, and .25 ($p<.001$) (Carter, Larussa, and Bodner, 1987). First year geology students showed significant correlations with their overall geology class score and two pre and post spatial tests. The correlations were .35, ($p<.05$), .41, ($p< .02$), .51, ($p<.003$) and .52 ($p<.002$). (Orion, et. al, 1997). All of these correlations are moderate and could be influenced by other factors related to the course instruction or curriculum materials. When measuring learning by human subjects in an authentic environment, the number of factors influencing learning is often large and could include motivation and attitude, technical skill level, and time among others. In other studies, spatial visualization has been shown to correlate significantly with GPA (.3477, $p<.001$) and short term comprehension (.2622, $p<.05$) (Hays, 1996.)

CONCLUSIONS

Through extensive formative and summative evaluation we found that:

1) Students working with GIS-based activities can experience difficulties related to the technical aspects of the software. These difficulties can be overcome by making some features initially transparent to the user (e.g. loading a preset legend for mapping a theme as opposed to creating a new legend.)
2) A lack of basic geography skills can interfere with successful progression in a GIS-based activity.
3) Some conceptual difficulties inherent in visualization can be helped by increased scaffolding in the materials (e.g. providing guiding questions that help the student interrogate visual data more effectively.)
4) Some misconceptions persist even after direct instruction (e.g. interpreting two dimensional maps and graphs, or three dimensional block diagrams of three dimensional seafloor topography.)
5) There is a positive correlation between spatial thinking and GIS – based learning.

In Fall 2001, we will investigate the nature of the relationship between spatial thinking and GIS usage in more detail using pretests and posttests of visual skills and using control groups in other introductory geoscience courses. Research has shown that the ability to visualize and think in two- and three-dimensions is an asset to successfully interpreting many science concepts, especially in earth science (Chadwick, 1978; Kali and Orion, 1996). Spatial ability in all students can be significantly improved by manipulating imagery (Kali, et.al., 1997), as is done with a GIS.

Demonstrating how students create mental models, learn new concepts, and develop critical thinking skills when they use a GIS to manipulate data remains an area for further research (Tinker,1994). Gobert and Clement (1999) found that manipulating visual images to reinforce understanding of reading material is a more effective learning strategy than summarizing the material in writing exercises. They found that students who manipulate visual information build mental models to understand the material more deeply. Clearly some misconceptions remain when using GIS as a visualization tool and more work is needed to identify effective methods for addressing these misconceptions. Similarly, research on understanding how a GIS influences geography skills is also lacking.

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2. Along the western edge of South America, oceanic crust of the Nazca Plate collides with continental crust of the South American plate. Whate geologic process would you expect to find at this convergent bound
a. shallow, small magnitude earthquakes and volcanic activity only
b. subduction of oceanic crust into a trench, earthquakes, and volcanic activity
c. the formation of new crust at a ridge, earthquakes, and volcanic activity
d. large, deep earthquakes and volcanic activity only

3. Which of the following features are you most likely to find at a divergent plate boundary?
a. earthquakes occurring below 200 km depth
b. a deep trench
c. a thick crust and lithosphere
d. volcanic activity

6. The primary driving force of plate tectonics is
a. heat from the sun warming the surface of Earth
b. gravity
c. centrifugal force from the spinning Earth
d. heat from decay of radioactive minerals and from the formation of Earth

9. Which of the following can be concluded from examining historical records of earthquakes?
a The deadliness of an earthquatek comes from its magniture so that the stronger the quake, the more people it kills.
b. There has been little change in the geographic distribution of earthquakes over time.
c. The number of deaths per earthquake is less today than in the past because more small earthquakes that don't cause deaths are recorded today.
d. All of the above.

10. Which of the following is not a factor contributing to the damage potential of an earthquake?
a. type of soil
b. lahars
c. the population density
d. building design

12. Prior to 1000AD there are no records of deadly earthquakes in Africa. What is the likely explanation for this?
a. People did not record the earthquakes that occurred in Africa prior to 1000 AD.
b. No earthquakes took place in Africa prior to 1000 AD.
c. People were not living in Africa prior to 1000 AD.
d. Only small magnitude earthquakes, (inflicting no damage), occurred in Africa prior to 1000AD.

Table 2. Sample of Pre/Posttest Questions.

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“Repeated historical events, whether over nanoseconds or millions of years, that show a haunting similarity are the patterns—the phenomena, the real data—of all science.”

The Pattern of Evolution
Niles Eldredge