

Learning volcanology: Modules to facilitate problem solving by undergraduate volcanology students

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Abstract

Six modules are presented that are designed for use in an undergraduate physical volcanology course. Each module uses a four-step mathematical problem-solving approach following Polya's *How to Solve It*, to guide students to: (i) understand the problem, (ii) devise a plan for solving the problem, (iii) implement the plan, and (iv) reflect on their solution. The modules cover topics in estimation of volumes of debris flow and tephra fallout deposits, lava effusion rate, calculation of melt density and viscosity, and development of dynamic models of bubble ascent in magma. Core quantitative issues, such as linear regression and error propagation, are introduced using these modules. The modules are included as supplementary material in PowerPoint and Portable Document Format (PDF). Cumulatively, the modules are designed to help volcanology students construct their own schemas, through which they can master abstract concepts in volcanology and in the geosciences generally. Physical volcanology can play a central role in the Earth Sciences curriculum by promoting quantitative problem solving using modules such as these.

KEYWORDS: PHYSICAL VOLCANOLOGY COURSE, MODULE, SCHEMA, LEARNING OUTCOMES, QUANTITATIVE LITERACY, GEOSCIENCE EDUCATION

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CITATION:

Connor, C. B. and Vacher, H. L. (2016) Learning volcanology: Modules to facilitate problem solving by undergraduate volcanology students, *Statistics in Volcanology* 2.3 : 1 – 13. DOI: <http://dx.doi.org/10.5038/2163-338X.2.3>

Introduction

At many universities, physical volcanology is not part of the standard undergraduate curriculum and may not be offered as an elective. This omission is unfortunate because many students are fascinated by volcanic processes and can benefit from learning about them. Indeed, students are often attracted to the Earth Sciences by first-hand experience with volcanoes or by learning about volcanoes in informal settings. In this paper, we describe how undergraduates can benefit from learning quantitative methods, particularly elementary statistical methods, in a physical volcanology course and provide materials that can assist instructors in developing such a course.

Volcanology should be part of the standard Earth Sciences curriculum, we believe, because it can play a pivotal role by introducing geoscience students to structured quantitative thinking and methods, while engaging the students with content that can keep them interested. That is, students are likely to persist in mastering quantitative skills, such as statistical modeling, because they are excited about volcanology and volcanological data. Conversely, students who wish to pursue advanced studies in volcanology are often unprepared for the rigor of the discipline. In fact, many students who wish to work in volcanology in graduate school quickly encounter a highly quantitative research environment, where success requires an understanding of physics, chemistry, mathematics and statistics, and more importantly, requires skills in problem solving and quantitative reasoning. Physical volcanology is precisely a course in which students can begin to acquire and apply these skills.

One goal of this paper is to describe a model of the cognitive mental framework one develops, ideally, as we learn volcanology. Construction of this framework, or schema, likely begins during an undergraduate course in volcanology, and it continues to develop throughout one's professional career. The volcanology schema is similar to a more general framework for learning geology and geophysics, but it emphasizes the framework students must develop in order to contribute to solving most research questions extant in volcanology. Second, the paper describes a series of modules developed to assist undergraduate geology students striving to learn volcanological concepts in a problem-solving context. These modules use problems in volcanology to promote abstract thinking. The modules are freely available and, to date, have been used by faculty from least 15 different universities in volcanology courses. Third, the paper discusses how additional materials, like additional modules and materials that improve upon them, might be developed to further enlarge students' schema, working at different levels of complexity and ultimately accelerating research progress in the discipline.

The Volcanology Schema

Professional success of volcanologists, whether working in academia, at observatories, elsewhere in government, or in private industry, requires them to develop a schema, a mental framework for acquiring knowledge that encompasses a range of experience and abstract thinking about volcanoes and volcanic processes. Consider one visualization of the volcanology schema using the general structure proposed by Wallace (2011), building on earlier studies (Piaget, 2001; Fischer, 1980; Skemp, 1987) (Figure 1). An individual geoscientist's schema becomes more useful as experience broadens through lecture, lab work, field courses and research activities. The adage "the person who sees the most outcrops wins" speaks to the idea that a useful schema relies on broad experience in observing diverse volcanological features (Kastens *et al.*, 2009), often strongly motivated by the field experience itself (Mogk & Goodwin, 2012; Huntoon, 2012). The role of this observational experience is to provide a foundation for abstraction of concepts.

As one's experience broadens at one level of the schema, it becomes practical to consider more abstract concepts – the next level. In volcanology, this abstraction initially involves stepping from static observations to kinematic and dynamic models. That is, observations about outcrops are most useful if they are used to deduce the movements, such as dilute surges and tephra falls, necessary to create the features observed in an outcrop. One must have experience comparing the features of numerous outcrops in order to successfully deduce the nature of a specific flow from these observations. A next level of understanding describes the forces at work to produce these movements, using varying levels of mathematical sophistication. As before, experience with many flows (*e.g.*, their volumes, velocities, concentrations of particles within them) is required to begin to describe the forces that produce such flows.

As thinking about volcanological processes becomes more abstract, observations become more important to constrain and validate these abstract concepts. What observations might be made to constrain the magnitude of a model parameter, such as turbulent diffusion of particles, from observations made at the outcrop scale? What statistical analyses are needed to estimate these parameters and understand their uncertainties? Ultimately, research success involves experience with diverse observational data and the ability to work at high levels of abstraction. The schema is the structure we use to develop these translational skills, building from our first encounter with the science.

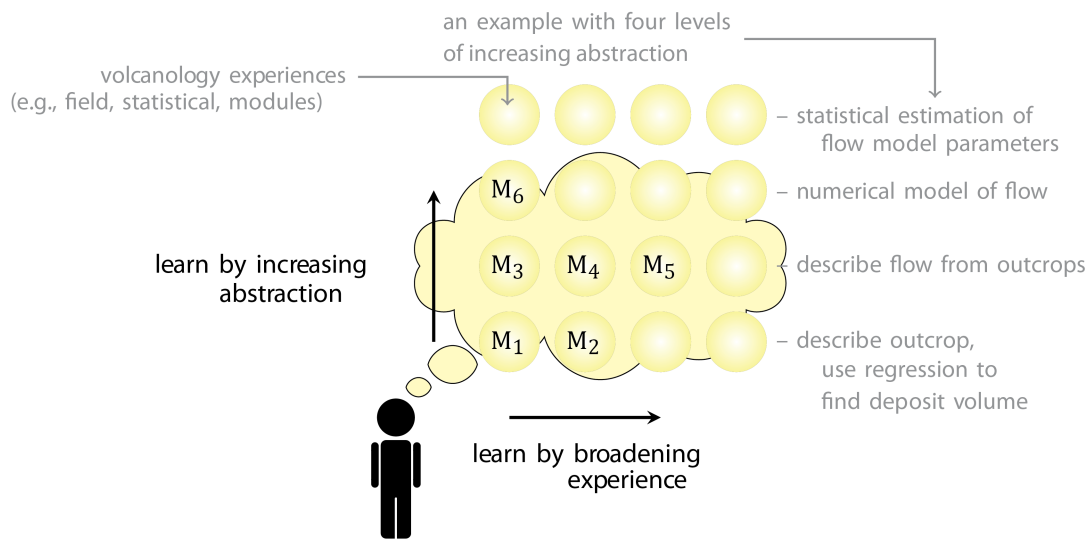


Figure 1: Volcanology schema. Students learn volcanology by broadening experience through specific activities (shaded circles) involving increasingly abstract concepts. Ideally, these activities help a student transition from static views and skills (*e.g.*, how to calculate the volume of a deposit) to kinematic and constitutive relationships (*e.g.*, how to estimate effusion rate or infer flow conditions). Dynamic views of volcanological processes are more abstract (*e.g.*, how do we use force balance to model magma movement or mass flow). Finally a data-centric view of processes and models develops (*e.g.*, how are data used and analyzed to constrain parameters in a dynamic equation). The physical volcanology modules (labeled circles, $M_1 - M_6$) are designed to serve as experiences in the early stages of this hierarchy. Other experiences that help students construct a schema include field activities, laboratory exercises and lectures.

Frodeman (1995) characterized advances in geological science in terms of a balance between historical observations and models of physical processes. For example, success at forecasting volcanic eruptions relies on a balance between broad experience observing volcanic phenomena and development of physics- and chemistry-based models that attempt to explain and extend our observations. Volcanological research is characterized by this interplay between broad observational experience and modeling. As in other fields, this relationship is cyclical in nature, and can result in both positive and negative impacts on the rate of scientific advance (*Vacher & Florea, 2015*). Ideally, observations guide us about which models to develop; models guide us to refine our observations. Thus, we suggest that the volcanology schema applies to all levels of learning in volcanology. At any level, the interplay between observations and physical modeling is the purview of statistics in volcanology.

Teaching volcanology

Such translational skills certainly fit with the changing needs of employers, even those who employ volcanologists to solve problems well outside the discipline. Students and their employers need the broad set of geological skills as represented in most core geology curricula courses. There are equally important skills that are not well represented in curricula, largely involving quantitative reasoning and problem solving, but extending into other aspects of cyberinfrastructure, such as understanding the use and limits of numerical simulations of natural processes. In its most basic form, these needs are represented by quantitative literacy (*Macdonald et al., 2000; Fratesi & Vacher, 2005; Vacher, 2005; Manduca et al., 2008*) and model literacy (*Turcotte, 2006; Bice, 2006; Courtland et al., 2012*). One can easily add data literacy, or geoinformatics (*Manduca & Mogk, 2002; Ledley et al., 2008; Deng & Di, 2014; Palma et al., 2014*). Students need to understand how their observations can test models and be used to develop new models. Successful training helps students develop a schema that aids them regardless of the details of their professional path. For example, a person with a doctoral degree in volcanology can find success employed by an oil exploration company if the individual's schema allows for cross-disciplinary application of concepts, like the application of the advection-diffusion equation to a variety of earth processes or the role of particle settling velocity in building a river delta as well as in building a tephra fallout deposit.

In most respects, facilitating abstract thinking about volcanology involves helping students think about how to solve quantitative problems, and so it creates transferable skills. Quantitative literacy is defined as a habit of mind that allows one to engage in problem solving using concepts such as measurement, data presentation and analysis, statistics, and calculus (*Gilman, 2006; Wallace, 2014*). Considering this broad definition, nearly all papers published today in physical volcanology require some level of quantitative literacy to write and to read. Most volcanologists take a wide range of quantitative skills for granted, such as how to estimate the volume of tephra fallout or pyroclastic flow deposits from map data, how to calculate the height of a volcanic plume, or estimate effusion rate of a lava flow. Often more sophisticated concepts are equally taken for granted, such as characterization of the viscosity of a magma using a linear model, or using a constitutive equation, such as the ideal gas law, to calculate volume fraction of gas in an erupting magma. While professionals use these concepts in routine conversation, students new to the field generally do not understand them (*Parham et al., 2010*). In fact, lack of understanding of these concepts may be a significant barrier to students as they first engage with the field. Students need to broaden their experience in order to achieve the abstract thinking needed to follow the conversation and, ultimately, to contribute to the field (Figure 1).

In teaching physical volcanology it is necessary to understand the structure and variation of the volcanology schema, the cognitive dissonance students encounter as they master increasingly abstract concepts, and the cognitive load that is appropriate at each stage. Invariably students are introduced to volcanology using a series of examples, generally represented by a set of static observations and models, termed pictorial representations (*Ishikawa & Kastens, 2005*). Examples from volcanology lectures include the shapes of shield volcanoes, composite cones, and calderas; illustrations of volcanic plumes with associated tephra fallout or pyroclastic density currents; elements of subduction revealed through diagrams showing the ocean trench, the subducted ocean lithosphere, asthenospheric wedge; and so on. Early experiences in the field are often transformative for volcanology students and, at least initially, these experiences involve studying outcrops as pictorial representations. At outcrops, students learn to describe features, such as sorting and bedforms and learn the vocabulary required to describe these features to others. These static pictures and associated vocabulary are essential for broadening experience (e.g. *Rapp & Uttal, 2006; Edelson et al., 2006; Taber & Quadracci, 2006*). The more vocabulary one knows, the more outcrops one studies, the fuller the picture of volcanic systems one develops. Yet such static pictures are likely not perceived by students, at least at first, in terms of the concepts educators wish to convey (*Libarkin & Brick, 2002; Ishikawa & Kastens, 2005; Stillings, 2012*). For example, it can be conceptually challenging to infer bubble nucleation, growth and transport from illustrations of strombolian eruptions, but that is what we often ask

students to do. This gap in the connection between the static picture and the concept can be a roadblock, if not addressed.

The struggle to develop a dynamic picture of volcanological processes from static observations is a classic example of cognitive dissonance. The volcanology schema is substantially enlarged when a student can take a set of static images and vocabulary and resolve the dilemma of how they are related by putting things in motion. Achieving this level of abstract thinking – spatial reasoning at this early stage – is problematic for many students but can be aided through the use of problem solving to visualize motions and forces (*Ishikawa & Kastens, 2005*). The critical step is to actively engage students (*Reynolds et al., 2006*). There are myriad ways this active engagement might be achieved in order to build quantitative skills and trigger abstract thinking (*Libarkin & Brick, 2002; Reynolds et al., 2006; Bice, 2006; Liben & Titus, 2012*). The challenge is to design an environment in which students can work on interesting problems to enlarge their volcanology schema efficiently.

In the following, modules are described that present students in a physical volcanology course with volcanology problems that they can solve in a highly structured environment. The modules are designed to broaden experience in problem solving and to promote abstract thinking about volcanological processes. In other words, they are designed to assist students in constructing a schema that will aid them in becoming problem solvers in volcanology, or in the Earth Sciences more generally.

Physical Volcanology Modules

To address issues in quantitative literacy generally, a structure and format for modules called spreadsheets across the curriculum (SSAC) was created for a materials development project in geoscience education of the same name. SSAC modules are highly formatted, stand-alone, computer-based activities, each designed to engage students in a problem-solving activity that invokes their interest (*Vacher & Lardner, 2010, 2011; Lehto & Vacher, 2012*). Every SSAC module is a PowerPoint presentation, usually consisting of 12–18 slides, with embedded Excel spreadsheets, and perhaps including supplementary slides with ancillary information. The core of a module consists of slides that lead the students to identify a quantitative problem, consider how to design a solution to the problem, and build their own spreadsheets to solve the problem (*Vacher & Lardner, 2010; Wetzel, 2011*). For the physical volcanology collection, each module has (i) a title slide that notes the quantitative concepts and skills introduced by the module, (ii) one or more slides that present volcanological background, (iii) one slide that clearly states a volcanological problem (often repeated from the title slide), (iv) a set of slides dedicated to designing a plan for solving the problem, (v) a set of slides for carrying out the solution to the problem (using Excel), (vi) a slide that allows students to reflect on the solution to the problem and that provides additional reference material, (vii) and an end-of-module-assignment slide. Text boxes in the slides are color-coded to distinguish between information, assignments, and prompts. Cells in embedded spreadsheets are also color-coded to distinguish between cells in which students enter numbers, and cells in which students enter equations.

To date, nine physical volcanology modules have been developed; all are freely available through the SERC website (*SERC, 2008*), the VHub website (*VHub, 2015*), and six are provided here as supplementary material. Answer keys have also been developed for the modules and are available to university faculty by request. The six modules provided in supplementary material are summarized in terms of student activities and expected learning outcomes in Table 1.

The structure of each of these modules roughly follows the four-step mathematical problem-solving approach first developed by George Polya in the 1940s (*Polya, 2014*). Briefly, the four-step approach guides students to: (i) understand the problem, (ii) devise a plan for solving the problem, (iii) implement the plan, and (iv) reflect on the solution. The modules are designed to create interest in a problem and guide students through the solution. For example, in the module entitled “What is the volume of the 1992 eruption of Cerro Negro volcano Nicaragua?” (module *M2*, Table 1), students are first asked to consider what tephra is, how the volume of a tephra deposit might be determined, and how the volume is used to estimate the volcano explosivity index (VEI) for an eruption. Next they are asked to consider a specific eruption and its consequences, with the intent of motivating interest in solving the problem of eruption volume estimation. The problem is then posed specifically: How can the volume of the 1992 tephra deposit be estimated? Issues such as the required data (*e.g.*, deposit thickness and density) are considered (*Connor & Connor, 2006*). Then a plan is provided for solving the problem. In this case, thickness is estimated using an exponential thinning model for tephra (*Pyle, 1989*) and steps are presented for obtaining a volume. Students are asked to consider the steps that must be implemented: (i) plot the natural logarithm of isopach thickness against the square root of isopach area, (ii) find a best-fit linear model for these data, (iii) estimate model parameters, (iv) estimate volume from these parameters, using the assumptions made by *Pyle (1989)*. This plan is a daunting set of steps for most undergraduates, so the next slides present a methodology for carrying out the individual plan steps. Students are asked to follow along as the steps are implemented and to enter

Table 1: Six of the physical volcanology modules described in terms of student activities and expected learning outcomes. Modules are listed in order of increasing complexity, approximately.

Module Name	Student Activities	Learning Outcomes
M₁ : <i>What is the Volume of a Debris Flow?</i>	Estimate area inundated by a debris flow from a gridded map. Calculate average flow thickness across the covered area. Calculate debris flow volume and estimate the uncertainty.	Recognize the value of calculations based on approximate assumptions. Consider the relationship between planimetric area inundated by debris flow and debris flow volume. Consider the uncertainty associated with area and volume estimations.
M₂ : <i>What is the Volume of the 1992 Eruption of Cerro Negro Volcano, Nicaragua?</i>	Perform unit conversion. Find a best-fit linear model of data. Estimate parameters from a best-fit linear model.	Increase skill with unit conversions. Distinguish, conceptually, between areas and volumes. Introduce exponential decay within a physical model.
M₃ : <i>What is the Relationship between Lava Flow Length and Effusion Rate at Mt Etna?</i>	Gather data on lava flow length and effusion rate. Find a best-fit linear model. Implement a simple numerical model.	Consider data uncertainty. Discover the log-log linear relationship between effusion rate and lava flow length. Compare statistical and physical model results.
M₄ : <i>How Do We Estimate Melt Density?</i>	Use mole fraction, molar mass, and fractional volume of major oxides to determine overall melt density. Calculate the change in melt density with water content, temperature and pressure.	Increase unit conversions skills. Learn to use weight percent and molar mass to calculate mole fraction. Consider thermal expansion and compressibility. Introduce the concept of partial differential equations.
M₅ : <i>How Do We Estimate Magma Viscosity?</i>	Use a linear model to calculate magma viscosity. Examine how water and crystals affect magma viscosity.	Increase unit conversion skills. Use linear regression to determine the relationship between multiple variables. Consider statistical models of viscosity.
M₆ : <i>Bubbles in Magmas</i>	Use the ideal gas law to estimate the growth of bubbles in magmas. Calculate the net forces acting on the terminal velocity of a bubble. Calculate the change in volume of a bubble as a function of depth.	Recognize the relationship between volume and pressure in an ideal gas. Consider the role of forces involved in bubble movement with respect to magma. Recognize the concept of iteration when simulating the motion in magma.

isopach area and thickness data into an Excel spreadsheet. These data are provided along with relevant hints concerning unit conversion. With these data in hand, students are presented with a formula relating tephra deposit thickness and isopach area:

$$\ln T = \ln T_o - k\sqrt{A} \quad (1)$$

where T is the thickness associated with an isopach that encloses area A . Students are asked to realize the relation is a linear equation of $\ln T$ as a function of \sqrt{A} , and that the slope, k , and y -intercept, $\ln T_o$, can be estimated based on the graphed relationship between $\ln T$ and \sqrt{A} .

Since students are given thickness, T and isopach area, A , they are required to first calculate $\ln T$ and \sqrt{A} . The Excel formulae for making these unit conversions are not supplied; students are encouraged to discover them on their own, but the correct results are shown in appropriate columns in an Excel spreadsheet embedded in the PowerPoint, so students can check their results obtained with their own spreadsheets. Steps are then provided to estimate parameters through linear regression using Excel functions. Once these parameters are estimated, formulae from (Pyle, 1989) must be entered into the Excel spreadsheet and used to estimate deposit volume, V :

$$b_T = \frac{\ln 2}{k\sqrt{\pi}} \quad (2)$$

$$V = 13.08T_o b_T^2 \quad (3)$$

Students are asked to provide their volume estimate in units of cubic kilometers, so again they must suffer a unit conversion. As before, the correct answers are provided in the spreadsheet within the module, but not the formulae. Students must figure out and enter the correct Excel formulae, and they can check to be certain they have obtained correct results. With this volume estimate in hand, students are asked to verify the magnitude of the 1992 Cerro Negro eruption, using the volcano explosivity index (VEI) (Newhall & Self, 1982).

This experience in problem solving naturally leads to discussion in the classroom of both volcanological and quantitative issues. Volume estimates are commonly made in volcanology, and other sub-disciplines of the geosciences. The module illustrates application of a simple statistical model to volume estimates. It is reasonable to ask students to consider uncertainty in the application of the model, both in terms of the data presented to them, the thickness and isopach area data, and the uncertainty associated with application of the model (Klawonn et al., 2014; Biass et al., 2014; Bonadonna et al., 2015). This discussion can lead to more general discussion of the proper application of statistical models to volcanological processes (Courtland et al., 2012).

The modules are presented in Table 1 in order of increasing complexity of the spreadsheets, and roughly in order of increasing level of abstraction. The first module, *What is the volume of a debris flow?*, uses the example of the Panabaj debris flow that occurred adjacent to Lago de Atitlán, Guatemala, in 2005. Students are motivated by the human tragedy of this event and similar debris flows to understand the log-log relationship between volume and area inundated (Iverson et al., 1998). Data are provided in the form of map and thickness measurements. Students are introduced to summation, as they sum grid cells to determine the lahar deposit area, and use these data to estimate volume. They are also asked to propagate measurement error associated with area and thickness estimates using a simple estimate:

$$\Delta V = V \left[\frac{\Delta T_m}{T_m} + \frac{\Delta A}{A} \right] \quad (4)$$

where ΔV is the estimated error on volume, V , ΔT_m is the estimated error on average measured thickness, T_m , and ΔA is the estimated error on deposit area, A . Finally, students are asked to report their answer with appropriate significant figures, one in this case, a step often overlooked. What makes this module appropriate for early use in a course is that the topic engages students, often in ways coinciding with their original motivations for enrolling in a volcanology course; the steps in problem solving are comparatively straightforward; and the spreadsheet is not technically difficult. For some students, the module immediately introduces the cognitive dissonance that volcanology is more quantitative than what they were expecting. Students are then asked to reflect on the importance of volume estimates in volcanology, considering topics like eruption magnitude (Mason et al., 2004), volcano debris avalanches (Siebert, 1984), and the role of edifice volume in sector collapse (Tibaldi, 2001).

The second module, discussed previously, and the third module, *What is the relationship between lava flow length and effusion rate at Mt. Etna?*, continue the theme of surface flow processes and their characterization. This third module introduces a more complex mathematical relationship that depends on less intuitive physical parameters, such as tensile

strength of lava flow crust and bulk thermal diffusivity (Kilburn, 2015). In this module, the lengths of lava flows are modeled based on effusion rates, from a statistical perspective. These considerations introduce the kinematic concepts of discharge and effusion rate, whereas the first two modules in the series involve static concepts, volume deduced from maps and map data.

The next two modules in the series (\mathbf{M}_4 and \mathbf{M}_5 ; Table 1) deal with more abstract concepts of density and viscosity. These modules use the same format as the previous modules, but they introduce parameters that are used in constitutive equations in many dynamic models. The density module concentrates on introduction of thermodynamic concepts of mole fraction, molar volume, and fractional volume (Lesher & Spera, 2015). Students develop a model of density based on the major element geochemistry of a melt, given pressure and temperature conditions. In order to account for compressibility and thermal expansion, students are introduced to the notation of a partial differential equation. Similarly, in the viscosity module, students construct a statistical model of viscosity and consider the effects of water content and crystal content on viscosity using this model (Hess & Dingwell, 1996). Both models move toward dynamic concepts, in the sense that such properties must be known in order to understand and model the forces acting on magmas and the products of volcanic eruptions.

Module \mathbf{M}_6 , *Bubbles in Magmas*, instructs students to use the ideal gas law and to consider the forces acting on a single bubble in a melt. This module is intended to encourage students to examine the dynamics of volcanism, considering factors such as bubble expansion and the change in magma flux in a conduit in response to bubble expansion. Modules $\mathbf{M}_4 - \mathbf{M}_6$, are technically more difficult than modules $\mathbf{M}_1 - \mathbf{M}_3$ (Table 1). For example, *Bubbles in Magmas* (\mathbf{M}_6) requires iteration using Excel to estimate the change in diameter of a bubble with its rise in a volcano conduit. While this module is challenging, the intent is to move students' thinking toward geocomputation and numerical methods for exploring problems in physical volcanology.

Discussion

Although the volcanology modules have been in use since 2008, formal assessments concerning their effectiveness have not been conducted. Anecdotal experience from instructor impressions and student evaluations indicates that the use of these modules improves learning outcomes (Table 1) for students. Module use in the classroom certainly does increase student involvement. Such active participation may be key toward developing computational skills in the geosciences (Liben & Titus, 2012). Similar to other laboratory, classroom and computer-based activities in volcanology (Harpp & Sweeney, 2002; Harpp et al., 2005; Boudreaux et al., 2009; Courtland et al., 2012; Teasdale et al., 2015), active student engagement is comparatively easy to achieve with these modules because of the natural interest students have in the subject matter.

The modules are self-contained and may be used in any order. Nevertheless, there is a natural progression from relatively simple modules ($\mathbf{M}_1, \mathbf{M}_2$) to more complex modules (e.g., \mathbf{M}_6), envisioned as experience at different levels in the volcanology schema (Figure 1). Partly, this order stems from the need to motivate students. Students enrolling in physical volcanology are usually most interested in the surface processes and their potential impacts on people. Consequently, they are more easily motivated to solve problems associated with these phenomena. In contrast, these students have rarely considered the complex processes that lead to eruptions. So, they are rarely motivated to consider magma transport and the dynamics of conduit flow prior to gaining additional knowledge as the course progresses. Furthermore, magmatic processes tend to be more abstract (no one has seen a volcano conduit during a volcanic eruption) and more complex than surface processes. Thus, the modules associated with magma transport and eruption tend to present less intuitive and more complex problems than modules based on observed surface phenomena, such as debris flows, although complex models are certainly developed by volcanologists to study all of these processes.

The sequence of modules, starting with surface phenomena, eruptive products and their effects, runs counter to the presentation of material in most textbooks. Volcanology textbooks have most recently taken a bottom-up approach, starting with the magma source region and transport, then eruptions, and then surface phenomena (Bardintzeff & McBirney, 2000; Schmincke, 2005; Parfitt & Wilson, 2008; Lockwood & Hazlett, 2013). This differs from earlier texts (Rittman, 1962) that consider observable surface processes first, followed by chapters examining the origin of magmas and magma transport. Although the chapter order used in current texts tracks the order of physical events, it is not consistent with student motivations. The module order in Table 1 is a more pedagogically promising construct because it may motivate students to look deeper into magmatic processes once surface phenomena are covered and students have become familiar with the problem-solving environment.

The physical volcanology modules have been used as self-directed homework assignments, as laboratory-type group experiences, and as parts of interactive lectures. Anecdotally, we have found that beginning the module as a group

exercise reduces cognitive load on students and increases their motivation. By introducing the modules in a lecture or lab environment, students can immediately begin constructing Excel spreadsheets to solve the problem posed in the module, and then complete the end-of-module assignments outside of class. Module discussion, such as an online forum or discussion group, is highly recommended to encourage student engagement and participation in finding solutions. Finally, it appears to be important to discuss the learning outcomes once the modules are turned in and graded.

Ultimately, the development of a volcanology schema is most useful if it enables students to solve new problems. Again anecdotally, it appears to be effective to ask students to develop new modules about volcanological topics of interest to them as a term project. This activity may help students internalize the problem-solving approach. Students benefit from the experience of presenting their completed module to the class; they gain confidence and are more likely to remember what approach they took to solve the problem.

The approach developed in SSAC and in the physical volcanology modules could be implemented in more advanced courses, such as graduate level volcanology, or for teaching quantitative concepts more effectively outside the classroom. PowerPoint and Excel, although not particularly robust choices for extremely large and complex datasets, are widely available and most students have encountered them before. These tools are used in the physical volcanology modules to reduce cognitive load, although in practice many students struggle with the design of the problem and the implementation of the solution in Excel. A plethora of other tools, such as Ruby, GnuPlot, Python or PERL, could be used to create a data-rich problem-solving environment for more advanced students. Similarly, Wikis, Latex Beamer, or another presentation framework could be used instead of PowerPoint for module presentation. The underlying goal is to assist the learner in moving through the problem-solving environment by keeping the framework consistent and structured so they can see an example problem, design a plan to solve the problem, implement the plan, and reflect on what has been accomplished.

Acknowledgments

Peter La Femina participated in early use of the physical volcanology modules in the classroom at Pennsylvania State University, and developed one of his own. Judy McIlrath (formerly Harden) edited the modules before they were included in the SERC collection. Sylvain Charbonnier and Aurélie Germa have provided valuable feedback about the modules, based on their use of them to teach volcanology. This manuscript was improved by the comments of two anonymous reviewers and the editor, Mark Bebbington. Laura Connor provided great copy-editing.

Additional Files

There are 13 additional files. These files include the physical volcanology collection of modules available as Microsoft PowerPoint files (*.ppt) and Adobe Portable Document files (*.pdf). A movie file saved as a Quicktime multimedia file (*.mov) is included for completion of module **M₃**. All additional files are named with their corresponding module number (**M₁** – **M₆**).

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