Visual Communication: Do You See What I See?

Barbara L. Dutrow*

**INTRODUCTION**

Since prehistoric times (e.g. cave paintings), visual images have been used to inspire and to communicate information. The first stunning image of our planet, “Earth Rise,” is considered to have raised social consciousness—an awakening that grew into the environmental movement (Gore 2006). Our knowledge of the world around us and our everyday decision making commonly rely on visual information. With new measuring and imaging devices capable of nanoscale resolution, remote sensing on the planetary scale, Google Earth®, and more powerful computers for modeling geo-hydro-biosphere processes, our world is increasingly filled with visual displays (e.g. Domik 1999).

The fields of mineralogy, petrology, and geochemistry (MPG) are particularly rich in visual imagery (FIG. 1), the visual display of quantitative information (FIG. 2; TABLES 1 AND 2), and the application of visuals to communicate in both teaching and research. These images extend our ability to see across many scales of observation (planetary to atomic) and over time intervals inaccessible to direct human observation (e.g. computational modeling of processes from femtoseconds to billions of years). Visual display of data is a powerful tool for cognition, facilitating comprehension, learning, and memory (e.g. Levie and Lentz 1982; Tversky 1995; Tversky et al. 2002). In addition, visuals are used as a key to problem solving (e.g. determining the reaction path on a phase diagram) and to test hypotheses (e.g. by graphically representing relationships to determine cause and effect; Tufte 1997). Well-designed graphics can accelerate data transfer (i.e. the amount of information transferred at a single time) and provide a second mode to convey information (i.e. a combination of text and visual communication is better than a single mode; e.g. Tversky et al. 2002). Computational models of complex Earth processes may produce gigabytes or terabytes of data that can only be analyzed, interpreted, and comprehended by utilizing computer visualization methods.

Each of these visual depictions requires a special set of cognitive skills to interpret and understand. While these skills may be intuitive to experts (professors and technical workers) in the field, non-experts (students and non-technical employees) may lack the prerequisites necessary to extract meaning from the representation if they must understand how the visuals are created and how to appropriately use and interpret them. This, in turn,
creates additional barriers to communication and learning. Because the preferred learning style of over 60% of students is visual (e.g. Felder and Spurlin 2005; Boyle 2007), visual literacy is essential. To think like a scientist requires visual literacy, a skill that is continually acquired (Stonehill 1994). “People learn to do well what they practice doing” (AAAS 1996).

As a result, teaching visual literacy is necessary because it is as fundamental to our discipline as is our discipline’s vocabulary. The ability to know what, and what not, to look for and to derive meaning from in visual representations are skills that are practiced and valued across the MPG disciplines and can be used to teach attributes of lifelong learning (see Wirth 2007). But do we use methods that help students develop skills of visual literacy? What do we know about the effectiveness of visual representations in teaching and in communicating during our professional presentations?

**VISUAL LITERACY**

For any type of visual representation, the associated learning and communication derive from prior knowledge and experience (e.g. Larkin and Simon 1987; MacEachren 2004). As we continually learn how to read visual signals, translate these into understandable information, form a mental image, and commit to long-term memory where it is stored as knowledge, visual literacy gradually develops (e.g. Larkin and Simon 1987; Stonehill 1994; Perkins 2007). This visual memory is then invoked to analyze new data structures, to recognize relevant information, and to draw inferences for interpretation and understanding (e.g. Larkin and Simon 1987; Barry et al. 2002).

Consequently, in a given discipline experts and non-experts do not “see” equivalent meanings in the same visual. The information conveyed to each audience is vastly different because of the requirements for prior knowledge, association, and inference (e.g. Larkin and Simon 1987). To underscore the non-equivalence in “seeing” a single image, consider an unlabeled polished rock slab containing several copper-bearing minerals (FIG. 3A). A beginning geology student might “see” the cross-cutting relationships and recognize that there are different minerals. A second-year mineralogy student might recognize these minerals by color and determine the sequence of formation. A third-year geochemistry student, or an expert, might infer the decrease in log \( P_{CO2} \) of the fluid phase as required by the transition from azurite to malachite (FIG. 3B). To evaluate the level of insight and to identify the appropriate use of visuals, specific assignments can be developed that require visual interpretation. This recognition of non-equivalence is especially relevant as our research and teaching become increasingly multidisciplinary.

Awareness of prior knowledge and the need for a visual understanding are critical when developing and utilizing visuals for teaching (see also discussion of constructivist theory of learning in Manduca 2007, Perkins 2007, and Wirth 2007). Otherwise, one is unable to recognize relevant information, the visual representation is largely meaningless, and learning fails. One such example is the high-resolution transmission electron microscope (HRTEM) photomicrographs included in some introductory mineralogy books. To view and accurately interpret these images requires an understanding of (1) how crystals are constructed (e.g. crystal structures, symmetry, axes, periodicity), (2) the analytical technique and acquisition of the data to supply context, (3) the projection of a 3D image onto a 2D surface, (4) the meaning of black and white in the image, (5) the usual appearance of this mineral in HRTEM, and (6) how to differentiate “atypical” features from the “typical” features

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**Figure 2**

Space is used to organize data that are not inherently spatial, such as in this REE diagram (modified after Sorensen et al. 2006). Symbol sizes include errors. For these types of graphical representations, pattern recognition is commonly the skill required for understanding and interpretation. Exercises that compare and contrast several different patterns facilitate pattern recognition and develop skills needed to interpret non-spatial data. **Diagram courtesy of Dr. Sorena Sorensen, Smithsonian Institution**
of an HRTEM image. Although each of these aspects is easily understood and interpreted by an expert crystallographer, to a non-expert HRTEM photographs may appear to be nondescript black and white clusters with little relevance. Instructors can use these images more effectively by adding a superimposed crystal structure and thus address the high level of background required by 1, 4, 5, and 6, above (FIG. 4). Together with a concomitant verbal explanation of the visual, and perhaps a physical structure model, the non-expert gains the visual literacy to interpret and appreciate these complex images—the natural progression from simple to complex.

To bring non-experts to the expert level, visual literacy must be practiced at appropriately more complex levels during the teaching and learning cycle. This is clear when one considers the range of visuals, their uses (see Introduction), and the inferences needed to understand, interpret, and communicate Earth’s processes and products. These visuals portray both (1) spatial data, where space is used to represent changes in inherently spatial data (TABLE 1), and (2) non-spatial data, which is organized in a spatial context (Tversky 2004; TABLE 2). For many of these data-rich spatial representations, no number of words could capture the relations displayed in the images (e.g. FIG. 5). In some cases, there is considerable visual “noise” (e.g. in a landscape or thin section), which requires one to make cognitive decisions about what to “see” and what is irrelevant to the question (e.g. Reynolds et al. 2006). Could this explain why so few passengers in the window seat of an aircraft observe the ground below? Expert geologists can readily recognize and interpret the geologic features in the vast landscape below, but non-experts are awash in visual clutter. For non-spatial representations, it is commonly the pattern developed in the spatial arrangement that becomes the basis for communication and interpretation of the data (e.g. a powder XRD pattern or an isochron plot; FIG. 2). Thus, knowing what to look for and what to ignore in the visual are also important attributes that must be specifically taught.

With careful and detailed explanations complementing each new diagram or representation, the fundamentals of visual messages and objects are conveyed. When each representation is constructed with enlightening annotations and when assignments are specifically generated to develop
mize communication and facilitate teaching visual literacy. These principles include, in part, constructing diagrams that are task oriented and follow the “congruence” and “apprehension” principles (e.g. Larkin and Simon 1987; Tversky et al. 2002), which are defined and briefly discussed below.

**Keep it Simple and Task Oriented**

Studies have shown that one focuses attention on that portion of the diagram specific to the task, directing more attention to salient features (e.g. Larkin and Simon 1987). Consequently, it is necessary to identify the goal and task of the visual and to develop the visual in this context (i.e. to test a specific relationship, to motivate, to engage, to test an hypothesis). The more one knows what to look for, the more attention focusing increases (see also Johnson and Reynolds 2005). Thus, simplified graphics may communicate more effectively than realistic representations (e.g. Dwyer 1978; Tufte 1983; Tversky et al. 2002). To strengthen visual thinking, assignments requiring the use of various task-specific visuals (e.g. problem solving, hypothesis testing) can be given. Those graphics that are goal oriented and provide a clear depiction of a single concept are the most valuable.

**Congruence Principle**

Diagrams constructed to be consistent with physical reality are more intuitive and more readily accessible (e.g. Tufte 1997; Tversky et al. 2002). This congruence explains why some pressure-temperature (P-T) diagrams have the origin on an x, y relational plot at the upper left with P increasing downward, congruent with Earth’s physical system. This principle also requires that if one names a formation “the red unit,” the unit be colored red on a diagram (see Fig. 3). Congruence is also embedded in the principle of “graphical integrity,” that is, the effect in the data should match the effect portrayed graphically (developed and discussed by Tufte 1983). The literature contains numerous instances of overemphasizing a conclusion by enhancing a graphic. For example in a recently published article, circle sizes were used to portray the area \( A = \pi \times r^2 \) burned by various fires (Running 2006). However, the circle representing a 200,000 ha fire is twice the diameter (radius) of a 100,000 ha fire \( (t_1) \), although it should have been \( 1.41 \times t_1 \). Thus, the resulting graphic portrayal is larger than that shown by the data.

**Apprehension Principle**

Visually familiar forms are more “accurately perceived and comprehended” (the apprehension principle of Tversky et al. 2002). If a new visual representation that is not accessible via prior knowledge is presented, communication typically fails as the observer searches for meaning. The response to these abstract visuals can be confusion, a sense of being overwhelmed, or worse, distrust. Such negative responses decrease motivation and learning. With computational experiments prevalent in our disciplines, mapping of data into new graphical spaces using visualization techniques provides a mechanism for discovery and data analysis. However, these new depictions present unique challenges for presentation and communication.

One such example is shown in **Figure 6**. To communicate the duration and spatial region of heating surrounding a pluton as calculated from a series of computational experiments, a 3D visualization was developed (Dutrow et al. 2003). This graphic was constructed from individual x−y planes extracted from a 3D volume at specific z coordinates \((z')\) for a set of times \( t_1, t_2, \ldots, t_n \) (Fig. 6A). The slices were then stacked vertically to depict the \( x−y−z' \) region through time, with time increasing upward along the vertical axes. Once compiled, colored isosurfaces contour and highlight regions of heating (red) and cooling (blue), and mark the...
change from one regime to another (beige, \( dx/dt = 0 \)). By developing these types of images for a series of calculations, the impact of various controlling parameters on the duration of heating (or cooling) can be observed at a specific \( z' \) (cf. Figs. 6B, 6C, 6D). While this graphic revealed new behavior and provided insight to the analyst, it had the undesired consequence of invoking negative responses when presented to an audience. These ranged from “Can you explain that again?” to “I don’t trust fancy graphics.” Such negative reactions inhibit effective communication and impede learning.

These graphics fail the apprehension principle, in part, because they are newly developed depictions. The observers (some experts) had no prior knowledge with which to interpret the figures, resulting in the negative emotional responses. This highlights the point that it takes time for an audience, including our students, to absorb the visual nuances and understand the relationships. However, despite being poor presentation graphics, they are excellent analysis graphics.

**Animations Commonly Fail the Apprehension Principle**

With the ease of creating movies and their coherence with time (time is used to portray time), geoscience animations are now widely used for portraying the evolution of systems, for providing multiple viewpoints by repositioning an object within the observer’s frame, and for teaching processes that occur over unattainable time scales. Animations capture the fine as well as the coarse features of a process, not apparent from a few motionless graphics (e.g. Tversky et al. 2002.) Because more information is contained in an animation, superior communication can result.

Although animations may be appealing, their ability to improve communication and learning is equivocal (e.g. Tversky et al. 2002 and references therein). While they maintain coherence with time, they commonly fail the apprehension principle. Many animations involve multidimensional data representations of a complex system. The graphical illustration used to portray the system may be new and abstract; thus not only are the concepts embedded in the animations difficult, there is the compounded complexity of both new concept and new data display that requires new inference. Additional difficulties may arise because animations commonly lack scales (spatial and temporal), orientations, and annotations. They may be too complex and, with saturated rainbow color palates, may be unpleasant for viewing. Only experts in the field may adequately comprehend the elegant visual and the underlying causality.

Research does suggest that simple schematic animations, removing non-task-oriented features, are better than complex, realistic animations (e.g. Tversky et al. 2002.) These researchers also found that animations must be sufficiently slow and clear to allow movements, timing, and relationships to be perceived. Adding a series of stationary images provides easily accessible, but restricted, information for extended viewing, comparison, and comprehension of the fleeting animation.

**Figure 6** Visualizations displaying regions of heating and cooling located 0.5 km above a pluton through time. (A) Diagrams are constructed by extracting an x-y slice from a 3D volume at \( z' \) for specific time intervals \((t_1 \ldots t_n)\), stacking planes with time increasing vertically, and coloring the volume with isosurfaces to highlight regions of heating and cooling. (B–D) Variations in the diagrams developed by this method result from using different permeability and geothermal gradient parameters in the calculations. While these visualizations are excellent analysis graphics, they fail the apprehension principle for effective communication because of their unfamiliar form.

Interactivity is known to facilitate learning (e.g. Schnitz and Grzondzeil 1999). The ability to stop, start, review, and view different perspectives increases the utility of an animation. This self-guided exploration of processes and products is different from choosing among a number of “canned” options that may not actually be interactive. Are students simply being entertained by animations that enable “passive” learning, or can the visualizations be effectively incorporated into active-, discovery-, and inquiry-oriented exercises? Providing the opportunity for students to construct animations develops insight into the topic’s essential steps; otherwise the sequence of events portrayed would not mesh together and flow continuously (K. Kastens pers. comm.) Because of the time and cost to produce these learning aids and the need to sacrifice valuable class time to appropriately explain and comprehend them, great care must be taken to assure learning occurs. Research into how students view and learn from animations, if they learn at all, is a growing field of scholarship (e.g. http://serc.carleton.edu/files/research_on_learning/ROL0504_2004.pdf), and contributions from the geosciences should be beneficial to this effort.

Bearing in mind these few principles, visuals for teaching can be developed to clearly communicate a message and assure that it is accurately perceived and quickly comprehended. These visuals can then be used in a variety of teaching exercises to strengthen visual literacy. Suggestions for using visuals are found in the figure captions and include such tasks as compare and contrast, sketch and label, interpret, generate hypotheses, and predict behavior of systems. (Additional exercises can be found at...
Maximize Ink Used for Data

To draw attention to the relevant purpose and to help “see” meaning, ink in graphics should be devoted to display of data or “that portion of the non-erasable essence of a graphic” (Tufte 1983; cf. Chabris and Kosslyn 2005). An X-ray powder diffraction pattern and the many spectra of, for example, counts versus energy use most ink to convey data (“data ink”). In turn, ink without information (“chartjunk” of Tufte 1983) causes visual clutter (cf. Figs. 7A, 7B). Commonly, this occurs when analysis graphics are used (inappropriately) for presentation. Chartjunk has proliferated as computer drafting allows the developer to easily add “fill patterns.” Too often, these are constructed from parallel black lines that activate the intervening white space resulting in vibration and movement that makes the visual difficult to observe (Tufte 1990). As Tufte highlights, this is a useful attribute for artists (www.haring.com) but detrimental for scientific communication. Removing visual clutter focuses attention on the relevant data, minimizes translation and interpretation time, and produces a more informative diagram (Fig. 7B).

Maximize Data Density

It follows that space in graphics is best used for the display of data (Fig. 8). Maximizing the amount of data over the area covered by the graphic also maximizes information transfer. The discipline of geology creates some of the most data-dense images, such as topographic maps, digital elevation models (DEMs), and overlays of geologic maps onto digital elevation models (Fig. 8). These representations allow unprecedented amounts of data to be communicated within a single eye span.

Color

Color can be a powerful tool in visual communication. Whether using color to attract and maintain the viewer’s attention, to enliven and motivate, or to differentiate data elements, deliberate and careful use of color is essential. Colors of nature rather than saturated color schemes reduce tension and minimize graphical puzzles (e.g. Tufte 1990; Light and Bartlein 2004). A superb use of color is found in the topographic map (Tufte 1983), where color differentiates the underlying substrate of glaciers (white), rivers (blue), forested areas (green), and rocky areas (brown). These colors also imitate reality (coherence principle) and improve the aesthetic qualities, while dark contour lines add a further dimension by providing altitude and steepness (e.g. Tufte 1983). Such clarity improves visual messaging, and the use of multiple methods to convey the same information allows different audiences to be reached.

Placing saturated colors from opposite ends of the visible spectrum near one another (or on one another), such as saturated red next to blue, results in a fuzzy, blurry image because our eyes cannot focus on these widely different wavelengths at once. About 15% of the population has deficiencies in color recognition, and critical data should not be encoded in green and red (http://vis.sdsc.edu).

Explain the Data, Add Annotations

Because we manipulate data into forms that are familiar or functional in an attempt to understand the heterogeneous, open, and complex world around us, a clear understanding of the graphical input is necessary to establish limits of certainty and credibility. This is extremely important for computational models of complex systems, i.e. explain the boundary conditions, simplifying assumptions, limitations, etc. (e.g. Figs. 4, 6).

Keep Quantitative Data Quantitative

Numerical data, whether derived from a computer simulation or from a laboratory measurement, are key to understanding and communicating MPG processes. As such, the display of quantitative data should remain quantitative by including error bars and scales, grids, dimensional aspects, and reference frames when appropriate (e.g. Tufte 1983). These annotations allow a quicker interpretation and a more complete understanding of the image (e.g. Figs. 4, 5). Every field geologist takes photographs with a scale specifically to maintain the quantitative aspect of the image.
Creating eye-catching, message-rich visuals engages students in the exploration and development of visual communication. When visuals inspire, they can tap into positive emotions and improve learning. “The most important visuals in science are the images in our minds” (Barry et al. 2002).

SUMMARY

Visuals are essential for teaching, problem solving, hypothesis testing, and communicating in the MPG disciplines. Teaching non-experts to “see” the visual language of the experts is an essential element of learning and a foundation for visual literacy. By incorporating specific explanations as new visuals are introduced into our courses, visual literacy is attained in parallel with conceptual material. Alternatively, one can specifically design a communications course that encompasses visual literacy (e.g. http://geol.lsu.edu/dutrow/presn).

Research on learning from visuals provides a firm foundation for instructors to improve learning and communication through effective visuals (problem sets, visual aids). When we use appropriate annotations, scaffold layers of meaning and interpretation, and incorporate elements and concepts of good design, visual literacy is more easily attained. This challenges us to design appropriate, effective, task-oriented visuals and animations that utilize prior knowledge and impart meaning in appropriate context. In addition, teaching why these visuals communicate efficiently enables students to develop the necessary skills to create their own visuals (e.g. instructors can discuss font size, labels, data density, relevance of ink, etc.). Visual literacy can be an explicitly stated course goal, and activities can be chosen to allow direct assessment. Assignments and exams can include specific questions requiring use of these visuals. In concert with this, instructors can design appropriate interactive learning activities, not simply passive watching, that allow hypothesis testing and discovery, and also inspire inquiry.

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REFERENCES


