Concept Sketches – Using Student- and Instructor-generated, Annotated Sketches for Learning, Teaching, and Assessment in Geology Courses

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ABSTRACT

To promote active learning and increase student involvement in their own knowledge construction, we have implemented the use of concept sketches, which are simplified sketches that are concisely annotated with processes, concepts, and interrelationships, in addition to labels of features. When concept sketches are instructor-generated, they help students see how we organize and explain our knowledge. Students can generate their own concept sketches after seeing animations, video clips, photographs, and detailed textbook-style illustrations. They can also generate concept sketches while reading their textbook or after participating in inquiry exercises and in-class demonstrations. By generating such sketches and explaining them to their peers, students necessarily process the information more fully, consolidate their understanding, and personalize the information to suit their learning styles. Concept sketches are also excellent for identifying student conceptions prior to instruction, for directing student study as homework, and for assessing student understanding in exams. Concept sketching engages students in the learning process, develops critical thinking skills, teaches communication skills, and makes the course more enjoyable. Abundant educational research indicates that such sketches promote better student comprehension of the system under study and permit students to better use this knowledge to investigate the underlying processes and principles.

INTRODUCTION

Geologists are natural sketchers - in our field notebooks, on the blackboard, in our publications and formal presentations, or on napkins. Sketches and other illustrations are an important way we record our observations and thoughts, organize our knowledge, try to visualize geometries of rock bodies or sequences of events, and convey ideas to others (Rudwick, 1976; Hawley, 1993). Sketching is one way many people, in science and other disciplines, make their thoughts visible (Temple, 1994). If this is an important way we learn and wrestle with problems, why not help our students explore the visual world of geology in the same way?

Geology textbooks contain a plethora of detailed and beautifully illustrated diagrams, each depicting some fundamental geology concept or system. Unfortunately, many students simply skip through the textbook without really examining or internalizing the figures, or they fail to appreciate the value of these figures in constructing their own knowledge. For whatever reason, most students do not know how to interpret these scientific illustrations, nor can they identify the important factors represented in each (Lowe, 1989, 1993; Schwartz, 1993). We propose that an easy way to improve how students interpret or use scientific illustrations is to allow them to sketch their own versions of the concepts in an active-learning environment.

One way to envision our mental knowledge structure is as a hyperlinked network of concepts, with our ability to recall and apply any concept being related to how extensively that concept is linked with other pieces of information. Accordingly, much thought and research have gone into designing ways to help students relate and link otherwise disparate pieces of information (Novak and Gowin, 1984). From this line of inquiry arose the idea of concept maps, which are flow-chart-like or web-like diagrams that attempt to portray the hierarchies and other relationships of related concepts (Novak, 1998). Concept maps are a useful tool to help students articulate ideas, identify and arrange key concepts, and see how these ideas and concepts are connected. Concept maps have been shown to help students construct and organize knowledge and learn more than students who did not construct concept sketches (Novak and Wandersee, 1991; Esiobu and Soyibo, 1995). The process of constructing a concept map evidently encourages students to try to relate different aspects into coherent knowledge, more so than if simply reading or hearing about a subject.

For geology, concept maps fail to take advantage of the very visual nature of our science and do not preserve the spatial relationships of different features, such as an andesitic stratovolcano positioned above a subduction zone. We therefore developed the idea of a concept sketch, trying to help students identify and link key concepts, but retaining the spatial relationships between concepts and mimicking the more "geologic" portrayals, such as cross sections, we commonly employ.

This paper describes what a concept sketch is and is not, summarizes the research supporting the use of concept sketches, examines the degree to which concept sketches are useful, discusses when and how to use them, and identifies some of the drawbacks. We have both taught with concept sketches for several years and have collected some preliminary assessment data. Our limited data, when combined with a wealth of general educational research by others, support the positive impact of concept sketches on student learning. From this perspective, concept sketches are an important tool for teaching, student learning, and assessment in a science classroom. Incorporating concept sketches into a course requires very little effort and few, if any, new materials.

CONCEPT SKETCHES

In our view, a concept sketch is a simplified sketch illustrating the main aspects of a concept or system,

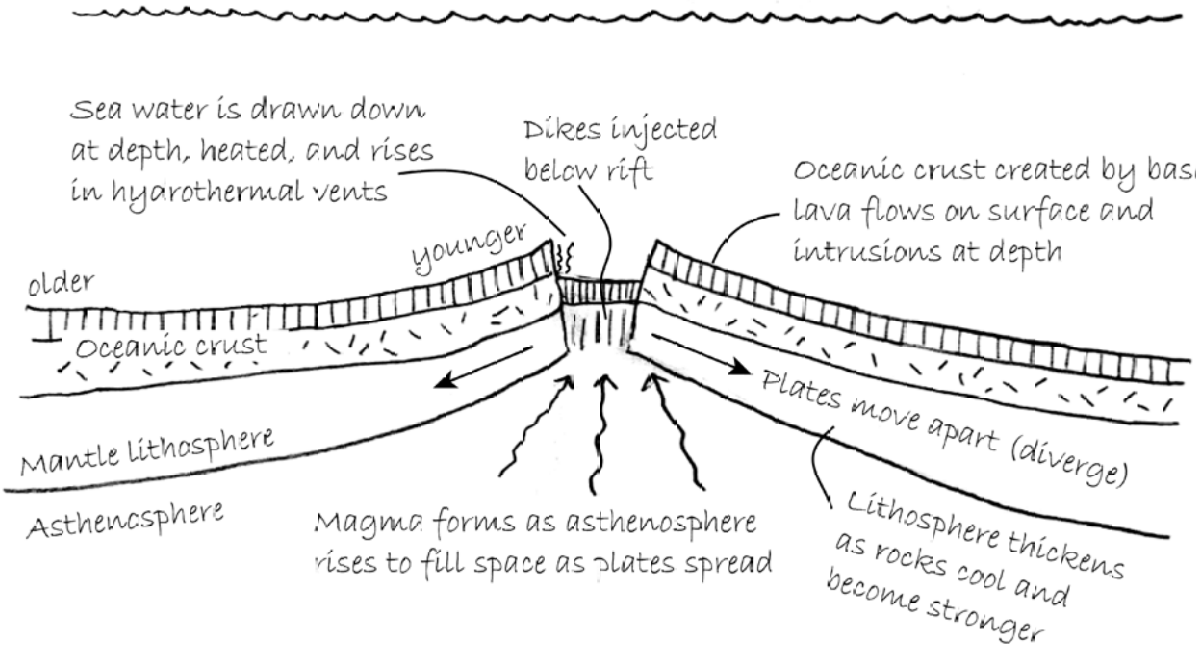


Figure 1. Concept sketch illustrating a divergent oceanic boundary.

annotated with concise but complete labels that (1) identify the features, (2) depict the processes that are occurring, and (3) characterize the relationships between features and processes. It is not simply a sketch labeled with only the names of features, as is generally seen in textbooks. A concept sketch of a mid-ocean ridge is shown in Figure 1. This sketch illustrates some of the processes occurring (rising magma, submarine eruptions), the main features produced (rift, oceanic crust, lithosphere), and how the processes and features are related. Depending on the interests of the student or instructor, such a sketch could instead emphasize hydrothermal activity and its role in the unusual communities of life found in these settings. We note that the term concept sketch is used in a different sense by artists and architects to imply a preliminary portrayal of an idea or future project (Rodgers et al., 2000).

Figure 2 is a concept sketch illustrating how a cone of depression forms because of over-pumping of groundwater. This two-panel sketch is labeled to show two stages of development, before and after over-pumping. The flow direction of groundwater is shown with one set of arrows, and the lowering of the water table is shown with another set of arrows. For such diagrams, it is critical to clearly indicate what each arrow is trying to show, differentiating between (1) the movement of material (e.g., flow of water), (2) how a feature changes over time (in this case lowering of the water table); or (3) the sequence in which the diagrams should be read. Students are often confused as to which of these meanings an arrow represents, and consequently draw meanings other than the ones we intended (Horn, 1998; Tversky et al., 2000).

Although most concept sketches are simplified cross sections, it is sometimes more appropriate to have concept sketches that are map views or 3D perspectives. Figure 3 is a map-view concept sketch of a meandering river highlighting the sites of deposition and erosion.

CONSTRUCTING CONCEPT SKETCHES

Concept sketches can be constructed by the instructor or by students, and each approach has some advantages. An instructor can generate a concept sketch to guide students toward the key aspects of a subject and show how the aspects are related. Such sketches could be constructed in advance, but we have found much more success drawing, labeling, and describing them in real time during a lecture. The pace of drawing and describing the sketch on-the-fly seems about right for students to be able to think about the topic as they sketch. If the instructor generates the sketch and the students copy it, we strongly recommend letting students describe the sketch to a neighboring student - otherwise they may have copied it without processing the key points. The main advantages of instructor-generated sketches are (1) the instructor can model thinking for the students and teach students how to create such a sketch; (2) the resulting sketch is more likely to show the most important features and correct relationships between them, omitting less important details and incorrect interpretations; and (3) more material can probably be covered, but this may come at the expense of student understanding. We tend to use instructor-generated concept sketches early in the semester, for reasons 1 and 2 above, or for concepts, such as atmospheric circulation patterns, that are especially difficult for students to figure out on their own. Also, some topics, especially very abstract or theoretical ones, presently lack good materials with which students can derive a sketch, so sketches of these topics may be best constructed by an instructor familiar with the necessary background knowledge and proper geologic context.

The general procedure for student-generated concept sketches is to have students first interact with some prompting material about a topic and then construct a concept sketch that portrays the essential aspects. The prompting material could be photographs,

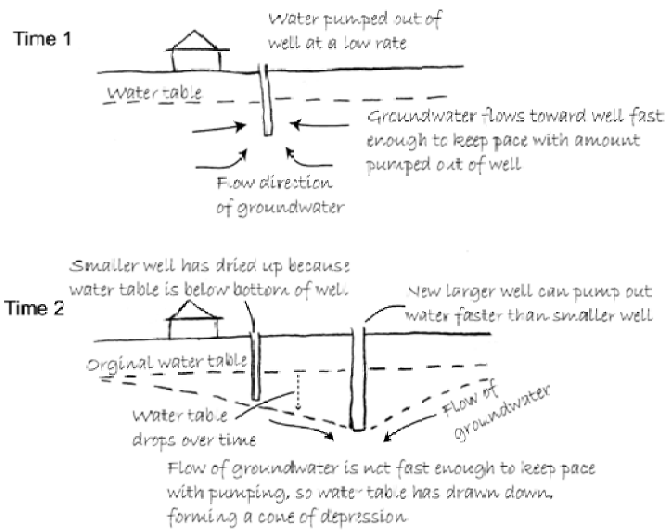


Figure 2. Concept sketch illustrating the formation of a cone of depression by overpumping of groundwater.

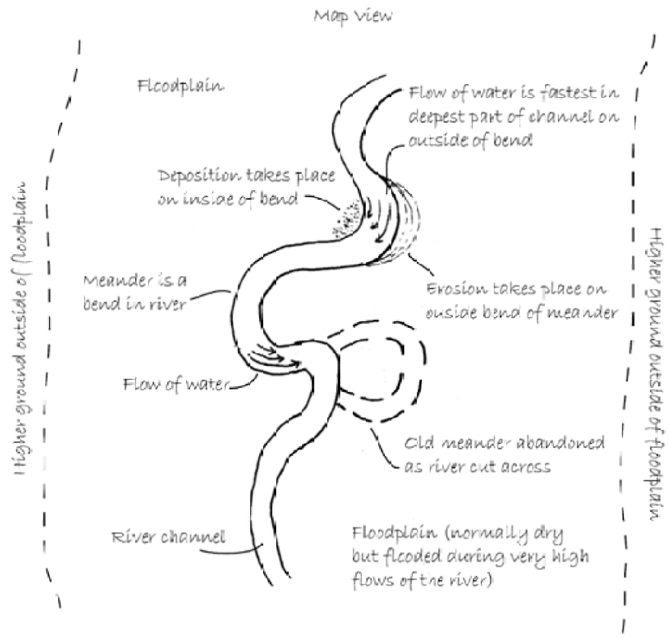


Figure 3. Map-view concept sketch illustrating a meandering river.

textbook-style illustrations, computer animations, video clips, in-class demonstrations, hand specimens, or maps. We use each kind of prompt many times during a semester.

To complete a successful concept sketch, students should do the following steps:

(1) interact with and observe the prompting materials;
(2) list what they think are the key features and processes, versus those things they observed that are nonessential;
(3) decide how the various aspects are related;
(4) brainstorm how to depict the system; and
(5) draw and annotate the sketch.

Unless the sketch is being used as an assessment, we generally have adjacent students compare their lists during step 2, share their ideas in steps 3 and 4, and compare their final results from step 5. Then, we have students use their sketches to describe to each other how the sketched system operates, to negotiate any differences, and to identify remaining questions and gaps in their understanding. At the end of step 2, we commonly help the students use the proper terms, perhaps by starting a whole-class discussion or doing a short lecture burst. For complex topics, the instructor might intervene during any step to help students over a known hurdle, but typically this is not necessary.

One main advantage of student-generated concept sketches is that students are actively engaged - that is, they have to interact with the material in a meaningful way in order to create a sketch. It clearly takes a deeper level of mental processing to decide what is important and what is not, to think about relationships between features, to arrange items in a hierarchy, and portray these relationships on paper (Lawson, 1995, 2003), than it does to simply copy an instructor's sketch. Students are likely to be better at comprehending and using a sketch they construct because the sketch contains the student's own words and linework (Roth and McGinn, 1998). Finally, by creating and discussing a sketch, students get the chance to use geologic words to talk about geology, and verbalizing to one another promotes transfer of information from short-term to long-term memory (Baker and Piburn, 1997) and encourages construction of shared meaning among peers (Driver et al., 1994).

Once the students have created a concept sketch, we recommend having them use the sketch to think more deeply about the system or use the sketch to solve a problem. An excellent way to do this is to have students apply their knowledge by answering a transfer question, that is a question that requires them to transfer their knowledge to a new situation or new problem. We find four types of transfer questions to be most useful (Mayer, 2001):

- Prediction questions, which ask the student to make a prediction,
- Troubleshooting questions, which ask the student to think about how the system might fail or function abnormally, or how to "fix" the system if it did,
- Refinement questions, which ask how to improve the system, and
- Causal or conceptual questions, which ask about the underlying processes and the causes and consequences.

For example, the concept sketch about groundwater pumping (Figure 2) could lead to the following four types of questions: (1) predict what would happen to the shape of the water table if you turned off the large pump; (2) how could you have prevented the smaller well from drying up; (3) what could you change now to decrease the impact of pumping from the larger well; and (4) what factors influence whether a cone of depression forms from pumping. In order to answer such transfer questions, students must understand a system well enough to manipulate or control variables.

A LEARNING-CYCLE APPROACH

An excellent way to use concept sketches in the classroom is to employ a learning-cycle approach (Lawson et al., 1989; Lawson, 1995). A variety of learning

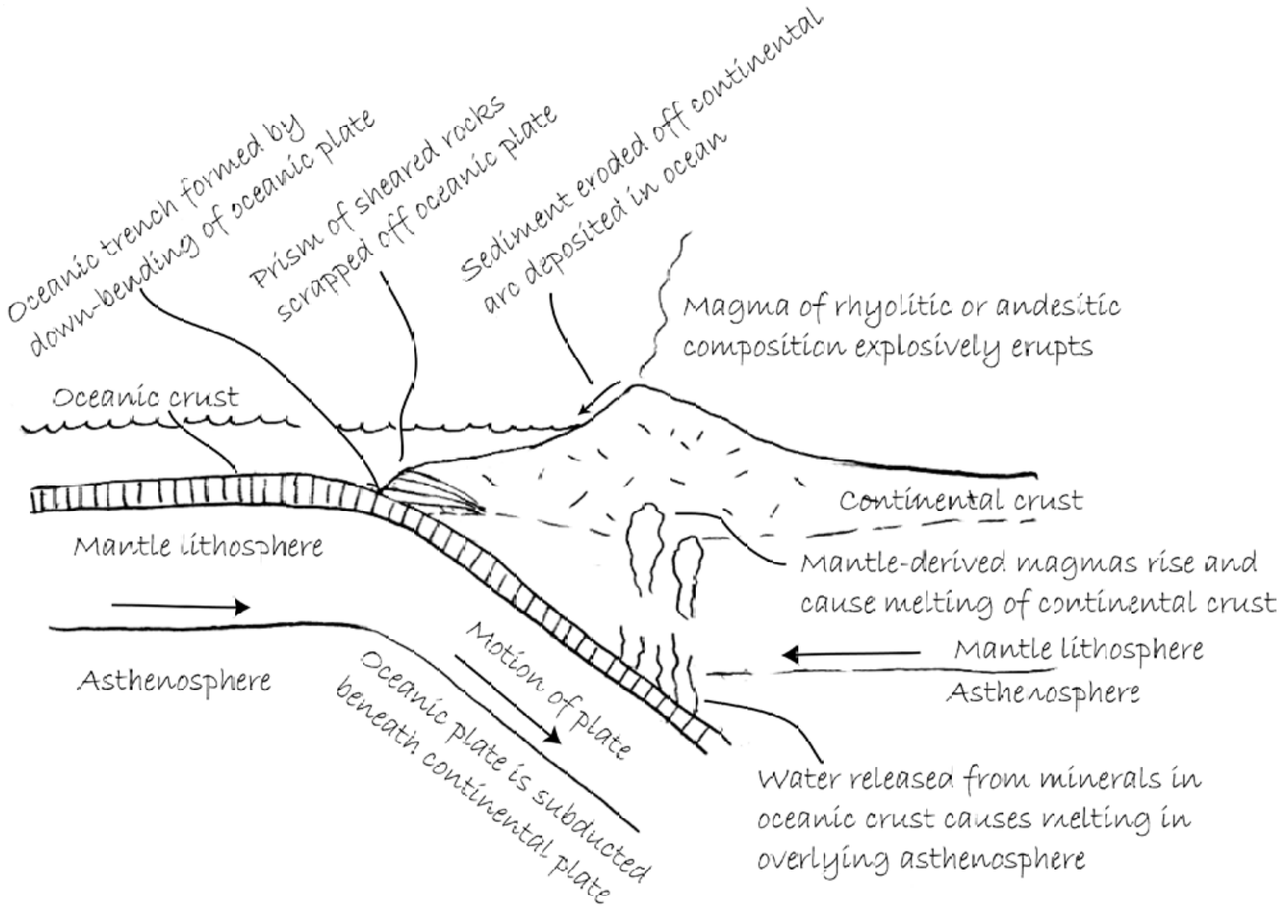


Figure 4. Concept sketch illustrating an ocean-continent convergent boundary.

cycles exist, but each variation shares three common elements: engaging the students through an exploration phase; introducing students to formal nomenclature and definitions in the term- and concept-introduction phase; and finally, having students apply concepts and skills in new situations in the concept-application phase (Lawson et al., 1989; Lawson, 1995).

During the exploration phase, the instructor creates interest and generates curiosity in the subject matter by giving students an opportunity to explore and observe some concept or phenomena without much instructor intervention. This should raise questions and elicit responses from students that might give the instructor some idea of what they already know, or what common misconceptions might exist. Students should start to ask questions about why something happened or how it happened. If students observe something unexpected, they may experience a kind of disequilibrium (Piaget, 1977), realizing that their current conceptions may not be consistent with the event. During this exploration stage, students should generate hypotheses and predictions, devise ways to test their predictions, discuss alternatives with their classmates, and record their observations.

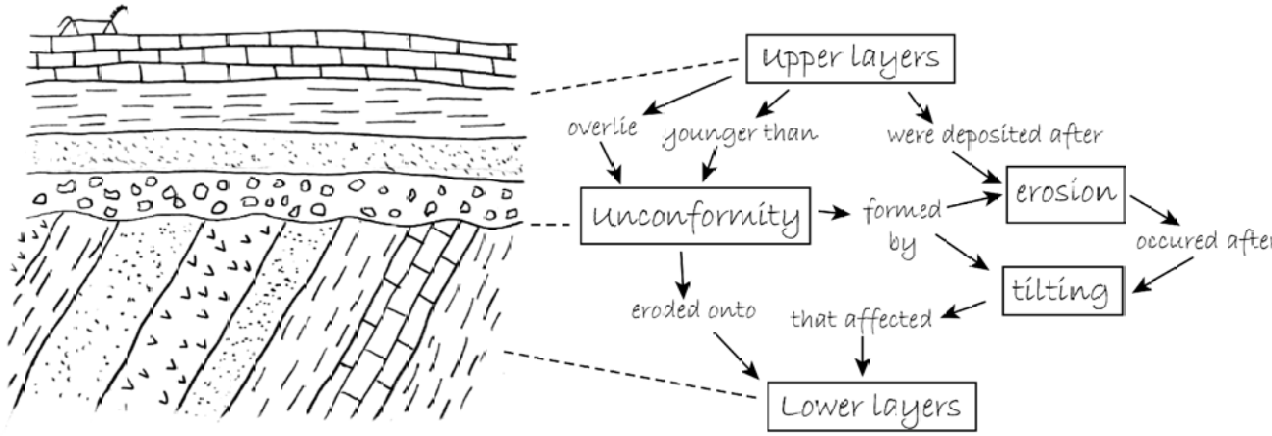
The term- and concept-introduction phase affords the instructor an opportunity to introduce or elaborate on useful terms and concepts. The instructor provides definitions and explanations to aspects the students themselves observed and experienced during the exploration phase. We view the term- and concept-introduction phase as a chance for the instructor to help the students construct a coherent mental framework that is consistent with the norms of science. Even during this phase, however, students should be encouraged to explain concepts in their own words.

In the third phase, the concept-application phase, students apply concepts and skills in new, but similar, situations. Students should be using the new terms and concepts to ask questions, propose solutions, make decisions, experiment, and record observations. Transfer questions are well suited for such applications.

Looking back, you will note that the steps we described for constructing a concept sketch is precisely a learning cycle. The students first observe (i.e. explore) and try to recognize the key aspects. Then, perhaps with instructor guidance, they use the proper terms, learn key concepts, and explain their sketches to one another. The concept-application phase takes place when students answer a transfer question or otherwise use their sketches to solve a problem. This phase helps students consolidate their knowledge and have one more chance to identify what they do not understand. Implementing concept sketching using a learning-cycle approach allows students to use their own observations to construct personal concepts and mental frameworks, and encourages them to take ownership of this knowledge.

USING CONCEPT SKETCHES FOR TEACHING AND LEARNING IN THE CLASSROOM

Concept sketches can be implemented in a variety of contexts - in large classes, small classes, labs, and on field trips. For use in a classroom, the choice of prompting



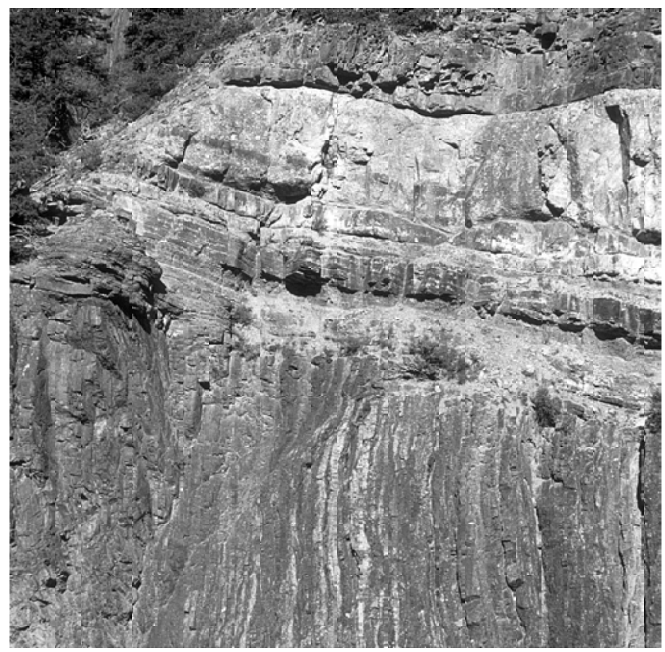


Figure 5. Photographs of unconformities in the Grand Canyon (left) and at Ouray, Colorado (right), and a concept sketch of an unconformity integrated with a concept map (top).

material is in part influenced by class size. Prompting with photographs, textbook-style illustrations, computer animations, video clips, and in-class demonstrations can be done in any class size, but using paper maps, hand specimens, and experiments in which students participate, while possible in large classes, is logistically easier in smaller classes.

Photographs make excellent prompts for many subjects. For example, we show several examples of a feature, such as photographs of different unconformities, and then have students generalize these examples into a "typical" unconformity. To do this, students have to observe the examples, recognize what is shown in each one, identify the aspects that are common to all the examples, and judge which aspects are only local variations. Such comparisons and generalization, a form of inductive reasoning, require the students to process the information more deeply than if they were simply given a description of an unconformity. This mode of prompting with photographs is suitable for helping students build a view of many geologic concepts, such as folds and faults, sedimentary environments, and sedimentary structures. When shown a number of landscape photographs using this technique, students readily learn how to recognize whether a landscape consists of sedimentary, metamorphic, volcanic, or plutonic rocks. Using photographs to elicit slide observations (Reynolds and Peacock, 1998) has been so successful at our university that most geology instructors use this technique in one form or another to instigate critical thinking and active learning.

Video clips, with their ability to show motion and changes over time, are wonderful prompts for visually active processes, including volcanic eruptions and destructive weather. We show students video clips of many different styles of volcanic eruptions (e.g., pyroclastic flow), with multiple examples of each type in random order. After observing all the clips, students discuss with their neighbor how many types of volcanic eruptions they observed. For each type, we then introduce the proper term (e.g., pyroclastic flow), rerun one of the video clips, and ask the students to construct a concept sketch for that type of eruption. In this way, students have observed several different examples of a pyroclastic flow before they are told the actual term.

Textbook-style illustrations are useful prompts, but may require a somewhat different approach because we are asking students to derive the general features from a single, complex instance, in this case an illustration. For example, we use textbook illustrations of the hydrologic cycle, rain shadows, formation of meanders, and evolution of landscapes. Students may understand these illustrations better once they have transformed the illustrations into their own simpler sketches and in the process had to determine what is important, what is not, and how to depict each aspect. Helping students make sense of textbook illustrations is not easy, because students see different things in these diagrams than do we (Bowen and Roth, 2002).

Computer animations are also excellent prompts, especially for systems that are too large, too small, too theoretical, too difficult, or occur over time scales that are too short or too long to directly capture. Such systems include plate-tectonic boundaries, continental drift, caldera eruptions, sense of fault displacement, and meteorite impacts.

Many geology instructors use in-class demonstrations to liven up the classroom, to increase student involvement and interactivity, and to provide analogies for subjects that are otherwise difficult to experience. These demonstrations can function as a hands-on, tangible prompt for constructing concept sketches about a geologic feature or process. This approach works for many types of demonstrations, such as the seismic dance (Metzger, 1995), using a miniature house and bulldozer with a pile of sand to illustrate slope stability, and having students compress modeling clay containing pennies to illustrate ductile deformation and strain.

TEACHING PLATE-TECTONIC BOUNDARIES USING CONCEPT SKETCHES

Plate tectonics provides an excellent example of how we have students construct concept sketches in class. We begin with an exploration phase by showing a short, silent animation depicting the evolution of one type of plate boundary. Students are asked to observe the processes and write a list in their notebooks or on a sheet of paper of any essential elements to include in their concept sketches. After students have made their observations, they are asked to think-pair-share (Lyman, 1987; Macdonald and Korinek, 1995), whereby they share and compare observations with their classmates. Then, we call on different groups to contribute their observations and list these observations on the front board. Typical student observations for an ocean-continent convergent margin might be:

- Two plates are moving toward each other.
- One side is being pushed down into the Earth.
- Ocean water is being pulled down along the descending side.
- The side being pushed down gets hotter the deeper it goes.
- Blobs of hot material are rising off the down-going side.
- Volcanoes are being formed above the down-going side.
- The ocean side is losing.

We may have a whole-class discussion to decide which aspects seem most important to show, or we may let student groups negotiate this among themselves. This list of observations provides some natural starting points for elaboration and introduction of terms and concepts, such as subduction, the causes of melting, why the oceanic plate gets subducted, or why a chain of volcanoes forms on one side.

After this brief term-introduction phase, students incorporate their observations into a concept sketch, usually on a portable whiteboard shared by 2 to 4 students. Their sketch should include drawing and labeling pertinent features and writing short explanatory remarks that capture the dynamic elements of plate tectonics better than a static diagram (Figure 4). Students then explain their sketches to neighboring classmates or to other groups, and some may present their sketches to the entire classroom by giving a mini-presentation. We repeat the entire process for each type of plate boundary, one at a time, but may skip the public listing of observations as students get better at deciding what is important. A short term-and-concept lecture burst should accompany each new type of plate boundary because specific features are original to each setting.

There are a number of possibilities for the application phase. Once the students have sketched all possible types of boundaries, students may combine two different plate boundaries into one sketch, i.e. an ocean-ocean divergent boundary linked with an ocean-continent convergent boundary. Alternatively, students can observe the major physiographic features for a large region, like the South Atlantic Ocean, and construct a cross-sectional or map-view concept sketch that interprets the types of plate tectonic boundaries indicated for this region.

Students' concept sketches, once constructed, may serve as a framework to scaffold later learning (Bransford et al., 1999) throughout the semester. For example, students add information to their plate-boundary sketches about other geologic phenomena related to plate tectonics, such as types of volcanoes, types of igneous rocks, and ore deposits.

TEACHING PRINCIPLES OF RELATIVE DATING USING CONCEPT SKETCHES

Principles of relative dating can generate great concept sketches. For each dating principle, such as cross-cutting relations, students observe several carefully chosen slides depicting the specific principle. While viewing a slide, students make observations, think-pair-share, and then sketch the main features they observe. After a short whole-class discussion where terms and concepts are introduced, students create a general sketch that illustrates the principle, along with appropriate labels (Figure 5). After all the principles have been covered, the students apply their knowledge by observing more complex photographs and trying to reconstruct the geologic history using as many principles as they can. They create a cross-sectional sketch, highlighting the key relations and proposing a brief geologic history of the slide. An alternative might be to have students build a concept map around the sketch (Figure 5). An excellent, but challenging, application-phase alternative is to have students create a cross-sectional sketch that is consistent with a specified geologic history: three layers were deposited, then folded and faulted, and the fault was crosscut by an intrusion. Try this one; it is quite fun!

USING CONCEPT SKETCHES FOR ASSESSMENT

Concept sketches are an efficient and authentic means of assessment. Concept sketches constructed by students before instruction are an invaluable and extremely

General Rubric (12 points possible)			
Content	Essential concepts all shown; important relationships correctly portrayed; no conceptual errors or evidence of misunderstanding (10 pts)	Most concepts and relationships shown correctly; some aspects left out; minor conceptual errors or misunderstandings (9, 8, or 7 pts)	Essential concepts left out; relationships not correctly portrayed; major conceptual errors or misunderstandings (6, 4, 2, or 0 points)
Detail and Presentation	Sketch detailed and clearly drawn and labeled (2 pts)	Sketch lacks some detail or not clearly drawn or labeled (1 pts)	Sketch lacks detail or is illegible; difficult to interpret (0 pts)
Specific Rubric for an Unconformity (15 points possible)			
Content	flat-lying upper layers (2 pts) unconformity (3 pts) tilted lower layers (2 pts)	erosion (2 pts) sequence of events (2 pts)	
Presentation	excellent detail (2 pts) neat and clear (2 pts)	good detail (1 pts) fairly neat (1 pt)	inadequate detail (0 pts) messy (0 pts)

Table 1. Examples of a general and specific rubric for assessing concept sketches.

revealing way to assess what students already know and to quickly identify student misconceptions. Concept sketches can be assigned as homework to help students learn from their textbook, especially for concepts you choose not to cover fully (or at all) in class. Sketches require students to interact with the text and illustrations in an active, sense-making manner, discouraging students from skimming and underlining without comprehension. For the instructor, such homework sketches are a time-efficient way to encourage students to read the book and allow the instructor to evaluate whether students read and thought about the assignment. It takes only seconds to examine and grade a student's sketch.

Concept sketches form an integral part of our quizzes and examinations. If you teach with concept sketches, you should assess with concept sketches. Concept sketches can serve as quizzes during class time, such as at the end of the class or after a topic has been covered. They also may constitute all or most of larger, more comprehensive exams. Test questions eliciting concept sketches are easy to write, such as the following:

- Draw a cross-sectional concept sketch showing how the water table relates to hills and valleys, a spring, lake, and water well; label which way the water is flowing in five places on your diagram.
- Draw a concept sketch illustrating how magmas are generated at a mid-ocean ridge.
- Draw a concept sketch depicting how cutting into the base of a hill of loose material may impact houses further up the slope.

We grade such sketch questions with either a general or specific rubric (Table 1). A general rubric assigns points based on a holistic assessment of the sketch, such as full points for a sketch that shows all essential concepts and contains no conceptual errors, or partial points for a sketch that does not include some key aspects or contains one or more conceptual errors. A specific rubric assigns a specific number of points for each feature or process that the instructor thinks should have been shown on the sketch, deducting appropriate points for anything that has been omitted or incorrectly portrayed.

EDUCATIONAL RESEARCH BASIS OF CONCEPT SKETCHES

Studies in science-education reform suggest that effective learning takes place when instructors allow for a more student-centered classroom, where students explore, discuss, negotiate meaning, and construct their own knowledge. Learning is a naturally active process (Bonwell and Eison, 1991; Bransford et al., 1999), and active-learning curricula encourage students to actively think, write, read, speak, or listen, and to be responsible for their own learning. Some typical active-learning activities might include classroom discussions (Brookfield and Preskill, 1999), collaborative learning (Linn and Burbules, 1993), think-pair-share (Lyman, 1987; Macdonald and Korinek, 1995), problem solving (Albanese and Mitchell, 1993), and concept mapping (Novak and Gowan, 1984). There is very strong evidence that actively engaging students results in more learning than a traditional lecture-only approach (Hake, 1998). Concept sketches are one more way to promote active learning.

Our implementation of concept sketches is supported by cognitive research experiments into the interplay of text, illustrations, animations, and narration in student learning, as summarized by Mayer (2001). In each of these well-designed experiments, researchers evaluated whether a given condition resulted in (1) more or less retention and (2) more or less transfer (i.e. being able to use the knowledge to think about the problem in new, creative ways, such as making predictions about the system).

In one series of experiments, students had better retention and transfer after interacting with text and pictures, than with text only (Mayer, 2001; see also Larkin and Simon, 1987). In other experiments, students had better retention and transfer if the words were close to the pictures, rather than being farther away. One implication is that for multi-panel illustrations, any caption or explanatory text should be right next to its associated panel, rather than in a long caption underneath the entire group of figures. Even better, such text should be imbedded into the figure itself (Mayer, 2001). These research findings help us understand why students have so much trouble making sense of illustrations in modern textbooks (Lowe, 1989, 1993; Bowen and Roth, 2002), where figures and the text that describes them may be widely separated. Students experience too much cognitive load trying to hold the text or figure in memory while they search out its companion. Similar obstacles arise when lecturers show a textbook-style illustration in class (Roth and Bowen, 1999), and later show a bullet list, or visa versa. Research again shows that students learn best when they interact with pictures and associated textual explanations at close to the same time (Mayer, 2001). Integrating, or at least closely sequencing, pictures and text is one of several strategies for reducing cognitive load and improving student learning (Paas et al., 2003).

In another set of experiments (Mayer et al., 1996; Mayer, 2001), some students were given annotated figures accompanied by lengthy explanatory captions, and other students received only the annotated figures. In a result that may surprise some people, students who received only the annotated figures scored higher on both retention and transfer tests than students who received the full caption too. Students were better able to make sense of the system if they could concentrate on the key points, using only a simple figure annotated with concise text. They were overwhelmed - too much cognitive load - if a long text-based explanation accompanied the annotated figure. Less really is more in this case!

These research results are clearly consistent with the idea of a concept sketch, in which a complex system is abstracted to its key elements and annotated with a few well-chosen words explaining the features and processes. In a concept sketch, the concise text is not only imbedded directly into the figure, but is spatially associated with the part of the figure to which it pertains.

The value of student-generated sketches has been demonstrated by several studies (e.g., Schwartz, 1993; Cox, 1999), including one done on the subject of plate tectonics (Gobert and Clement, 1999; see also Gobert, 1997). In this study, students who sketched as they read outperformed students who wrote summaries while they read or students who simply read the text. In a similar study, students who either sketched or wrote explanations as they read were better able to explain the processes, whereas students who wrote summaries tended to have somewhat list-like recall of the material, but not a good working knowledge (Gobert, 2004, personal communication).

Other research found that many students resort to sketching as a means of processing and describing information (Chi et al., 1989, 1994; Tversky, 2002). Self-explaining (or verbalizing) and sketching are both constructivist activities, and together promote a greater understanding and deeper processing of science concepts (Ainsworth and Loizou, 2003). Incorporating some element of student discussion or explanation, therefore, is important when using concept sketches as a learning tool.

Sketching supports cognition in a number of ways, including useful reordering of information, directing attention to unsolved parts of the problem, identifying where knowledge is inadequate, refining and disambiguating mental images, helping to mentally animate a process, and even shifting the student's mode of reasoning (Cox, 1999). Sketching may especially help students with poor spatial abilities and students who are not practiced in generating multiple representations of a system (Cox, 1999).

The inclusion of arrows in concept sketches is key in several regards. Educational research shows that students using diagrams with arrows tend to describe processes and function, but provide only structural descriptions ("there is a layer here and another one there") if using diagrams without arrows (Heiser and Tversky, 2002).

BENEFITS AND POTENTIAL PROBLEMS

There are numerous benefits to concept-sketching in the classroom. Concept sketching requires students to actively process their knowledge as they (1) think about what they have seen or experienced, (2) determine what to show and what to leave off, (3) think about how best to portray the various aspects, and (4) decide what and how to label on their sketch. The finished product, a sketch with descriptions and explanations, lends significance and meaning to the sketch, especially if students have created the sketch themselves, using their own words, style of presentation, and personal knowledge. Concept sketching also encourages student discussion and small-group learning, which have been shown convincingly to improve student learning and attitudes (Springer et al., 1999).

Introducing students to concept sketching is quite easy and students adapt very quickly to this approach. Students find concept sketching to be stimulating and fun, rather than causing them to dislike science more after taking a science course (Tobias, 1990; Baker and Piburn, 1991). Via concept sketches, students have the opportunity to work together with their classmates, and this simple social activity greatly enhances the dynamics of the classroom setting and effectively promotes class enthusiasm and real learning (Driver et al., 1994; Baker and Piburn, 1997, p. 301). Many students have commented that this was the first time in their college education that they had been asked to actively participate in class, and that this sketching process was different than anything they had ever done in a lecture setting. Typically during these sketching sessions, student are actively engaged in discussions as they make suggestions, revise their sketches, thrash out alternatives, discuss possible explanations for certain features, and debate the mechanics of some geologic process. Allowing free discussion leads to more confidence, and as the semester progresses, classroom discussion is an integral part of the lecture period. Having students display their sketches on small, portable whiteboards or on the large board at the front of the room provides a wonderful starting point for whole-class discussions.

The activity of verbalizing to classmates, either in a think-pair-share or in an explanatory role, is also conducive to real learning (Baker and Piburn, 1997). Participating in think-pair-share discussions improves student confidence, and makes them more likely to participate in class discussion. By explaining their sketches to their classmates, students can help teach each other and evaluate their own understanding of concepts (Chi et al., 1989, 1994). The process of self-explaining helps students transfer information to long-term memory (Chi et al., 1994; Anderson, 1990; Lawson, 1994).

To understand something well means being able to explain it to someone else.

Concept sketching encourages students to generate their own representations of geology principles. This greatly enhances the significance and meaning of geology concepts when students have constructed their own framework in which to put information. These sketches have been personalized, and every point, line, and word means something to them.

Based on student feedback, this form of learning is easily applied in other subject areas, and we suspect such an approach is viable at middle-school and high-school classrooms, in addition to college where we know it works. Students can use concept sketching in their biology, chemistry, or even psychology classes to consolidate understanding and internalize the important points.

There are a few drawbacks to concept sketching. In the beginning, students will be very tentative about making observations. Many students fear they might not see the same thing as their instructor or classmates. Think-pair-share helps to alleviate some of these fears, but it is important that instructors are careful not to invalidate a student's suggestions, and thereby discourage that person from participating. This does not mean, however, to let misconceptions go unchecked, but rather to try and summarize student comments, rephrasing it to reflect correct meaning (McKeachie, 2002). Good classroom discussions transpire with questions that are open and thought provoking rather than simply questions with yes / no or right / wrong answers (Kindsvatter et al., 1996; Baker and Piburn, 1997). Many times we have observed that asking convergent (yes / no or right / wrong) questions will stifle student discussion, whereas divergent (open-ended) questions encourage discussions (McKeachie, 2002). Also, it is important to give students time to answer their own and each others' questions (Baker and Piburn, 1997). Successful class discussion also encourages constructive disagreement. If your students feel comfortable disagreeing with other students, and even with you, they will be more likely to contribute their perspectives, experiences, questions, reservations, and so forth. During any brainstorming of student observations and ideas, we try not to stymie the process by judging suggestions, either for good or bad, as they are offered (McKeachie, 2002; Kindsvatter et al., 1996).

For some instructors, it will be seen as a disadvantage that students will produce a variety of similar, but significantly different looking concept sketches for any one geology concept. The difficulty here is interpreting some sketches or making suggestions for improvement without hindering further efforts. Handling these corrections can be tricky, especially in front of the class, because it requires the instructor to make corrections without overtly judging or embarrassing the student.

Active learning in the classroom can consume time, and concept sketching is no exception. As much as 15 or 20 minutes can be spent on a single plate-tectonic setting, if you follow the model presented above from start to finish. In order to free class time, a What-to-Know List (Reynolds and Peacock, 1998; Reynolds, 2000) is given to students at the beginning of the semester. This list identifies key topics from each chapter that students are responsible for knowing at test time. Since there are always serious time constraints in such classes, simply teaching students how to construct understanding with concept sketches may increase their efficiency in learning from the textbook without formal guidance. Many science educators today feel it is more important to sacrifice some topics in the textbook in favor of teaching fewer topics in greater depth and devoting more time for critical-thinking skills (National Research Council, 1996).

Finding acceptable material to use as prompts for concept sketches is sometimes challenging. Video clips and pertinent landscape photographs are great, but if neither media are available, photocopying text without the illustrations from an article or book gives students a real opportunity to use their imagination in drawing concept sketches.

We have found that older students are less likely to participate, and may wonder why they are paying you to teach them if they have to do all the work. Providing a positive classroom experience for these students - and specifically explaining why we are doing this - can encourage their participation. Their involvement can often be increased by putting them in groups that need a leader and some direction.

Finally, it can be difficult to keep large groups focused on the task at hand. We recommend that the instructor move about the classroom, pausing and listening to group dynamics, and giving suggestions or encouragement when applicable. Ideally, groups should be limited to no more than four members so that no student is on the outside of the "inner circle".

SUMMARY

The use of concept sketching to communicate geologic processes, coupled with a learning-cycle approach, has been successful in our introductory geology classes. A typical concept sketching exercise consists of three phases: exploration, term and concept introduction, and concept application. The exploration phase involves students observing a geological process or principle, listing essential elements to be included in a sketch, posing questions, and debating possible explanations. This is followed by a term- and concept- introduction phase, involving teacher-guided introduction of formal terms and explanation of concepts, starting from observations posed by the students. At this juncture, students are asked to sketch the key features, processes, and principles in a sketch, with appropriate labels and description of the processes. The final concept-application phase involves students applying concepts and skills in new, but similar, situations. In this phase, students use their new knowledge to solve a different but related problem, to make predictions, or to suggest how to refine or troubleshoot a system. This learning-cycle process allows students to construct their own concepts and mental framework for complex scientific information. There is strong research-based evidence that using interactive engagement (Hestenes, 1987; Hake, 1998, 2002), a learning-cycle approach (Lawson, 1995), small-group learning (Springer et al., 1999), and annotated sketches in which text and pictures are integrated (Mayer, 2001) will all improve student learning. Besides, we geologists love to sketch.

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