Elements Author Guidelines

Thank you for accepting the invitation to write for Elements magazine! We hope that you will find it a rewarding experience. The Elements team looks forward to partnering with you over the coming months to bring your articles into the hands of over 17,000 readers and 1000+ libraries worldwide.

Writing for *Elements* differs significantly from writing for the technical scientific journals with which you are familiar. **Please read these instructions carefully before you begin writing your article.**

What is unique to writing for *Elements*?

Time

Elements adheres to a **tight production schedule** without the freedom to hold back, swap, or accelerate issues. It is necessary that you meet the required deadlines provided to you by the Guest Editors.

Space

You have a **fixed space** (defined by the number of words) for your article. Consider this as your "canvas" and design your article from the outset to fit this space, including illustrations. Do not plan to shorten your paper after review. Typical final printed six-page articles have ~4000 words of text, plus 3–6 figures/tables, acknowledgments, figure captions, and references. If you have fewer figures/tables, you can have more text. The maximum number of references is limited to 30. This is a hard number that cannot be negotiated. Similarly, the abstract is limited to a maximum of 120 words.

Target

The **target audience** of *Elements* is broader than that of a typical research paper. The audience includes academic and industrial scientists in a variety of disciplines, students, popular science writers, officials of funding agencies, and policy makers. This is your opportunity to promote the excitement of your field to a diverse readership. Writing at a level that is accessible and pleasurable for this audience—while remaining up-to-date, scholarly, and rigorous—can be a challenging task. We encourage you to stand back from what you have written and consider whether its level is appropriate for *Elements*' readership, particularly limit your use of specialized words and jargon. Remember, *Elements* is published in full color, so please use exciting and colorful illustrations that draw the casual reader into your article.

Review Cycles

Each *Elements* article goes through multiple revision cycles. First, the article will be evaluated for scientific content by the Guest Editor(s) and two (or more) independent expert reviewers. Second, the Principal Editor assigned to the issue will review the article in terms of suitability for *Elements*' readership, style, and context with the rest of the articles in the issue. The third review cycle occurs when the article is copyedited for language usage, grammar, and readability. Finally, authors will review a set of proofs. These multiple cycles ensure that the review article will be well received by the *Elements* readership and be of interest to the larger scientific community.

Writing Your Article

Authorship

Elements articles are relatively short reviews by acknowledged experts. We expect that most articles will have a single lead author, and not more than four co-authors. You can refer to close collaborators in the text or in an Acknowledgements section at the end of your article.

Title

Use a short, punchy title without technical terms that will attract non-expert readers.

Title Image

Elements uses a banner image or photograph behind the title that is related to the content. Please provide an eye-catching image for this space. Image should be in color, have 300 dpi, and be at least 2200 × 750 pixels in size.

Abstract

The abstract (<120 words) should summarize the content of your article so that (1) readers can determine their interest in reading further, (2) literature searches will find the article in relevant searches, (3) a broad audience can appreciate the significance of the article. The abstract should be complete and understandable in itself, and should avoid technical words unsuitable for a wide audience. Do not include references, figures, tables, or equations in the abstract.

Keywords

Please provide at least four keywords that will enhance access to your paper. *Elements* is indexed by Google and other online search engines so good keywords help readers find your article.

Language Guidelines

- Use either American or British English spelling and conventions, but please be consistent and do not combine the two.
- Consider your target audience described on p. 1 with great care, and where appropriate give your article a tutorial character.
- Avoid jargon and acronyms. Terms unfamiliar to the non-specialist should be defined or explained clearly in plain language. To avoid repetition in issues where the same specialized terms, acronyms, or mathematical conventions are introduced repeatedly, the Guest Editors may decide to include a general explanatory section in their introductory article—or as a separate 1–2 page *Elements* Toolkit, thus releasing space for the other articles.
- Carefully consider whether your language choice is comprehensible to our wide target audience. Be especially careful where ordinary words or phrases,

such as "enrichment," "productivity", or "ultra-high pressure" have been given limited technical meanings by specialist groups.

Manuscript Length

- *Elements* articles should fit well onto six printed pages. Manuscripts that are longer than the space assigned are not acceptable.
  - A single printed page in *Elements* contains ~1000 words. A figure or table that fills ¼ of page in size accounts for approximately 250 effective words.
  - Please use the provided Article Length Estimation Calculator.

Manuscript Style

- Please follow formatting guidelines provided in the Author Template at the end of this document.
- Please use continuous line numbers.
- *Elements* uses three heading levels
  - **BOLD CAPITALS**
  - ***Bold italics***
  - *Normal italics* set into the first line of text.
- Use standard SI units.
- Define terms in mathematical equations. If possible use symbols that correspond with common usage in *American Mineralogist*, *Geochimica et Cosmochimica Acta*, or *Clays and Clay Minerals*.
- We follow the recommendations of the International Mineralogical Association with regards to mineral nomenclature and the spelling of mineral names. See http://www.mineralogicalassociation.ca/doc/abstracts/ima98/ima98.htm

Tables and Figures

Take advantage of the fact that *Elements* will be published in color. Create striking figures. Authors are encouraged to read Barb Dutrow's article in *Elements* volume 3, issue 2, p. 119–126, for tips on producing effective figures.

- Please use the following naming convention for your figures and tables: First author's last name_Fig# (e.g., Green_Fig1.jpg)
- Create high-resolution images (300 dpi at published size) or line drawings (preferably colored) at 600 dpi.
- Save color in CYMK. *Remember that almost 10% of the population is color blind*—combining blue and red (or orange) fit well, whereas red + green is to be avoided.
- Embed all fonts.
- Preferred file formats: PDF, JPG, TIFF, AI, EPS
- Captions: provide sufficient detail in the caption (with each panel described individually) so that a reader can understand the figure without having to refer back to the associated text. Describe all colors, elements, and features.
- Image sources must be listed. Please see copyright information on next page.

References

Space restrictions do not allow extensive lists of references. A maximum of 30 references should be provided, many of which might be to technical reviews in the field. *Elements* has a reference style involving minimum punctuation and no changes of font. Examples are given in the Article Template and on the final page of this document.

- References should only be to titles published or accepted for publication. Personal communications should be noted only in the text, e.g. (pers com, JC Maxwell 2004).
- In the text, references should be cited by author and year, e.g. (Newton 2004); (Newton and Darwin 2004); Newton et al. (in press). List in order of publication (youngest to oldest).
- The reference list should include all works cited in the text, figures, and tables. Citations should be in alphabetical order with respect to last name. With identical names, arrange papers numerically started with the oldest. Papers with more than two authors (which will appear as 'et al.' in the text) arrange in order of first author and year of publication. Where more than one paper in a single year has the same authorship, the reference year should be amended with an a, b, c, etc. (e.g. 2004a, 2004b) both in the text and the reference list.
- Journal titles should be written out in full (e.g. Geochimica et Cosmochimica Acta, Contributions to Mineralogy and Petrology).

Articles

Sio CKI, Dauphas N (2017) Thermal and crystallization histories of magmatic bodies by Monte Carlo inversion of Mg-Fe isotopic profiles in olivine. Geology 45: 67-70, doi: 10.1130/G38056.1

Sio CKI and 5 coauthors (2013) Discerning crystal growth from diffusion profiles in zoned olivine by in situ Mg–Fe isotopic analyses. Geochimica et Cosmochimica Acta 123: 302-321, doi: 10.1016/j.gca.2013.06.008

Chapter in a Book

Schoene B (2014) U–Th–Pb geochronology. In: Turekian HDHK (ed) Treatise on Geochemistry, Volume 4 (Second Edition). Elsevier, Oxford, pp 341-378, doi: 10.1016/B978-0-08-095975- 7.00310-7

Book

Harrison TM (2020) Hadean Earth. Springer International Publishing, 291 pp, doi: 10.1007/978-3-030-46687-9

Author Biographies

Each issue of *Elements* contains a "Meet the Authors" page, which highlights the authors of the thematic articles. When submitting your initial manuscript to the Guest Editors, each author should also provide:

- A short biographical sketch (<100 words) written in the third person;
- A headshot photograph

Supplemental Material

As an author, your priority is to make your article in the magazine complete and comprehensive. Nevertheless, there may be a need to publish supplemental material such as teaching exercises, videos, data sets, etc. If this is of interest to you, please contact your Guest Editors and the Executive Editor.

Copyrights and Permissions

Ideally, the illustrations, images, and tables that you publish will be new material designed specifically for the *Elements* audience. However, it is also possible that you will want to reuse or modify previously published figures and or tables.

As the author, you are responsible for obtaining permission to reuse or modify existing figures and/or tables. This is also true for material that you have authored. Do not assume that work with your name on it is owned by you! Each publishing house has different standards and you should verify the copyright restrictions before reuse of a figure or table.

You are also responsible for any charges associated with these permissions. *Please use extra caution when using figures found on the internet.* There are often royalties or copyright restrictions associated with their usage. If you have questions about whether you need to obtain permission or how to obtain permission, please contact the Executive Editor.

Don't wait until the last minute to obtain permission.
Please complete this process while you are writing your article.

DO YOU NEED PERMISSION?

- YES when you make a copy (photocopy, digital scan, download) of published figure or table or image. Request permission and add the copyright permission information in the figure caption.
- YES when you make a copy (photocopy, digital scan, download) and make minor changes to the fonts to make it look nicer or add a single data point, etc. Request permission and add the copyright permission information in the figure caption.
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- NO if your figure is a significantly modified version of a figure that was previously published. These modifications include significant redrawing schematics, addition of data, omission of data, etc. In this case, give reference to the figure inspiration by adding a phrase such as (modified after Duff et al. 1999).
- NO if the figure is an original work of yours not previously published elsewhere.
- A special note about images on the internet: Do not assume that if you can download the image then it is free to use. Carefully check to see if there are copyright restrictions about their usage.

I NEED COPYRIGHT PERMISSION, NOW WHAT DO I DO?

- You (not the Guest Editors nor the Executive Editor!) must obtain permission from the publisher and/or copyright holder.
- Some publishing houses will charge you to use a figure. You are responsible for any charges.
- Permission must be granted prior to publication in Elements. Request permission from the copyright owner when you decide to use the figure/table in your article. The earlier, the better!
- To obtain permission, use the online submission forms available at the publisher web sites. Often these forms can be found as “Get Permission” links from an article web page or through the Copyright Clearance Center.
- Send copies of the authorized permissions to the Executive Editor.
- Please compile a list of the permission requests you have made and send it to the Executive Editor. Indicate which permissions have been received and those that are pending.

ACKNOWLEDGING COPIED FIGURES & TABLES

All figures/tables requiring permission MUST have its copyright information acknowledged in the caption of that figure/table using the following format: [Used by permission of Publishing Company, from Author (YEAR)].

Checklist for *Elements* Authors and Guest Editors

Please confirm the following items for EACH thematic article in your issue of *Elements*.

☑	**ARTICLE ITEMS/CONTENT**
☐	Title – short, engaging, catchy
☐	Author(s) – full name, affiliation address, and email included
☐	Abstract • maximum 120 words • this is a summary of the article—not an intro paragraph
☐	Keywords – 4–6 words
☐	Text style • Written as a magazine review article, not a scientific journal article. • Does the article present a good introduction to this subject for someone unfamiliar with the topic? • Can it be understood by an upper-level undergraduate student? • Is there a logical "flow" to the article? Does it move smoothly from one paragraph/section to the next? • Is it too technical? Boring? Wordy?
☐	Jargon (words used only by a specific group/discipline) • Should be avoided • If used, check that the words are clearly defined using simple language
☐	Figures • High-resolution (fonts are smooth, concise lines/arrows, crisp images, etc.) • Eye catching, colorful, informative • Color usage (Can the color blind discern the relevant features? Avoid usage of color as the sole mechanism for conveying information.) • Title image (banner) provided
☐	Figure captions • Address each panel in the figure • Figure & caption can stand alone without associated text
☐	References • Maximum 30 • Confirm that any references in tables/figures are included in reference list
☐	Word count (for six-page article) • Maximum = 6100 words, including all the text, abstract, titles, acknowledgments, references, captions, and 200–250 words per figure/table
	OTHER ASSOCIATED ITEMS
☐	Biographical sketch and photo provided for each author
☐	Signed forms • License to publish • Pro forma invoice (if contributing to costs of your article or ordering extra copies)

Article Template: Your Title Should Be Short and Punchy

Author A. Ready[1] and Author B. Timely[2]

ABSTRACT

Your abstract should no more than **120 words**. It should give an accurate description of the article and state the main messages you would like the reader to come away with. The abstract also acts as a come-on: if it is clear and sharp, readers will be more likely to trust the findings and read on. As many *Elements* readers are undergraduate students, interested mineral collectors, scientists working in industry, high school teachers interested in self-educating in the Earth and planetary sciences, and journalists—try to convey the main messages of your article in terms accessible to non-specialist readers.

KEYWORDS: choose at least four keywords for indexing purposes, separated by semi-colons.

INTRODUCTION

In this template, we will guide you through the writing of your article. We suggest you start with this file to write your article. This way, you will be using the right level headings, right font size, etc. We thank you for the attention you will pay to these instructions.

WRITING YOUR ARTICLE

Naming of File

[1] Company/Institution/Department for author 1
City, State/Province Zip/Mailing Code, Country
E-mail:
[2] Company/Institution/Department for author 2
City, State/Province Zip/Mailing Code, Country
E-mail:

Please use the following convention to name the file of your article – LASTNAME_v#n#, where the # symbols refer to the volume and issue numbers. Do not use dots. You might want to add the version number or the date at the end.

Specifications

- Use 1.5 line spacing
- No right justification, no indent at beginning of paragraph.
- Please use continuous line numbers.

Levels

We use three levels of heading:

- **CAPITALIZED, BOLD, AND SIZE-14 FONT**
- ***First Word Capitalized, Italicized, and Size-12 Font***
- *Sentence case, italicized, and Size-11 font, in line with the paragraph.*

WRITING FOR *ELEMENTS*

You will be given a carefully defined space by your Guest Editors. This is your "canvas" and you should design your paper from the outset to fit this space, including illustrations. Do not expect to shorten your paper after review. We often find that authors wish to increase the length of their papers after review in order to address potential reviewer criticism, so a first version slightly shorter than the allotted space may be desirable

Word Count

One of the challenges of writing for *Elements* is to adhere to a strict word count. Only under exceptional circumstances will a manuscript exceed six published pages. This translates into 6,100 words equivalent (which includes all the text, headings, figure/table captions, references, and figures/tables). Estimate that each figure/table equals 250 words. Please consider using the Article Length Calculator Excel file that your Guest Editors will provide.

American or British Style?

We accept both styles of English. When an author uses a mix of both styles, we will choose American style.

References

You are limited to **30 references maximum**. You are not expected to reference every statement.

This is how you should refer to an article in your text (Brantley 2005). Please note that there is no comma between last name and year (Brantley and Rogers 2006; Brantley et al. 2007). If you list several references, do so in chronological order starting with the oldest one first. If the reference is part of the sentence, do it this way: Tremblay et al. (2007) prepared a master file to take the guesswork out of authors. Tremblay et al. (2005, 2007) suggest that you review the instructions to authors for examples. This is how you should refer to another article in your issue (Volkmann 2022 this issue).

We use a reference style similar to that of *Contributions to Mineralogy and Petrology*. Journal names are written out, not abbreviated. Include a full doi with the reference.

Mineral Names

Make sure you use mineral names and formula approved by the International Mineralogical Association. Check https://rruff.info/ima/

Level of Writing

One article that hit the mark perfectly in terms of level of writing is Hochella and Madden (2005) and we encourage you to read it.

The Review Process

You have completed your first draft, reread it, and asked a colleague (or one of your students) to review it informally and you are within your budgeted word count: your article is now ready to be sent to the guest editor team which will have it reviewed by two (or more) external reviewers, but not until the Guest Editors have themselves read your manuscript to ensure it is ready to be sent out for external review. If not, they will return it to you for further work. If yes, they will send it out for external review.

After external review, your manuscript will be returned to you by the Guest Editor team with instructions for how to revise your manuscript according to the external reviewer reports, which you will also receive, and their own reviews of your article and you will revise your manuscript accordingly. You will reiterate this process until the Guest Editors are satisfied with your revised article. It will then be sent by the Guest Editors to the Principal Editor in charge of your issue, who will now read, edit, and otherwise annotate your manuscript and, when done, return it to the Guest Editors who will return it to you for a final, or several, rounds of further revision until the Principal Editor is satisfied. Send a Word version of your article with your figures pasted at the end of the article. You may also send a PDF version as well.

Figures

A maximum of one figure per page is a good target. We encourage you to read Dutrow (2007) regarding principles for good use of color and for easy reading of figures. Vector files are preferable (.ai, .eps), but .jpg, .tiff, and .pdf work well too. Provide an image that can be used as a background for the title of your article. We refer to it as a banner. Images should be 300 dpi and a minimum of 2200 × 750 pixels in size.

Copyright Issues

You are responsible for securing the permission to reprint a figure. It is not acceptable to reproduce a caption from an article already published, even if you were one of the authors of that paper. Please see the documentation above regarding permission to reproduce/modify images.

What's Your Fog Index?

The Fog Index measures the readability of a text. In a sample of writing, you count the number of words with more than three syllables and the number of words per sentence on average. The higher your fog index, the harder to read. Check your fog index at https://readabilityformulas.com/free-readability-formula-tests.php. To increase the readability of your text, break down long sentences and choose shorter words when possible.

Pruning Your Text

Watch out for padded words! Beware of sentences beginning by "It is well known that..." and "It is estimated that..." We suggest you do a global search for "ly" and "very", and ask yourself: is this adverb necessary? You might be quite surprised at the number of words you can prune from your text.

Conclusions

Before you start writing, we strongly encourage you to read this entire manual. It will betime well invested, we promise.

REFERENCES

Elements uses a "light" style for its citations of published work—in particular, a minimal use of punctuation. In the interest of saving space, when a publication is written by six or more authors, the citation in the References section gives the name of only the first author, the remaining being referred to as "and xx coauthors." For publications with five authors or less, all names are given in the citation. See below and also look at recent issues for Elements' protocol on style and the hierarchy of listing. When available, the doi (document object identifier) hyperlink is also included. Note that for references only, the hyphen is used for page ranges (not the otherwise correct en dash). Please be sure to include the reference DOI as indicated in the following examples.

Articles

Sio CKI, Dauphas N (2017) Thermal and crystallization histories of magmatic bodies by Monte Carlo inversion of Mg-Fe isotopic profiles in olivine. Geology 45: 67-70, doi: 10.1130/G38056.1

Sio CKI and 5 coauthors (2013) Discerning crystal growth from diffusion profiles in zoned olivine by in situ Mg–Fe isotopic analyses. Geochimica et Cosmochimica Acta 123: 302-321, doi: 10.1016/j.gca.2013.06.008

Chapter in a Book

Schoene B (2014) U–Th–Pb geochronology. In: Turekian HDHK (ed) Treatise on Geochemistry, Volume 4 (Second Edition). Elsevier, Oxford, pp 341-378, doi: 10.1016/B978-0-08-095975-7.00310-7

Book

Harrison TM (2020) Hadean Earth. Springer International Publishing, 291 pp, doi: 10.1007/978-3-030-46687-9

Visual Communication: Do You See What I See?

Barbara L. Dutrow*

Visual displays of data, images of subatomic to planetary-scale features, and animations of geological processes are widely used to enrich our disciplines. However, their communicative power may be dramatically different to a student and to an expert because of the need for prior knowledge and inference when interpreting visuals. To "see" equivalent visual information, the non-expert must learn the visual language of the expert. Teaching visual literacy is important to instruction at all levels and is as fundamental to a discipline as its vocabulary. The underlying foundations of visual literacy and the recognition of what one "sees" and interprets in a visual depiction are critical for enhancing student learning and for effective communication in our visually rich discipline.

KEYWORDS: Teaching, visuals, visualization, visual communication, images

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 giga- to 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,

FIGURE 1 MODIS true-color image of the Florida Straits and the Bahama Banks, south of the US coast, February 2003, developed from RGB data at 250 m resolution. Dry land, land-usage patterns, and carbonate platforms are clearly visible in this image and can be used to teach spatial attributes of visuals. IMAGE COURTESY OF EARTH SCAN LABORATORY, LOUISIANA STATE UNIVERSITY, BATON ROUGE, AND SPACE SCIENCE AND ENGINEERING CENTER, UNIVERSITY OF WISCONSIN–MADISON

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TABLE 1 VISUALS THAT PORTRAY SPATIAL DATA – VISUAL REPRESENTATIONS THAT USE SPACE TO SHOW CHANGES IN INHERENTLY SPATIAL DATA

Visual	MPG example
RELATIONAL GRAPHICS	Element concentration in mineral as a function of distance e.g. x–y plots, x–t plots
PROJECTIONS	Stereographic projections of crystal faces
DATA MAPS	Geologic, topographic, DEMs, remotely sensed, elemental X-ray
IMAGES	Photographs – field, optical, CL, SEM, TEM, AFM, tomographs
ANIMATIONS	Progression of a feature or process through space and time
VIRTUAL ENVIRONMENTS	Software and hardware (e.g. CAVE, Immersadesk, Geowall), with complex human–computer interactions

TABLE 2 VISUALS PORTRAYING NON-SPATIAL DATA – VISUALS USED TO ORGANIZE DATA WITH NO SPATIAL CONTEXT

Visual	MPG example
WHORLS	Geologic timeline, concept maps
RELATIONAL GRAPHICS	REE diagrams, isochron plots, counts versus energy or intensity, X-ray diffractograms, phase diagrams, activity–activity, T–X, P–T diagrams
PROJECTIONS	Phase diagrams that project free energy surfaces onto a prescribed coordinate system
ANIMATIONS	Rotating crystal structures
VIRTUAL ENVIRONMENTS	Software and hardware (e.g. CAVE, Immersadesk, Geowall)

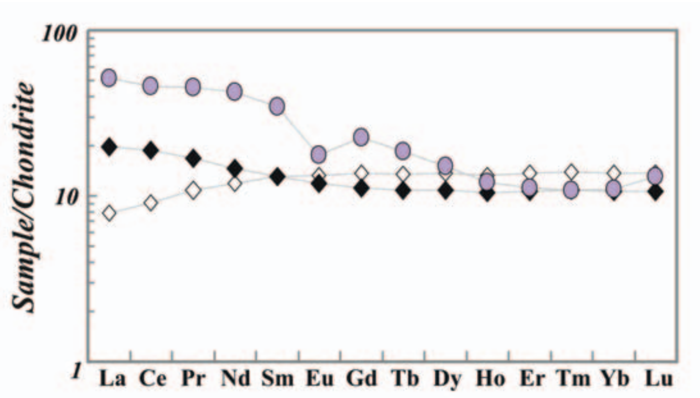

FIGURE 2 Space is used to organize data that are not inherently spatial, such as in this REE diagram (modified after Sorensen et al. 2006). Symbol sizes include errors. For these types of graphical representations, pattern recognition is commonly the skill required for understanding and interpretation. 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

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 1990).

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) photographs 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

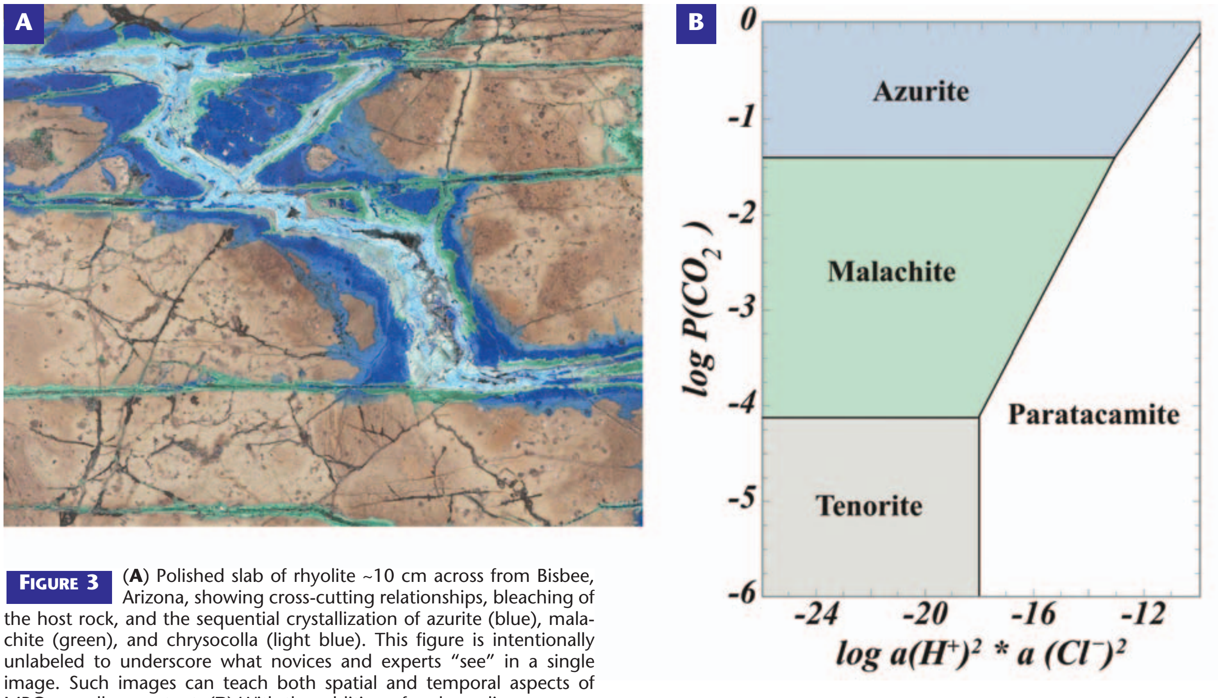

FIGURE 3 (**A**) Polished slab of rhyolite ~10 cm across from Bisbee, Arizona, showing cross-cutting relationships, bleaching of the host rock, and the sequential crystallization of azurite (blue), malachite (green), and chrysocolla (light blue). This figure is intentionally unlabeled to underscore what novices and experts "see" in a single image. Such images can teach both spatial and temporal aspects of MPG as well as content. (**B**) With the addition of a phase diagram, spatial and temporal sequences offer practice mapping of qualitative data acquired from (A) to non-spatial domains, which provide an additional method for interpretation. Relative stabilities of some copper-bearing minerals, colored to mimic reality and minimize cross-referencing, are shown by the 25°C, 1 bar activity–activity diagram (data from Woods and Garrels 1986). Asking students to interpret the image, at both the beginning and end of a course, allows assessment of learning and visual literacy. A complete laboratory exercise using these types of figures is found at http://serc.carleton.edu/NAGTWorkshops/petrology/teaching_examples/935.html, or from the author.

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

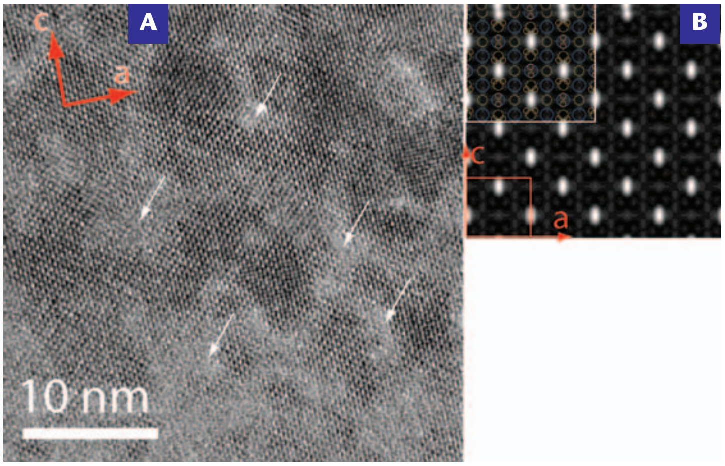

FIGURE 4 (**A**) High-resolution transmission electron microscope (HRTEM) image of a partially metamict zircon in a granitoid from Jack Hills, Australia, showing both periodic and aperiodic structure. Arrows indicate nanoscale amorphous domains, which were caused by recoil nuclei during alpha decay events of uranium. (**B**) Simulated HRTEM image of zircon from [010] at scherzer focus using MacTempas. The insert shows an overlay of atoms (circles) on the image (Si – yellow; Zr – blue; O – orange). The image is viewed along the *b* axis. Interpretation of this image requires significant prior knowledge. When viewed in conjunction with a ball and stick representation and a polyhedral model of the crystal structure, students develop skills to visually manipulate equivalent spaces by different imaging techniques. PHOTOGRAPH COURTESY OF DR. SATOSHI UTSUNOMIYA, UNIVERSITY OF MICHIGAN, ANN ARBOR

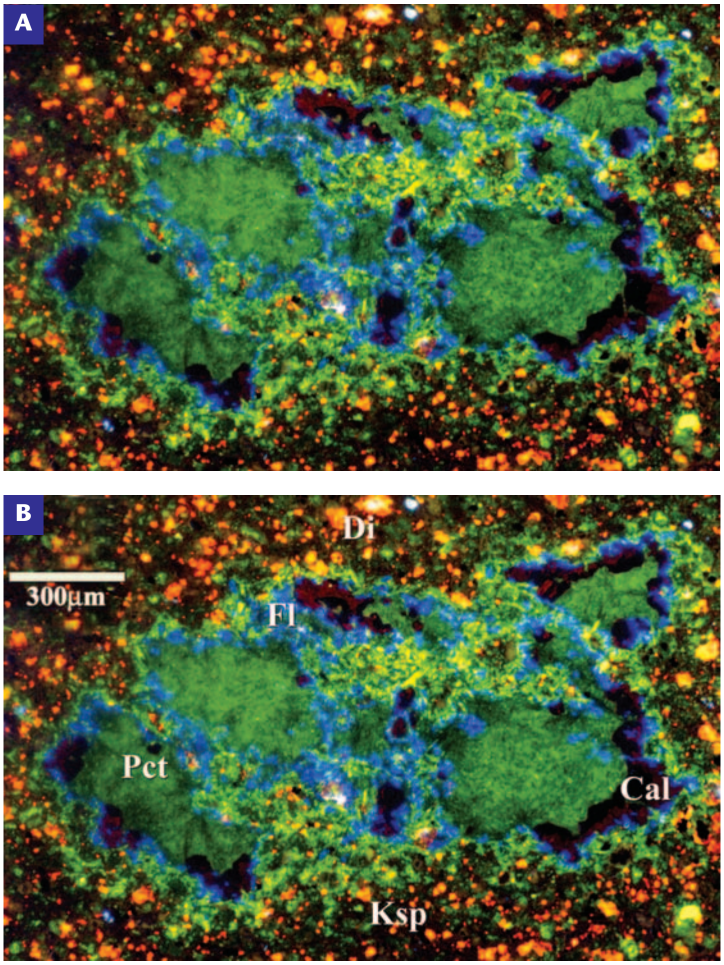

FIGURE 5 Cathodoluminescence image of a metasomatized calcareous siltstone from the subsurface of northern Louisiana. Green is pectolite (Pct), blue is fluorite (Fl), dark purple is calcite (Cal), the black matrix is K-feldspar (Ksp), yellow is diopside (Di) (see Dutrow et al. 2001 for details.) Instructors can ask students to draw and interpret salient features in images with large amounts of detail (e.g. photomicrographs) and thus provide them the opportunity to learn how to extract relevant data. This can be done by comparing an image lacking annotation (**A**) with an image with annotations (**B**) that provide limits to possible interpretations. Because of the similarity of many geologic features, scales and labels are essential for clarity. Nevertheless, a high level of background knowledge may be required for interpretation.

visual knowledge, observational skills are gained and new visual techniques are mastered. Student-generated explanations of visuals, with teachers and student peers providing feedback, provide an additional opportunity to develop visual proficiency. These experiences are then committed to memory, thus allowing retrieval and further inferences to be made in parallel with conceptual advances as new visuals are used. This visual education helps students learn to "see" and to think like a scientist.

CREATING VISUALS FOR EFFECTIVE COMMUNICATION: CONCEPTS

Although visuals are used for both presentation and analysis, their capacity for effective communication varies greatly. Analysis graphics are used primarily for discovery, insight, and hypothesis testing (e.g. Tufte 1997) by the researcher, and are rarely, if ever, appropriate for presentation. Presentation graphics are purposefully developed to communicate a specific concept effectively. As such, they integrate both conceptual and design principles that maximize communication and facilitate teaching visual literacy. This translates to improved student learning. 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 (r_1), although it should have been $1.41 \times r_1$. 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, … 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.

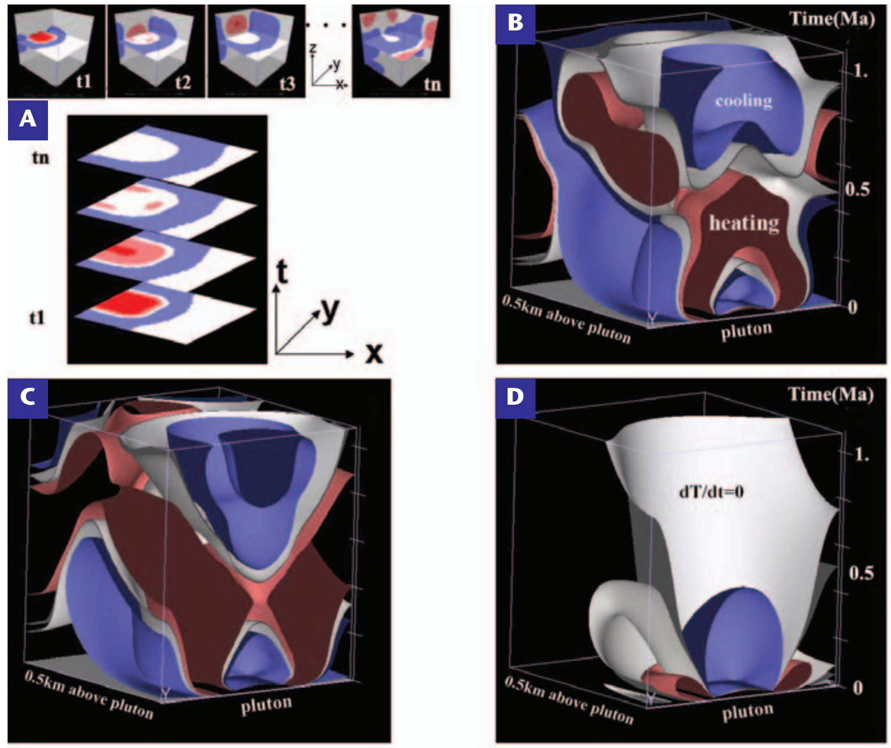

FIGURE 6 Visualizations displaying regions of heating and cooling located 0.5 km above a pluton through time. (**A**) Diagrams are constructed by extracting an x–y slice from a 3D volume at z′ for specific time intervals ($t_1 \ldots t_n$), stacking planes with time increasing vertically, and coloring 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.

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.

Interactivity is known to facilitate learning (e.g. Schnotz 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/ROL0304_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

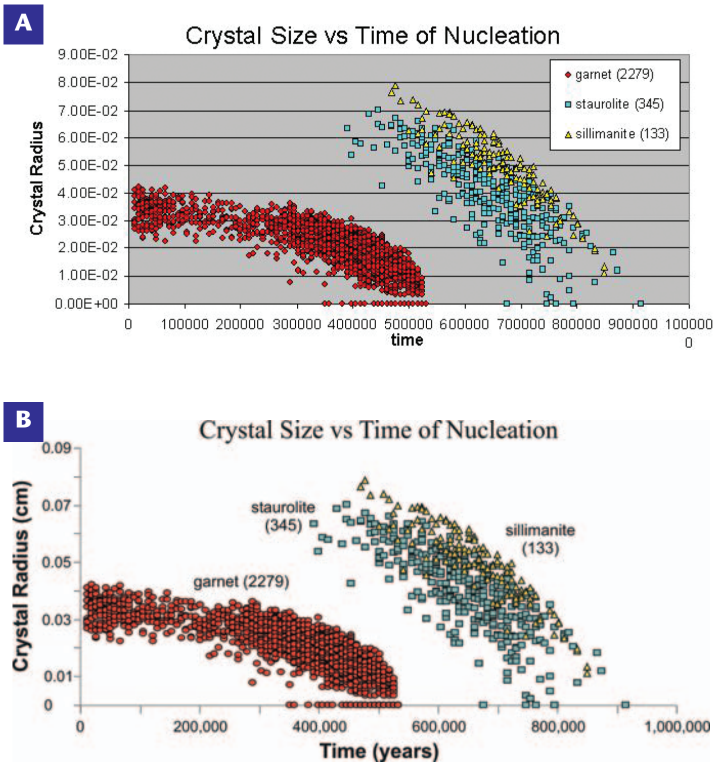

FIGURE 7 (**A**) Relational graphic of crystal size versus the time of crystal nucleation constructed from a typical spreadsheet program using default fonts and sizes and a key describing the symbol, with the number of crystal nuclei in parentheses. Visual clutter (lines, extra numbers, key) detracts from the clear display of data. DIAGRAM COURTESY OF DR. TOM FOSTER, UNIVERSITY OF IOWA. (**B**) The same plot redrawn, minimizing chartjunk and cross-referencing. Data elements are directly encoded, eliminating the need for a symbol key. This adds clarity and reduces interpretation time.

http://serc.carleton.edu/NAGTWorkshops/visualization). While we readily provide instruction about the use of a graphic (e.g. tracing a reaction path on a phase diagram), spending time to teach what makes an effective graphic to communicate the requisite information helps students to improve their visual literacy and to prepare their presentation graphics. This procedure can be incorporated into each class as new diagrams are introduced.

CREATING VISUALS FOR EFFECTIVE COMMUNICATION: PRACTICAL ASPECTS

By embracing a few easy suggestions, an instructor can improve the effectiveness of his or her graphical communication. Detailed explanations can be found in, for example, Tufte (1983, 1990, 1997, 2006) and Ware (2004).

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.

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).

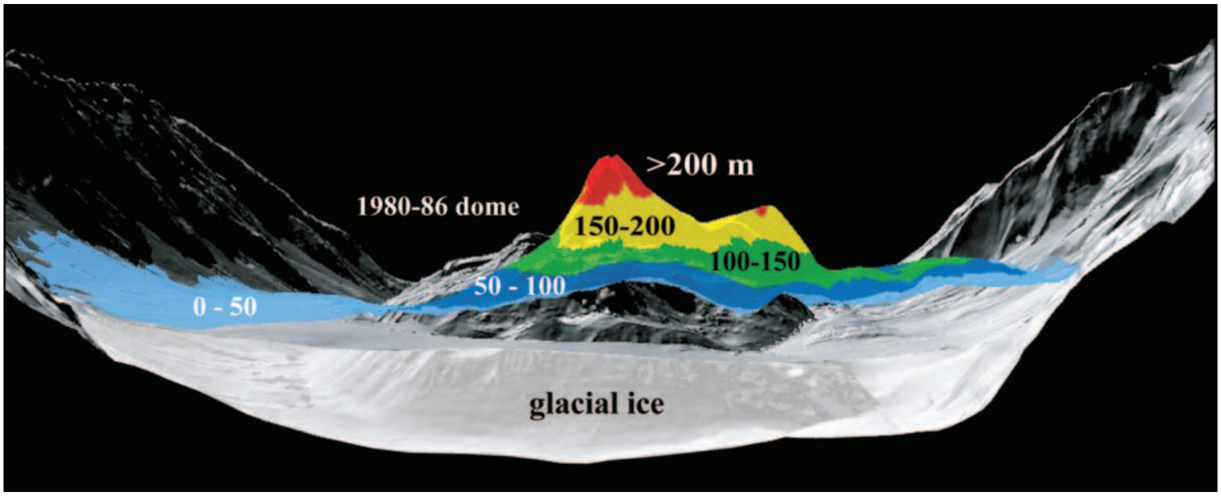

FIGURE 8 Shaded relief image of the crater at Mt. St. Helens as it appeared in July 2005, derived from the digital elevation models (DEMs) developed by soft-copy digital photogrammetric methods. The colored data represent the elevation change in meters of the new crater relative to that observed in 2003 and are overlain on the 2005 surface. Behind the new dome appears the 1980–1986 dome, partially buried by glacial ice nearly 200 meters thick. These image types contain about 1 million data entries. They provide excellent teaching tools for extracting lower dimensional data (e.g. to construct a cross section or draw a plan view) and furnish the opportunity to ask students to develop an hypothesis predicting what will happen in the future. See also Thompson and Schilling (2007). IMAGE COURTESY OF DR. REN THOMPSON, USGS

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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