Visualizing a 3-D Geological Structure from Outcrop Observations: Strategies Used by Geoscience Experts, Students and Novices

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1. QUESTION

How do people manage to create a mental image of a three dimensional geological structure from the limited, scattered information available in outcrops?

More particularly:

- How do novices and experts gather and record relevant field information?
- How do novices and experts reason from their observations toward a model of the shape of the structure?
- How do students who have trouble with this task differ from successful students and expert geoscientists in their underlying spatial abilities, learning styles, and strategies?

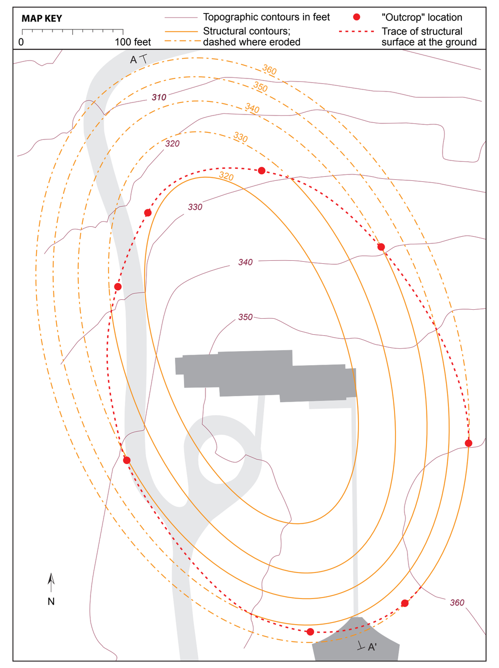
2. METHODS

Visualizing a geologic structure from outcrop information involves two of the most distinctive aspects of geoscience learning: (a) learning to think spatially about Earth phenomena, and (b) learning by direct observation of nature in the field. Both can present difficulties for students.

To explore this learning and thinking process, we have developed a simplified version of the field geologist's task, based on a set of "artificial outcrops." "Outcrops" are made of red and yellow "strata" of painted plywood.

Eight such "outcrops" are installed on our campus so as to constrain an imaginary "geological structure," of a realistic shape and scale.

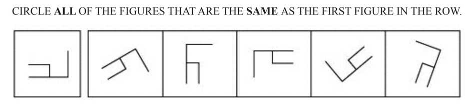
Map of outcrop localities.

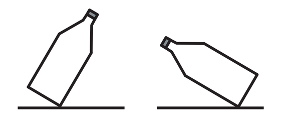


After an introduction to the field geologist's task, we led the participants, individually, to the eight outcrops, in a predetermined order. They could observe each outcrop as long as they wanted, and were encouraged to use pencil and paper to record anything they thought important.

When they returned to the starting point, we asked them to select which of an array of three-dimensional models could best represent a partially buried, partially eroded structure containing the eight observed outcrops. We asked them to explain their choice, and we videotaped their answers.

Finally, they completed standard paper and pencil assessments of spatial ability, plus a questionnaire assessing verbal/visual preference.





In the 2-D water level task, participants are shown a drawing of a tilted bottle and asked to sketch in the position of the water if the bottle were half filled.

We worked with four groups of participants:

- undergraduate non-science majors from a 4 year liberal arts college
- undergraduate science majors in a competitive summer internship program
- Geoscience graduate students
- professional structural/field geologists

Relationship between our experiment and the authentic field geologists' task:

What we are eliminating:

- Anxiety (about getting lost, poison ivy, snakes, where to go to the bathroom)
- Did student find all the relevant outcrops?
- Did student correctly identify the rock types?
- Did student correctly figure out the age relationships among the rock layers?
- Complex structures (faults, overturned folds, etc.)
- Technology (compass, GPS, topo map)
- Interplay between visualizing structure and hypothesizing about formative process

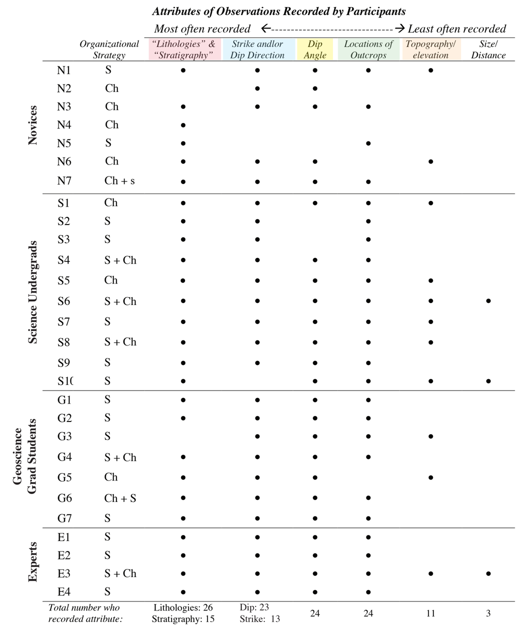
What we are retaining:

- Realistic scale structures (not lab table top)
- 3-D structures (not computer screen)
- Combine observation from multiple outcrops
- Cannot see entire structure from any single vantage point
- Most of structure is buried
- Relationship between structure and land surface (topography)
- Visualize structure
- Communicate visualized structure

3. RESULTS

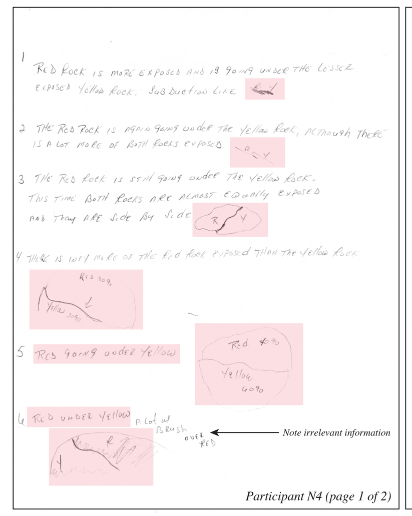
All experts, most advanced students, and a few novices, recorded their observations onto the blank paper in the form of a map or map-like representation. They organized their observations on the paper such that the 2-D space of the blank paper represented the earth's surface. In contrast, most of the novices and a few of the advanced students recorded their observations in chronological order, from top to bottom and left to right on the paper, as though they were taking notes in history class.

Key to Organizational Strategy Codes: S = spatial; Ch = chronological

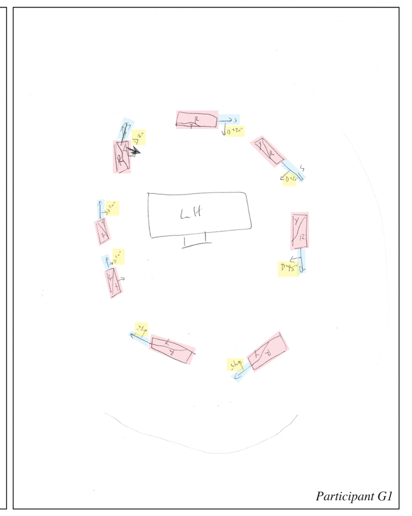


In the examples below the highlighter colors show how we coded the data and are keyed to the table above.

Example of chronological organizational strategy



Example of spatial organizational strategy

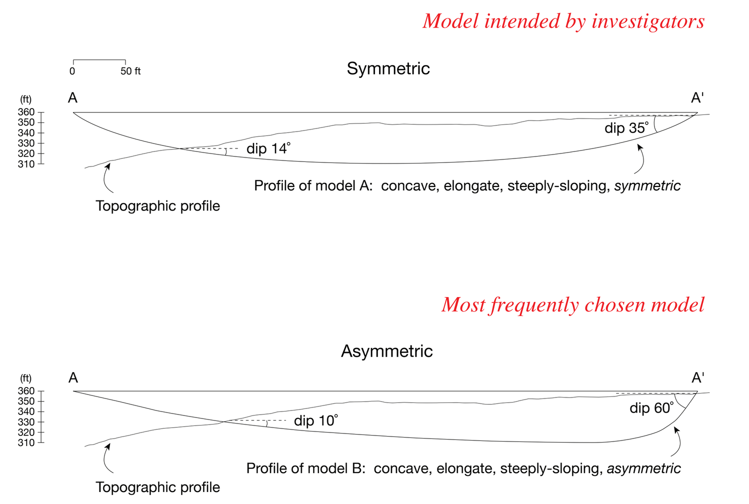


As the experts observed each outcrop, they scanned their surroundings for landmarks and observed spatial relationships among outcrops. In contrast, many novices focused on only the single outcrop in front of them at the moment and did not look back or around.

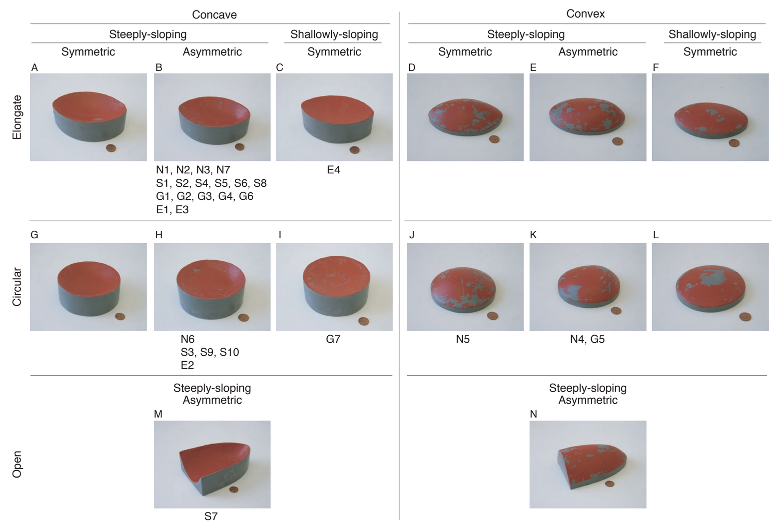
Less experienced students generally made accurate observations, but these were imperfectly matched to the needs of the task: they painstakingly recorded irrelevant information (e.g. presence of bushes), while failing to note essential information (e.g. which way the layers were slanting).

Experts began to develop a spatial hypothesis about the shape of the structure after observing the first few outcrops, which they then tested at subsequent outcrops; inexperienced students did not express a spatial hypothesis until confronted with the scale models.

At all levels of expertise, participants neglected the interaction between topography and structure, which led them to incorrectly dismiss one plausible model.



Surprisingly, there was not a clear novice to expert gradient in success at picking the intended model. The more notable contrast was in participants' strategies for approaching the task: what information they paid attention to, how they recorded their information, and how they reasoned from observation to interpretation.



By comparing what observations participants recorded with what model they selected, we identified two failure modes.

(1) Participant did not observe or did not record a specific attribute of the outcrops. This was the most common failure mode among novices.
(2) Participant observed and recorded the relevant attribute(s) but failed to integrate information spatially.

In this quadrant, participant recorded well and chose well.

In this quadrant, participant drew on information they had observed but not recorded (or guessed).

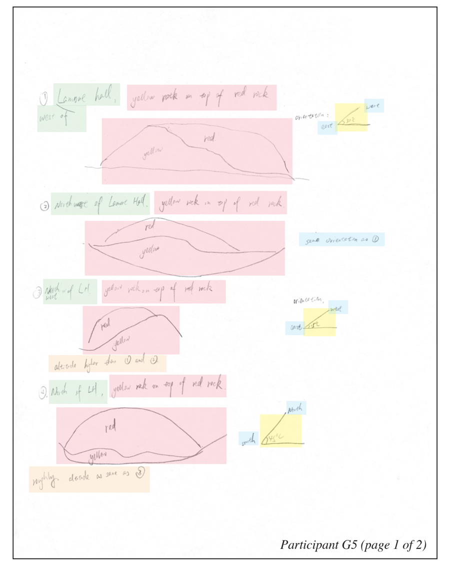
Observations recorded versus model selected: Concave/convex

	Recorded enough information to require concave	**Did NOT record enough information to require concave**
Selected concave	N1, N3, N7 S1, S2, S4, S6, S7, S8, S9 G1, G2, G4, G6, G7 E1, E2, E3, E4	N2, N6 S3, S5, S10 G3
Did NOT select concave	G5	N4, N5

In this quadrant, participant observed all needed information but failed to integrate spatially (failure mode 2).

In this quadrant, participant did not record enough information to choose correctly (failure mode 1).

Example of failure to spatially integrate observations pertinent to model choice along the convex/concave dimension.



This student observed and recorded all of the information needed to choose correctly between the convex and concave models, including the dip direction of each outcrop and its location relative to a prominent landmark (Lamont Hall). Yet she failed to integrate the information spatially, and chose an incorrect convex model.

4. DISCUSSION

Organizational Strategy:

To an expert, it seems obvious that the way to approach this task is to draw a map. This was not obvious to the novices.

Discussion question. Do you think that the proper inference here is that:

(a) We should teach students that they must make or use a map when they are doing any kind of field work?

(b) We should teach students about the power of spatial thinking and encourage them to consider using a spatial representation to organize their thoughts and observations when confronted with an unfamiliar problem?

(c) We should allow students, especially in courses for non-majors, to use the organizational strategy they are most comfortable with and not force them to use the conventions used by professional geologists?

Allocation of Attention:

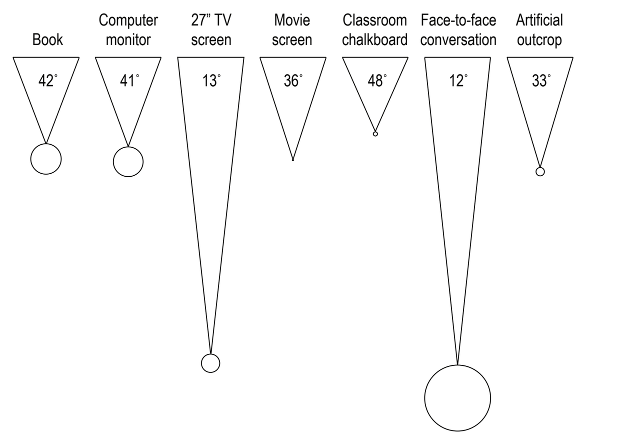
One major difference between learning from nature in the field and learning through a laboratory experiment is that in a field setting there is an overwhelming profusion of visually accessible information. For the novice, it is not obvious what to pay attention to.

Which attributes of the outcrops participants paid attention to and chose to record may give us a window into (a) what attributes they found conspicuous and/or (b) what attributes they understood to be important for the task at hand.

- The shape of the outcrop and colors of the layers, which were irrelevant for the task, were the most noted features.
- The overlying/underlying relationship of the red and yellow layers was conspicuous.
- Dip direction was more often noted than strike direction.
- Topography was commonly ignored.
- Metric scale (both size and distance) was almost universally ignored.

When accompanying participants in the field, one of the most striking phenomena we observed was the difference in visual focus between the experts and the novices. The experts, and some of the more experienced students, looked all around, gathering information from 360° of azimuth and at distances ranging from beneath their feet to the horizon. Many of the novices, in contrast, paid attention only to the individual outcrop that was directly in front of them. Why might this be?

For modern children, an overwhelming fraction of significant events and information appears within a field of view only a few tens of degrees wide. We hypothesize that modern life has inadvertently conditioned people to pay attention only to information that is directly in front of them, and that students carried that habit into our experiment.



Spatial Thinking in Geosciences

Geoscientists use a wide range of spatial thinking strategies in our work, as summarized in the table below. Spatial thinking skills are under-emphasized in K-12 education (National Research Council, 2006), and thus many undergraduates come to us with little practice in applying spatial thinking in a methodical or sustained fashion.

The weakest novices in our study exhibited only the most elementary of the spatial thinking strategies: "describing." The strongest students and experts, in contrast, utilized multiple spatial thinking strategies.

Taxonomy of Spatial Thinking in Geosciences (Novice ↔ Expert)

Category	Description	Examples
1. Describing, classifying	Observing, describing, recording, classifying, recognizing, remembering, and communicating the two- or three-dimensional shape, internal structure, orientation and/or position of objects, properties or processes of the Earth.	Observing and recording strike and dip; classifying clouds by their shape; identifying a fossil by its shape.
2. Manipulating	Manipulating those shapes, structures, orientations or positions, for example by rotation, translation, deformation, or partial removal, either mentally or with the aid of spatial representations.	Mentally "unfaulting" or "unfolding" a deformed sequence of layered rocks obtained from outbound outcrops to reconstruct the sequence of deformation.
3. Synthesizing/integrating	Combining spatial information obtained nonsynchronously from diverse sources into an internally consistent, integrated mental model of a 3-D structure or 4-D process or sequence of events.	Integrating information about the attitude of a deformed rock layer obtained from scattered outcrops to envision the shape of a geologic structure.
4. Interpreting	Generating explanations or hypotheses about what caused the objects, properties or processes to have those particular shapes, structures, orientations and/or positions.	Interpreting a lateral offset in a stream as a consequence of motion along a strike-slip fault.
5. Predicting	Making predictions about the consequences or implications of the observed and interpreted structures and processes, especially predictions that can serve as the basis for tests of hypotheses about causative processes.	Predicting where pockets of oil and gas will be found in a fold and thrust belt.
6. Using Spatial Metaphors	Using spatial thinking processes as a shortcut, metaphor, or mental crutch to think about the distribution of processes or properties that are distributed across some dimension other than length-space.	Geologic time scale shown along a timeline; P-T diagrams in igneous petrology, T-S diagrams in physical oceanography.

Inspired by Bloom's Taxonomy of Educational Objectives (Bloom, 1956)

Suggestions for Instructors:

- Fight blinkered vision! Explicitly stress the importance of observing in all directions and at various scales ranging from the outcrop to the horizon.
- For novices in our study, dip direction was more salient than strike direction. Consider introducing dip before strike, at least until students have established a conceptual understanding.
- Consider building a set of "artificial outcrops" for teaching purposes on your own campus.
- Explicitly discuss "spatial thinking" as a way to approach unfamiliar problems in science and as a skill to cultivate.