

Can Earthquakes Be Predicted?

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ABSTRACT

Modeling fault behavior with a simple slider-block apparatus can provide students with valuable insight into the difficulty of earthquake prediction and the complex behavior of Earth systems. I have developed an open-ended activity in which students are challenged to design an experiment that models fault behavior and to determine which variables in the earth might affect the number or magnitude of earthquakes that occur. I have used the activity with secondary-school science teachers and their students, but it is also appropriate for undergraduate geoscience majors. Students are provided with materials to construct a fault model, but few instructions are given. Their investigations are guided by curiosity and a few key questions that I suggest they investigate in their experiment. Working in groups, the students design the apparatus, develop an experimental procedure, determine what to measure, and analyze their data. In the process, they learn how science is done and increase their level of scientific literacy (NRC, 1996).

The activity provides many opportunities for graphing and basic statistical analysis. In addition, students are introduced to the complexity of scientific problems and to the value and limitations of models. Data collected from a simple mechanical model correspond well with the observed behavior of real faults and can be interpreted in terms of basic models for earthquake prediction.

Keywords: Apparatus; earth science – teaching and curriculum; earth science – teacher education; education – geoscience; education – undergraduate; geophysics – seismology; mathematical geology; pseudoscience.

Introduction

At 6:00 am on January 17, 1994, disaster struck southern California in the form of an earthquake that originated deep beneath the Santa Susana Mountains. Slippage occurred on a fault and the resulting earthquake damaged buildings and highways, ruptured gas lines, and created chaos in the largest metropolitan area in the western US. Every news organization had special reporters on the scene. Pictures of damage and fires as well as interviews with distraught victims formed a steady parade across television screens. Even the most jaded students were fascinated with the awesome power of the earth.

Earthquakes constitute a wonderful tool for motivating students to investigate and understand the behavior of the earth. "What causes earthquakes?", "What determines their magnitude?", and "Can we

predict when the next earthquake will occur?" are questions frequently asked. The mystery of when and where the next "Big One" will occur is a pressing and interesting question for the public. Unfortunately, most of the recent short-term earthquake predictions were based on lost-cat reports in newspapers or planetary tidal forces and weather (for example, Iben Browning's prediction for a big New Madrid quake; see Coleman and Soellner, 1995; Picard, 1995), rather than on sound science. The fact that these predictions can attract intense media attention reveals much about the scientific literacy of the public and the need for our students to know and use scientific methods and reasoning.

One of the greatest challenges to seismologists is to be able to predict earthquakes with enough precision to minimize loss of life and economic hardship. In an ideal world, we would know where all active faults lie, when they will rupture, and the magnitude of the next earthquake expected. Earthquake prediction is successful when it can routinely provide accurate information on time, location, and size of future earthquakes. Long-term predictions affect urban planning decisions. Intermediate predictions promote emergency preparedness and heighten awareness. Successful short-term predictions lead to evacuation orders that can save lives. Seismologists can determine probabilities of rupture for particular faults or fault systems, but these probabilities are only as good as our knowledge of past earthquakes, long-term rates of fault movement, and local fault interactions. Well documented historical accounts, geologic and geodetic studies, and modern earthquake recordings are used to develop some understanding of a particular fault's behavior. One of the problems encountered is that we rarely have more than one or two earthquake cycles in the historical record.

In the United States, improved understanding of fault behavior, responsible urban planning, and advances in building construction have greatly reduced the threat to life from earthquakes, yet more could be done to reduce our exposure to their hazards. Our growing understanding of the mechanics of earthquakes and the behavior of the earth will continue to bring us closer to safety. To help students understand the behavior of faults and the challenges of earthquake prediction, I developed an activity which allows students to investigate the mechanics of faults, model the earthquake cycle, and observe that natural hazards are more statistical than deterministic in their occurrence. In the course of doing the exercise, the students create models of faults based on the mechanics of earthquake slip to investigate and understand some of the variables affecting fault-rupture patterns and frequency.

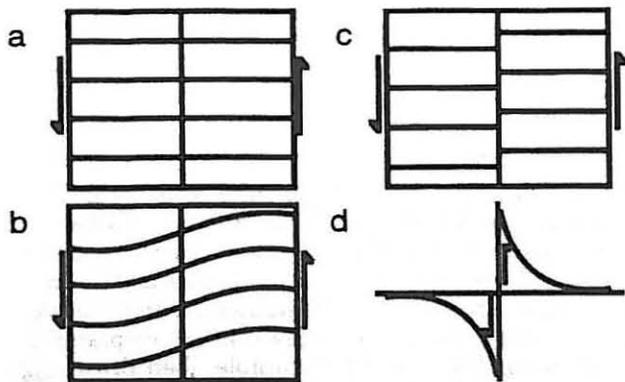


Figure 1. Ground displacement and strain evolution near a fault based on Reid's Elastic Rebound Theory. a) Initial state. b) Regional stresses applied to the crust cause strain deformation far from the fault. c) Stresses exceed strength of fault and rupture occurs returning the crust on either side of the fault to its pre-deformation shape. d) Displacement is largest near the fault and decays with distance from the fault.

The activity challenges students to design their own experiments, explore the interdependency of variables, and analyze data in an open-ended problem. Inquiry-based activities promote scientific literacy by teaching students to "ask, find, or determine answers to questions derived from curiosity about everyday experiences" (NRC, 1996, p. 22). I use the activity in an Earth Hazards course for secondary-school earth-science and physics teachers and have also worked with secondary-school teachers on using the activity in their classrooms. The activity is also appropriate for an undergraduate-level geology or geophysics class. In this paper I will describe the science background I cover in preparing students for the activity; then I will discuss the experiment itself.

The Cause of Earthquakes

In 1910, Harry Reid proposed the "elastic rebound theory" of earthquake origins based on field observations of the effects of the 1906 San Francisco earthquake (Reid, 1910). Prior to 1906, limited field observations had left scientists debating whether earthquake shaking caused ground surface breakage or ground surface breakage caused earthquake shaking. Reid carefully studied ground breakage near the San Andreas fault and geodetic data away from the fault after the 1906 earthquake and formulated the theory that crustal stresses resulting from large-scale shearing motions cause elastic strain to accumulate in the vicinity of faults. When the strain accumulation reaches a critical threshold imposed by the material properties of the rock and the fault surface, abrupt frictional sliding occurs, releasing some of the elastic strain energy (Figure 1). Much of the strain energy released is used in heating and fracturing of rock, but a portion is converted to seismic waves. After an earthquake, elastic strain begins to accumulate again to accommodate regional forces. This process leads to many cycles of strain accumulation and release over the life of a fault.

The dynamics of fault rupture are complex, but general fault behavior can be explained with a simple model in which slip promotes fault weakening. Fault slip occurs in three stages: (1) initiation of sliding on a small portion of the fault, (2) growth of the slip surface, and (3) termination of slip and fault healing (Scholz, 1990). Earthquakes occur on pre-existing faults operating in a "stick-slip" mode. Earthquakes are "slip" episodes; they are followed by periods of no slip ("stick"), during which elastic strain increases away from the fault. Although some growth of the fault may occur with each earthquake, we can generally assume that for large earthquakes ($M > 6$) the faulting process primarily involves repeated breaking of the same fault segment rather than creation of a new fault surface (Walsh and Watterson, 1988). Measurements of strain accumulation for several well documented large earthquakes indicate that the crust cannot accumulate elastic strain much larger than 10^{-5} without failure (Kanamori, 1977).

The crust of the earth is not homogeneous and several variables affect the behavior of faults. Brace and Byerlee (1967) and Byerlee (1967) showed that friction on existing fault surfaces is independent of rock type but that factors such as gouge, asperities and fluid pressure can significantly affect the level of stress buildup prior to an earthquake. Asperities, or protrusions on the fault, act like welded contacts between the sides of the fault. Younger faults have rougher surfaces with more asperities. As a fault repeatedly ruptures, the asperities can be worn down, creating fault gouge and smoothing the fault. The gouge material often decomposes to a fine clay and forms a thin layer which "greases" the fault for easier sliding. Fluids can also facilitate slip by reducing the normal stress on the fault.

Earthquakes have been triggered by pumping water into the subsurface in areas of nuclear waste disposal, mining, and oil production (Evans, 1966). Earthquakes are also triggered when man-made structures, such as water reservoirs or rock quarries, increase or decrease the overburden stress on a region (Simpson and others, 1988). The change in load may increase the stress on an underlying fault and cause rupture. Marone and Scholz (1988) showed that small earthquakes generally occur at shallow depths where the rocks are weaker and the lithostatic stress is lower. At shallow depths it is difficult to build up high stresses; therefore, the earthquakes that do occur have smaller slip displacements. At greater depths in the crust, larger earthquakes are observed. The higher lithostatic stress at these depths requires higher shear stresses to break fault segments, and when higher shear stress is reached, a larger earthquake can be generated (Wallace and Kemeny, 1992; Wallace and Wallace, 1993).

Theoretical Models for Earthquake Prediction

Reid's elastic rebound theory combined with our knowledge of plate tectonics suggests that we might someday be able to predict earthquakes. The observation that some faults fail with quasi-periodic behavior is fundamental for earthquake prediction and

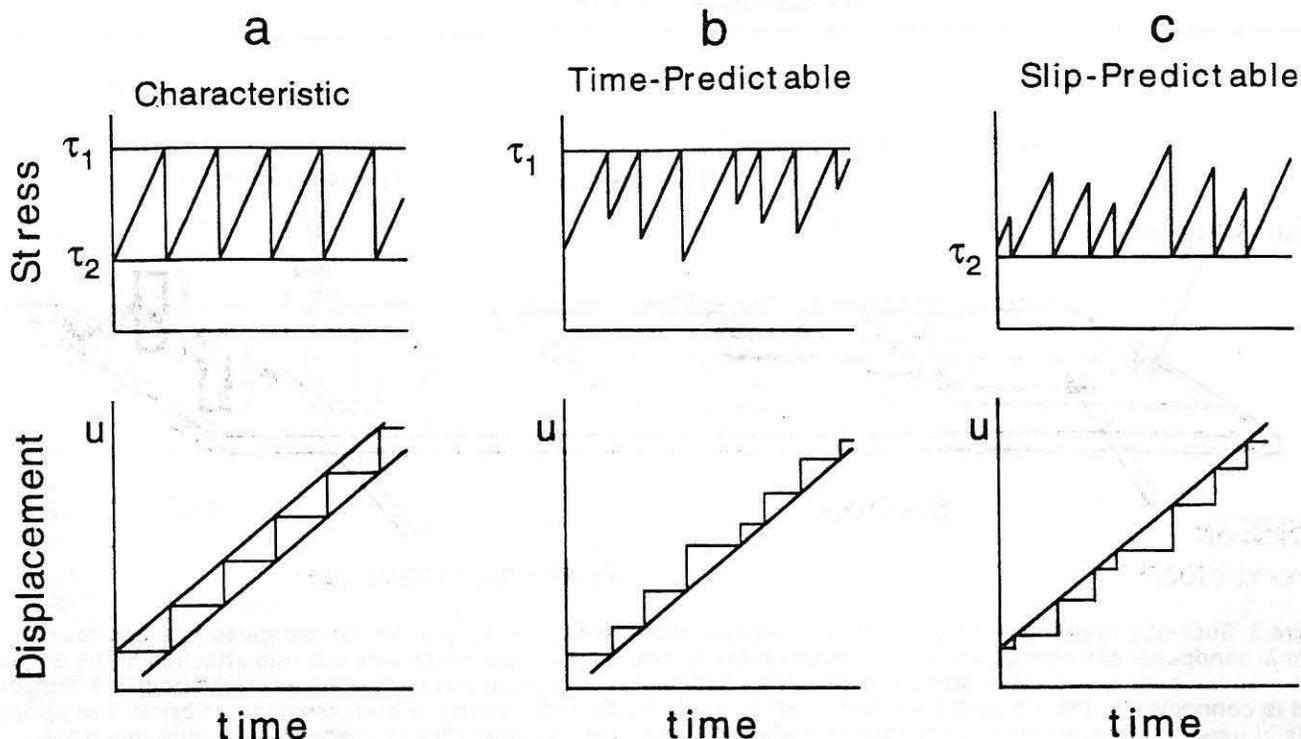


Figure 2. Models for earthquake prediction based on changes in fault stress for a constant loading rate. The upper box shows the stress history on the fault for the different predictive models. τ_1 is the shear stress at initiation of slip and reflects fault strength. τ_2 is the shear stress at which slip ceases and reflects fault friction. In the lower box, u is the slip or displacement on the fault that corresponds with the stress history. (a) Characteristic model of stick-slip faulting. Each earthquake is identical in stress history, recurrence interval and slip. (b) Time-predictable model. This model assumes the fault strength is constant and that slip initiates when the stress on the fault reaches τ_1 . If slip is proportional to stress drop, and plate motions are steady, we can predict the time of the next earthquake based on the amount of slip during the previous earthquake. (c) Slip-predictable model. This model assumes the stress on the fault is always reduced to τ_2 by an earthquake. Knowing the time of the last earthquake and assuming steady plate motion, we can predict the size of an earthquake expected at a particular time. (Modified from Shimazaki and Nakata, 1980).

hazard mitigation. Theoretically, if plate motions are steady, strain accumulation will increase steadily and slip will occur at regular time intervals; the amount of time between slip episodes is called the recurrence interval. There are three basic models for earthquake prediction: (1) the characteristic earthquake, (2) the time-predictable earthquake, and (3) the slip-predictable earthquake (Lay and Wallace, 1995). Each model is based on the history of stress accumulation and relaxation during an earthquake cycle (Figure 2). In the characteristic earthquake model (Figure 2a), shear stress builds on a fault to the level of the fault strength, τ_1 . When the shear stress reaches τ_1 , the fault ruptures and the shear stress is reduced to a level equal to the friction on the fault, τ_2 . The amount of slip on the fault is the same for each earthquake and the recurrence interval is constant over time. Unfortunately, characteristic earthquake behavior is not commonly observed in nature because the model assumes that plate motions are steady and fault friction and fault strength are constant. However, a section of the San Andreas fault near Parkfield, California may be one example of a fault that follows the characteristic earthquake model. This fault segment has had at least five $M > 6$ earthquakes with a mean recurrence interval of

22 years (Bakun and Lindh, 1985) since 1857. There is some variability in the recurrence interval, but studying this characteristic behavior may be the first step towards understanding fault behavior.

The time-predictable model (Figure 2b) assumes that fault strength is constant and that the fault will always rupture when the shear stress reaches the level of τ_1 . However, slip on the fault can vary with each rupture. This model assumes that a large slip on the fault will reduce the level of shear stress more than a small slip. Thus, after a large slip it will take longer for the shear stress to build to the level of τ_1 , assuming steady plate motions. Knowing the amount of slip during the past earthquake, the time-predictable model allows prediction of the time of the next earthquake. The Calaveras fault near San Francisco Bay, California appears to have time-predictable behavior over at least the short time window of observation from 1962-1977 (Bufe and others, 1977). The cumulative amount of slip is linear over time even though the amount of slip during any one earthquake varies.

In the slip-predictable model (Figure 2c), the fault does not rupture at the same shear stress, τ_1 , each time. Rather, an earthquake always reduces the shear stress on the fault to τ_2 , the level of the fault friction.

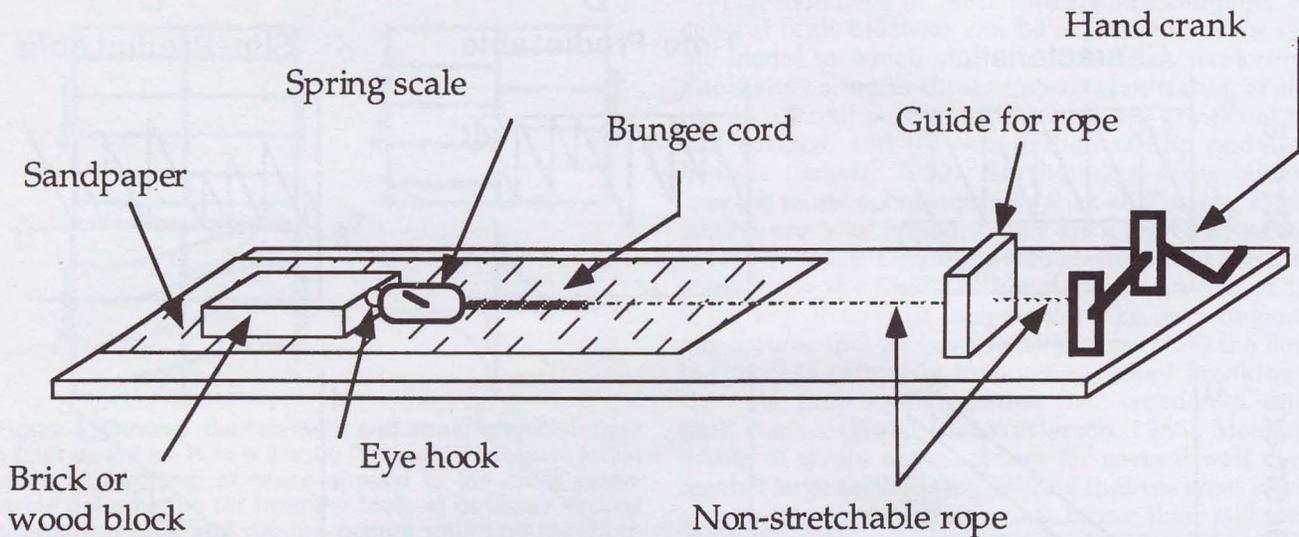


Figure 3. Stick-slip apparatus: We use a 6' x 8" wooden board with a long strip of sandpaper glued to its surface. Additional sandpaper of varying grit can be placed on the brick. A simple spool-crank mechanism attached at the end of the board is used to wind an inelastic climbing rope and induce a force parallel to the surface of the board. A bungee cord is connected to the inelastic rope and a spring scale is placed between the bungee cord and brick. The spring scale is used to measure the force before and after the brick slips. A meter stick is needed to measure slip distance. Bricks of different masses are attached to the end of the spring scale with eye-hooks and dragged across the sandpaper under various conditions.

This model cannot be used to predict when rupture will occur, but it can be used to predict the magnitude of the earthquake that would occur at any given time. After an earthquake, stress on the fault will increase at a constant rate from τ_2 . The potential fault slip at any time is proportional to the shear stress on the fault. Thus, if the time of the last rupture is known, the shear stress on the fault and the potential displacement can be determined at any particular time.

The Mechanical Model

Students can create a mechanical model of stick-slip fault behavior in the lab using a slider-block configuration like that shown in Figure 3. A brick or heavy wood block represents one side of a horizontal fault while the other side is a flat, six-foot board. One or both sides of the "fault" can be covered with sandpaper to create surfaces with higher friction. Under a microscope, the contact between the brick and sandpaper would look very irregular. The grains of sandpaper grit are the contact points that act as asperities on the fault. Attached to the brick is a short bungee cord, which is itself attached to non-stretching rope coiled on a hand crank or winch. A spring scale can be added to the model to measure the force at which the "fault" initiates rupture (f_i) and the force when it comes to rest (f_r). We use a metric ruler to measure the amount of slip during each rupture and use the slip as a proxy for magnitude, assuming that larger slip corresponds to larger magnitude.

The change in force from the initiation of slip until the block is at rest ($f_r - f_i$) can be used to calculate the change in stress, or stress drop, associated with the fault-slip event. Stress is calculated as force/unit

area. In our mechanical model, the fault area (A) is equal to the area of the brick in contact with the board. Thus, shear stress on the fault at rupture (τ_1) and at rest (τ_2) are equal to f_i / A and f_r / A , respectively. The difference between the shear stress just before the slip event (τ_1) and just after the slipping has ceased (τ_2) is known as the stress drop. Because the area of the fault does not change in our mechanical model, the values of f_i and f_r directly correlate with τ_1 and τ_2 as used in the theoretical models for earthquake prediction (Figure 2). In our analysis of the data, we use this correlation to compare the models for earthquake prediction to the data from our mechanical model.

The earthquake cycle is modeled by turning the winch, stretching the bungee cord, and thereby placing a horizontal shear force on the fault. The bungee cord stores elastic strain energy in the system much as crustal rocks do to accommodate plate motion. Static friction proportional to the normal stress on the fault works against the horizontal force to hold the brick in place. In general, no slip occurs on the fault until a critical value of shear stress, τ_1 , is reached; then, sudden slip occurs followed by a drop in shear stress to τ_2 . After each slip event, a period of no slip ("stick") occurs during which the stress builds again to the critical value and the sudden slip is repeated.

The Experiment

In the following section, I will first describe the use of the experiment for teacher education and then discuss its modification for use with secondary-school students. Prior to conducting this experiment, in my Earth Hazards class for teachers, we discuss the elastic, brittle, and plastic behavior of rocks and the mechanics

of fault rupture, friction, and plate motion. Additionally, we review the models for earthquake prediction and examine recurrence patterns on well documented faults. To introduce the experiment, the teachers are presented with a table full of materials they might need and are given the following instructions:

Given the materials on the front table, develop a model of fault behavior and determine what variables in the earth might affect the number or magnitude of earthquakes that occur. You might begin by thinking about how rocks behave, and about the driving force of earthquakes. In testing your model, you will need to investigate multiple variables in the earth-fault system and how you might model them. Keep detailed records of your experimental procedure, observations, and data. Develop physical or mathematical relationships that explain your observations, where possible. Show charts, graphs, and the analysis of your data.

Questions and ideas you might want to investigate in your group:

- List the variables in the earth and in your model which might affect the magnitude and number of earthquakes generated and try to rank them by their importance based on your current knowledge.
- Devise an experimental strategy to determine which of the variables on your list has the greatest effect, and which the least, on the magnitude and number of earthquakes.
- Describe your experimental procedure and data collection plan.
- Can you determine any relationships among fault inclination, friction, and slip? Do the values of the maximum, median, and mode slip vary with different variables?
- What is the relationship between f_r , $(f_r - f_i)$ and the slip behavior?
- How do your data compare to the characteristic, time-predictable, and slip-predictable models for earthquake prediction?
- What additional equipment might be helpful in modeling earthquakes in this experiment?
- How does your model of a fault compare with real faults in the earth?
- Write a report describing your results and address the questions above as best you can with the data you gather in class.

Few K-12 teachers have had much experience in designing experiments or exploring problems driven by curiosity. In this activity, their curiosity is stimulated by the knowledge that this is a real, unsolved research problem. The purpose of the activity is for them to design their own experiment and experience science as inquiry. Once assured that this is not a test, the teachers set to work with real enthusiasm. Groups are assigned so that each has a mixture of earth-science and physics teachers in hope that the physics teachers will recognize the classic friction experiment involved and that the earth-science teachers will lead the group in applying the laws of physics to the earth. The experiment is very open-ended, with

multiple variables to be tested, including the inclination of the fault surface, the mass of the slider-block, the coefficient of friction, and the elastic behavior of the bungee cord.

Initially, many groups do not understand the role of the bungee cord in the model or which observations to measure and record. I encourage the teachers to discuss the experiment among the groups and to exchange ideas. Most groups recognize the gravitational force across the fault as an important component in their experiment, with the force being affected by both the mass of the brick and the inclination of the board. Typically, after one hour, most groups have correctly assembled the instrumentation, have a good idea of the variables they need to test, and are gathering data. After each group has investigated at least one variable, I initiate a discussion of what they have learned and accomplished so far using the questioning strategy of Penick and others (1996). The questions help the teachers identify differences in procedures among the groups and make adjustments to improve their experimental methods.

With just a few results, the teachers begin to recognize patterns in the data and the different effects of the variables. Some of the teams divide the task of testing variables between team members and are able to complete most of the data gathering by the end of the lab period. Each teacher is responsible for evaluating his/her own group's data, predicting relationships, and drawing conclusions. The three-hour lab session in our short summer workshop is not long enough for each group to completely investigate the full problem. Rather than working in parallel, each group could take responsibility for investigating a particular variable and the data could be shared among the groups.

Modifying the Experiment for Secondary-School Classrooms

As a follow-up assignment, the teachers were required to modify the lab for use in their classrooms. Curiously, most teachers designed the activity to include very specific instructions on how to build the instrumentation and what to measure and record, thereby removing the joy of pure experimentation from the exercise. Discussions with the teachers revealed two reasons for this change: (1) the teacher did not think the students could do the activity without more structure, and/or (2) the more structured activity was similar to what the teachers were already doing in friction experiments and thus was more easily introduced into the curriculum. To determine if this activity could really work in a secondary-school classroom, I needed to learn more about the teachers, their students, and the constraints on teaching in K-12 classrooms. I have worked with two teachers to do this experiment in their classroom. In one classroom, junior- and senior-level physics students investigated fault behavior using a similar but more structured activity that was designed by the teacher. In the week prior to the activity, the teacher had reviewed basic concepts about earthquakes to prepare them for the experiment. At the beginning of the activity,

the students were given specific instructions on how to construct the model, what to measure and how to analyze the data. The activity was completed in 50 minutes – a typical class period. Student-generated questions focused on the instructions and whether they were doing the experiment correctly. Discussions about the experiment and results were limited and difficult to stimulate. It was clear the students had not given much thought to the scientific method, the interpretation of the results, or the application of this experiment to the real Earth. The richness of the learning experience was lost to expediency and structure.

In the second classroom, I worked with ninth-grade earth-science students for 90 minutes. We used the more open-ended exercise described in this paper but shortened it by interweaving more class discussion to guide the activities. The exploration phase and building of the model lasted about 15 minutes. This was followed by a discussion of the variables involved in the experiment and the students' initial understanding of how those variables might influence fault behavior. I divided the students into groups and allowed each group to choose a variable to investigate. All of the groups had sufficient time to investigate their variable; however, some did a much better job than others. Many groups needed help in deciding what to record and how many measurements were needed to account for error and variability in the data. The student-generated questions focused less on the instructions and more on experiment design, data collection, and the behavior of faults. If there had been more time, I would have let them explore those questions more on their own rather than giving them hints and advice. Near the end of the class period, each group was asked to present its results and interpret them in terms of earthquake prediction. The presentations were quite promising. More sophisticated groups had graphed their data and calculated basic statistics. Other groups had generalized their observations qualitatively. In all cases, the students arrived at reasonable interpretations of their data and had genuine insight into fault behavior and earthquake prediction.

I continue to work with several teachers to design a still open-ended but more structured lab for secondary-school students. In the classroom with the earth-science students, it was apparent that secondary-school students need more structure in the activity but not in the form of instructions. Rather, the students have shorter attention spans and the activity therefore needs to be broken into smaller segments with more discussion and analysis intermixed to keep them interested and on task. Alternatively, this project could be extended over several weeks with a mixture of in-class and homework assignments that develop the scientific background necessary for the students to thoroughly investigate fault behavior and earthquake prediction (for example, see Conn, 1995).

Data Analysis and Evaluation of the Models

Data gathering and analysis will vary from student to student depending on understanding of the

Smooth sandpaper with bricks of different masses

Light Brick – Low Overburden Heavy Brick – High Overburden

f_i (N)	f_r (N)	$f_i - f_r$ (N)	slip (cm)	f_i (N)	f_r (N)	$f_i - f_r$ (N)	slip (cm)	
9.4	7.6	1.8	1.5	12.6	10.7	1.9	1.9	average
9.0	7.5	1.0	1.0	12.5	11.0	1.5	1.5	mode
7.3	6.0	0.2	0.1	10.5	8.0	0.5	0.5	min
15.0	14.0	5.0	5.0	17.5	12.0	7.5	6.5	max

Coarse sandpaper with bricks of different masses

Light Brick – Low Overburden Heavy Brick – High Overburden

f_i (N)	f_r (N)	$f_i - f_r$ (N)	slip (cm)	f_i (N)	f_r (N)	$f_i - f_r$ (N)	slip (cm)	
9.5	6.8	2.7	2.2	14.5	9.7	4.8	4.3	average
10.0	7.0	2.0	1.5	14.0	10.5	3.0	2.0	mode
8.0	5.0	0.5	0.5	10.5	1.0	1.0	1.0	min
11.0	8.5	5.0	4.2	19.5	15.0	15.0	11.5	max

Table 1. Basic statistical analysis of stick-slip data. Mass of light brick = 1.5 kg; Mass of heavy brick = 2.4 kg. The largest slip occurred in the model with the course sandpaper and the high mass of brick.

problem, curiosity, and initiative. In defining the assignment, I suggested questions the teachers should investigate in the experiment but specified neither how to investigate them nor what to do in gathering and analyzing the data. Most of the analysis can be done by applying simple statistics and graphing the data using a spreadsheet. In Table 1 and Figures 4-7, I present some of the data and analysis from experiments in which I varied: (1) the mass of the brick to simulate changes in lithostatic stress or overburden and (2) the coarseness of the sandpaper to reflect changes in friction and asperities. Each test was repeated 50 times to gather enough data for statistical analysis and to demonstrate the variability in slip behavior.

Basic data analysis can begin with a calculation of the minimum, maximum, mode and median values of f_i , f_r , $(f_i - f_r)$, and slip. The data in Table 1 reveal an increase in average f_i and slip with an increase in the mass of the brick or coarseness of the sandpaper. The largest slip event occurs with the heavier brick and coarser sandpaper. To determine the cause of an increase in number or magnitude of earthquakes, I compared the average and maximum slip for the different experiments. For the same amount of total slip, a smooth fault with low overburden will have nearly three times as many earthquakes as a rough fault with greater overburden. However, the rough fault has the potential for earthquakes with more than twice as much slip (Table 1).

More advanced statistics may include calculating a linear regression and correlation coefficient for the relationships between f_i and slip and $(f_i - f_r)$ and slip. An x-y plot of $(f_i - f_r)$ and slip clearly reveals that a positive linear correlation exists for all cases (Figure 4).

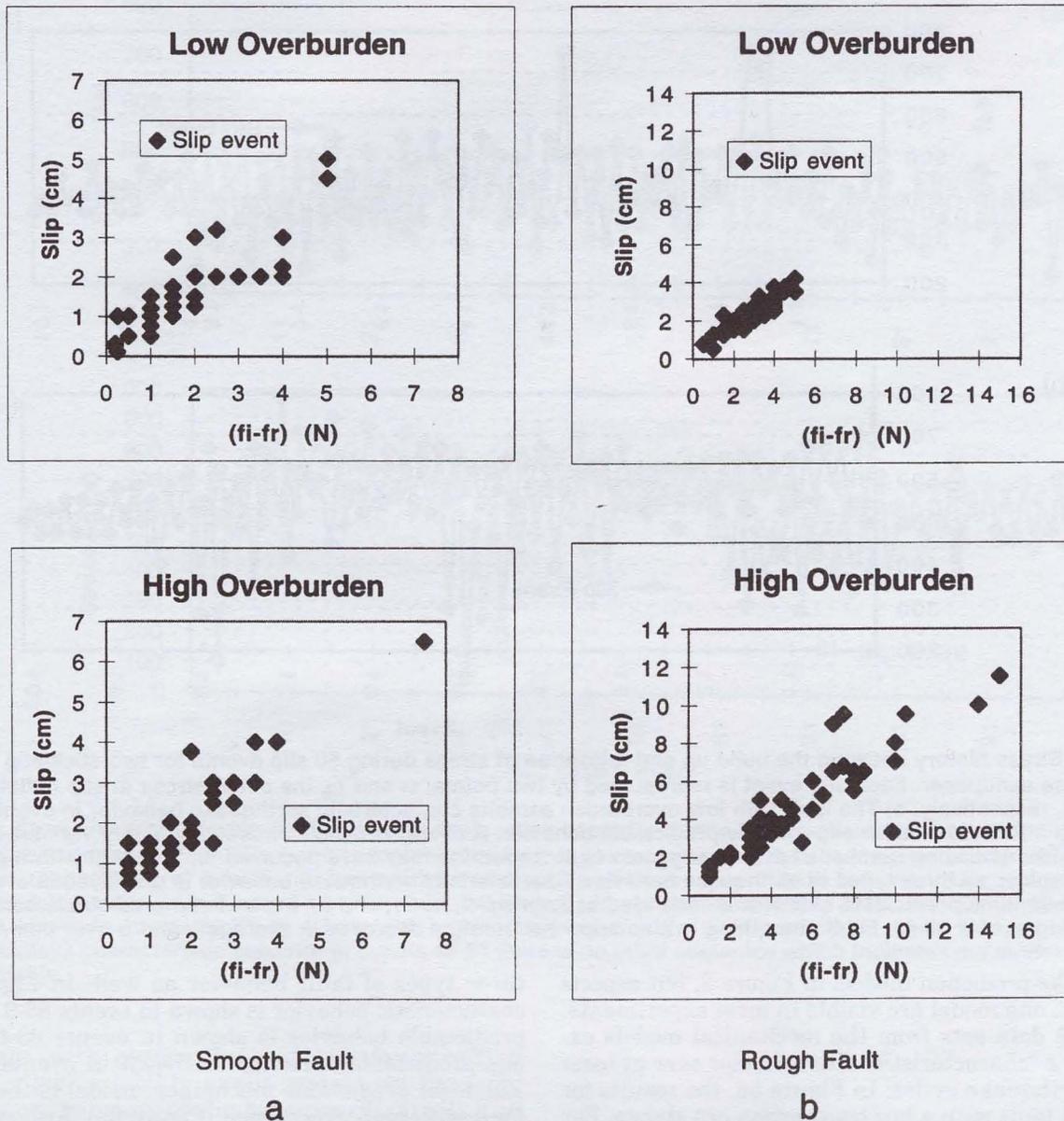


Figure 4, Comparison of slip with $(f_i - f_r)$. Slip in all models correlates strongly with the change in force from initiation of slip until the brick is at rest $(f_i - f_r)$. a) Data from a mechanical model using smooth sandpaper (grit = 220) for a low friction coefficient. Slip behavior for a model with a higher mass and overburden stress requires a higher f_i to initiate slip and results in higher average slip than a model with low mass and low overburden stress. b) Data from a mechanical model using coarse sandpaper reflecting a higher coefficient of friction (grit = 100). The coarser sandpaper results in higher average slip and $(f_i - f_r)$. The maximum f_i and slip distance for the model with higher overburden are nearly double those in the corresponding model with the smoother sandpaper.

However, there is no correlation between f_i and slip. Both of those results are consistent with observations of real faults in which slip is proportional to stress drop on the fault.

We can calculate the stress at the initiation and cessation of slip using f_i and f_r , respectively, for each event and then construct a stress history similar to those in the theoretical models for earthquake prediction (Figure 2). The time variable is not easily controlled in the mechanical model. The best approximation of time is to relate it to the amount of string coiled on the winch and assume that plate motion is

constant. However, in comparing the theoretical models for earthquake prediction to the results from the mechanical models, it is sufficient to focus on the stress history independent of time.

Figures 5 and 6 show the stress histories for the 50 slip events recorded for each model in Table 1. Each slip event is represented by two points, τ_1 and τ_2 , the shear stress at slip initiation and cessation, respectively. The buildup and relaxation of stress, and the great variability in the behavior of the stick-slip model under different conditions, are readily apparent. None of the data sets is identical to the end-member

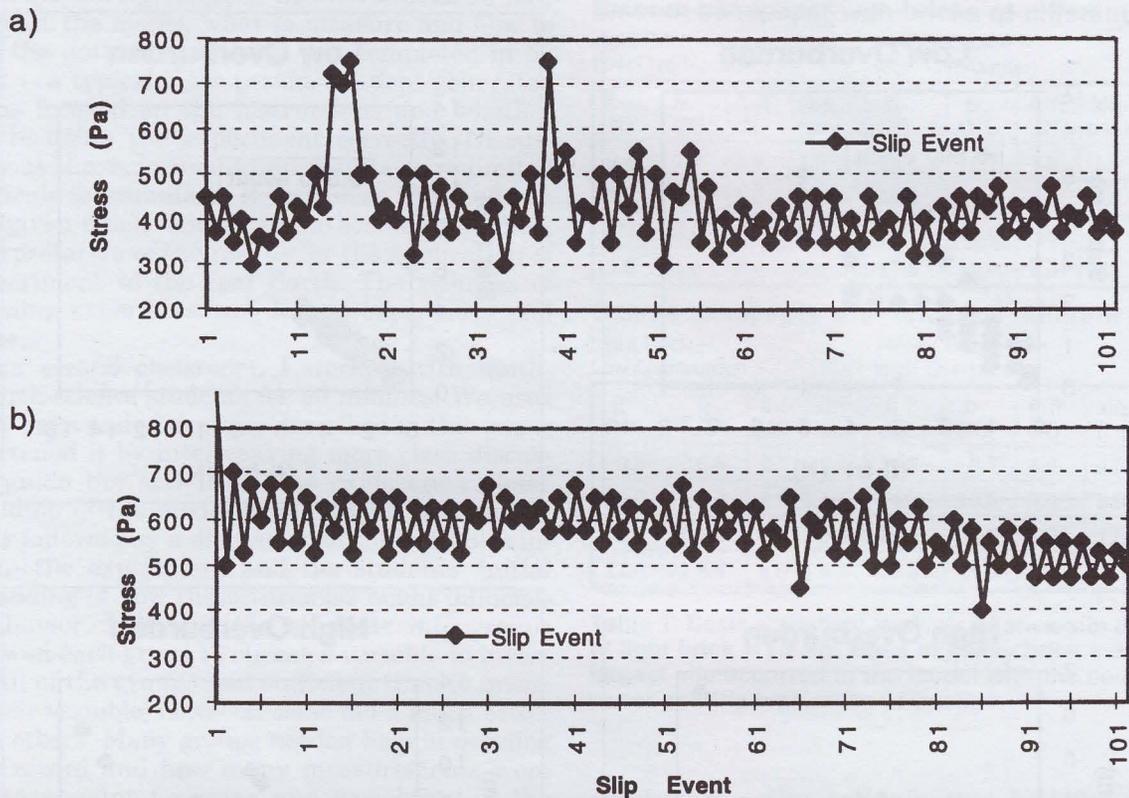


Figure 5. Stress history showing the build up and relaxation of stress during 50 slip events for two stick-slip models with coarse sandpaper. Each slip event is represented by two points, τ_1 and τ_2 , the shear stress at slip initiation and cessation, respectively. a) The fault with low overburden exhibits characteristic earthquake behavior in events 67-72 but shows little evidence for slip- or time-predictable behavior. A change in slip from initially highly variable to more uniform with increasing number of events suggests fault smoothing may have occurred. b) The fault with high overburden displays all three types of earthquake behavior. Characteristic earthquake behavior is displayed in events 21-26 and 85-91; time predictable behavior is displayed in events 5-9, 15-21, and 57-61; and slip predictable behavior is displayed in events 38-43. Fault smoothing is also apparent from the decrease in average f_i and f_r over time.

earthquake-prediction models in Figure 2, but aspects of at least one model are visible in most experiments. All of the data sets from the mechanical models exhibit some "characteristic" slip behavior over at least three earthquake cycles. In Figure 5a, the results for a smooth fault with a low overburden are shown. For events 67-72, the fault slip initiates at the same high shear stress τ_1 and ceases at the lower shear stress τ_2 as expected with the characteristic earthquake model, but there is little evidence for slip- or time-predictable behavior. There is also a change in the variability of stress drop and slip with increasing numbers of earthquakes, which suggests that smoothing of the fault over time takes place.

The mechanical model of a smooth fault with high overburden displays all three types of fault behavior (Figure 5b). Characteristic behavior is displayed in events 21-26 and 85-91. Time-predictable behavior, in which the fault always slips at the same τ_1 , is displayed in events 5-9, 15-21, and 57-61. Slip-predictable behavior, in which shear stress always relaxes to the same τ_2 , is displayed in events 38-43. Fault smoothing is evident in the decrease in τ_1 and τ_2 with increasing number of slip events. A mechanical model of a rough fault with low overburden displays all

three types of fault behavior as well. In Figure 6a, characteristic behavior is shown in events 86-91, time-predictable behavior is shown in events 83-92, and slip-predictable behavior is shown in events 62-71. The least predictable mechanical model is the rough fault with high overburden (Figure 6b). Although this model displays characteristic behavior in events 48-53, there is no other sequence of slip events which supports earthquake predictability.

A plot showing the frequency of different size (magnitude) slip events (Figure 7) corresponds well with observations of real faults. In all models, there is a much higher frequency of small to moderate slip events than of very large and very small events. In the stick-slip model, as for real faults, the number of small events reflects the difficulty in detecting and recording them. The smaller number of large events is expected because large events release more strain energy and require more time to build up that strain energy before rupture.

Finally, each mechanical model had five events (10%) with more than twice the average slip for that particular model. This suggests there may be a statistical basis for predicting the size of the larger earthquakes expected on a fault. These results are

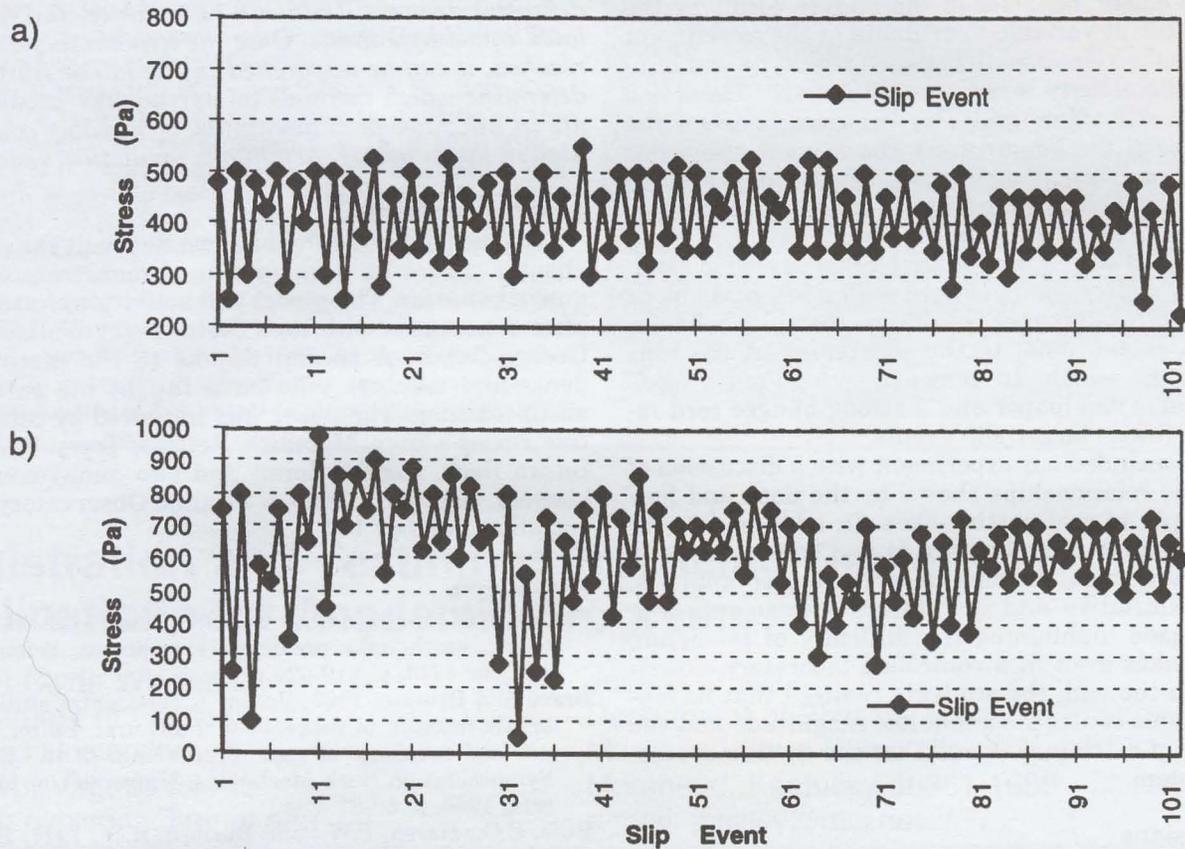
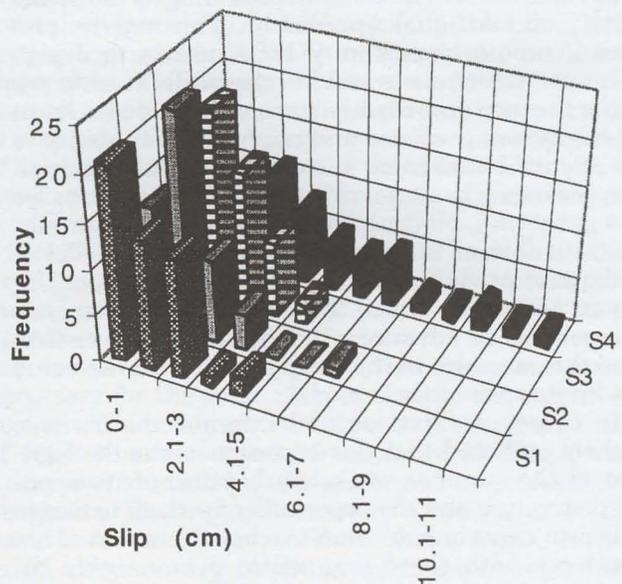


Figure 6. Stress history showing the build up and relaxation of stress during 50 slip events for two stick-slip models with coarse sandpaper. Each slip event is represented by two points, τ_1 and τ_2 , the shear stress at slip initiation and cessation, respectively. a) A fault with low overburden displays all three types of fault behavior. Characteristic earthquake behavior is shown in events 86-91, time-predictable behavior is shown in events 83-92, and slip-predictable behavior is shown in events 62-71. b) A fault with higher overburden is the least predictable model. Although the fault model displays characteristic behavior in events 48-53 there is no other sequence which indicates the model behavior is predictable.

consistent with observations of real faults which show similar variability in slip and do not fit nicely into any one category of slip behavior (Figure 2). The important point to remember in analyzing data from this experiment is that we rarely have a comparable amount of earthquake-recurrence information for real faults. Often we have records of just one or two major earthquakes in the past, and they may indicate either that a fault has quite predictable behavior, or just the opposite. Therein lies a major problem in earthquake prediction on real faults.

Figure 7 (right). Histogram of earthquake frequency and slip (magnitude) for the different stick-slip models. S1=low overburden/smooth fault; S2=high overburden/smooth fault; S3=low overburden/rough fault; S4=high overburden/rough fault. All models have a higher frequency of small to moderate slip events than of very large and very small events. The small number of very small events is due to the difficulty of recording them whereas the small number of large events is due to the greater strain energy required to generate them. The stick-slip model of rough fault with high overburden had the most large events reflecting the higher strain energy needed to overcome the friction on the fault surface.



The elastic behavior of the bungee cord was the most difficult variable to evaluate in the experiment because the relationship between rock type and bungee cord elasticity is not straightforward. There is a strong trade-off in stick-slip behavior between the elasticity of the bungee cord, the mass of the brick, and the coefficient of friction. Weak bungee cords with a lower sliding-block mass and smooth sandpaper provide the most stick-slip-like behavior. A weak bungee cord with a high-mass block and coarse sandpaper or a strong bungee cord with a low-mass block and smooth sandpaper results in creep-like behavior directly proportional to the shortening of the rope around the winch. In contrast, a high-mass block with coarse sandpaper and a strong bungee cord results in fewer, larger slip events.

We concluded our experiment with a discussion of the basic relationships shown by the data and how they apply to real earthquakes. In addition, we reviewed the lab procedures used and tried to identify ways they might be improved for better analysis. The quantitative and qualitative assessments students made highlighted the difficulty of predicting earthquakes even in a controlled laboratory experiment. In the end, the students realized that no single variable controls earthquake magnitude and the number of earthquakes and that the earth is a complex system.

Conclusions

Although the slider-block model cannot fully represent the complexity of the real Earth, the data and observations from the experiment illustrate quite well the general behavior of faults and the difficulty of predicting earthquakes. A variation of the fault model which includes two bricks in series separated by a short bungee cord was demonstrated at the end of the lab to illustrate the complex interaction between segments on a major fault as one segment triggers slip on the other.

The skills and knowledge gained in this activity go beyond an increased understanding of fault behavior and earthquake prediction. This activity provides a unique opportunity for students to design their own experiments and develop skills vital to scientific literacy or a career in science. Students learn science by doing science and reinforce their ability to use scientific reasoning to solve problems. In addition, the experiment provides many opportunities for data gathering, plotting and analysis, and determining the value of the data in developing a model of earthquake prediction, or any other phenomenon. Unlike an activity in which the procedure and analysis are specified in advance, students will discover first hand the variables in their experiment and the value and limitations of their model.

In course evaluations and informal discussions, teachers indicated that this experiment was the highlight of the summer workshop because of its open-ended structure and the opportunity for them to design their own experiments. One teacher summarized his experience with these comments: *"I thoroughly enjoyed the openness of this activity because it has no*

definitive answers. Data can be obtained and formulated into a hypothesis. Once the hypothesis has been reached, it can be researched in the lab or library to determine which methods [of earthquake prediction] are in use, have been attempted, or possibly could be used in the future as earthquake prediction systems."

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Registration and Testing of Practicing Geologists – Implications for Academic Programs

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This article was written by Robert C. Whisonant for the 1996 fall issue of *Saprolite*, the newsletter of the Southeastern Section of the Geological Society of America, and has benefitted from suggestions made by John C. Philley. The Geological Society of America has granted permission to reproduce much of the same information here. ASBOG has also given permission to share findings from the 1995 task analysis and blueprints. It was also published in the *Professional Geologist* with whose permission it appears here.

ASBOG began officially in 1989 when seven states, (Arkansas, Florida, Georgia, North Carolina, South Carolina, Tennessee, and Virginia) banded together to discuss common issues related to administering new legislated registration acts. At present, ASBOG consists of 16 member states and affiliates; others are expected to join soon. A principal activity of ASBOG has been the creation of two national licensing examinations, one on the fundamentals of geology (to determine basic knowledge) and another one on the practice of geology (to assess applied expertise). Two professional psychometricians are consultants for the continual process of generating and validating the testing instruments. ASBOG member states now have the options of using one or both of the ASBOG examinations, administering tests of their own construction, or choosing some other option to assess the competency of applicants. However, use of the ASBOG examinations can facilitate the establishment of reciprocity or comity among member states.

Among the many changes sweeping through the geoscience profession today is the increasing requirement for registration or certification of practicing geologists. At least 23 states now have registration or certification programs in place; legislation to create such procedures is progressing in several others.

An aspect of licensing with obvious implications for academicians is the development of examinations to assess minimal competency for those wishing to practice as geologists. Two national examinations have been created for this purpose by the National Association of Boards of Geology (ASBOG). As many as eight states use these tests; several others are poised to adopt them.

Geoscience departments wrestling with curriculum revision and other issues pertinent to survival can benefit from knowing about the substance of these examinations. The examinations are based on a nationwide survey designed to discover what knowledge, skills, and abilities geologists now need to be successful in the workplace.

In 1995, a three-year-long comprehensive national task analysis was completed for ASBOG under the direction of the psychometric consultants. The basic purpose was to determine if questions on the licensing examinations represented the important tasks necessary for the evaluation of competent practice of geology. The task analysis began by convening panels of subject-matter experts from across the nation in workshops to identify tasks performed by professional geologists. These panels came to a consensus on 88 basic tasks (see Table 1). These tasks were incorporated into a survey to obtain information regarding the amount of time geologists spend performing each