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Using a Differential Scanning Calorimeter to Teach Phase Equilibria to Students of Igneous and Metamorphic Petrology

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ABSTRACT

As an aid for teaching phase equilibria to undergraduate students of igneous and metamorphic petrology, we have designed a laboratory exercise that allows them to create a phase diagram from data produced by differential scanning calorimetry. By preparing and analyzing samples of naphthalene and phenanthrene, students acquire hands-on insight into thermodynamics and the melting behavior of pure samples versus mixtures, and ultimately create a binary phase diagram analogous to the system diopside–anorthite. In the process, students gain exposure to modern analytical instrumentation and practice quantitative skills such as calculation (e.g., calculation of weight % from molecular %), graphing, and assessment of error. Assessment of the effects of this laboratory exercise suggests that it improves student understanding of phase diagrams and the nature of reactions between crystals or between crystals and melt in metamorphic and igneous rock-forming environments. © *2011 National Association of Geoscience Teachers*. [DOI: 10.5408/1.3580766]

INTRODUCTION

Understanding Gibbs' Phase Rule and simple phase diagrams is fundamental to studying the origins of igneous and metamorphic rocks. Phase diagrams represent simplified systems, summarizing the presence, identity, and relative proportion of various phases (liquid or solid, solution, or pure), and allow us to envision processes that we cannot observe directly, such as melting or crystallization deep in the crust or mantle. Phase diagrams help students understand the origins of different rock types by serving as models that describe potential effects of changes in pressure, temperature, or composition on melting or crystallization within a given system. Unfortunately, most undergraduate students have had little experience with multicomponent phase equilibria and struggle to relate the lines and points on phase diagrams to the geologic processes they represent.

At the University of Southern Indiana, Introduction to Igneous and Metamorphic Petrology, a class that includes lecture and laboratory components, is required for the geology major, and is usually taken during the student's junior year. The prerequisite for this course is Mineralogy, which, in turn, has a prerequisite of Chemistry I. Historically, class size has ranged from 4 to 15 students. Typically, phase diagrams are introduced and described during lecture, and exercises are assigned as homework to reinforce key concepts. Common exercises involve tracing the paths of melting or crystallization for a given composition as temperature changes (e.g., Glazner, 2003) or constructing a phase diagram using a supplied data set (e.g., Smith, 2003). While these exercises are effective, it is clear that students can learn the systematics of a diagram and respond correctly to specific questions without really understanding what the diagram represents. Without a strong grasp of how such diagrams are created and how they are founded on principles of thermodynamics, phase diagrams are less meaningful, and many of our students seem to forget everything they have ever heard about phase equilibria by the next semester.

To enhance student understanding of phase equilibria, and to improve retention of that understanding, we have designed a laboratory exercise that allows undergraduate geology students to generate a binary solid–liquid phase diagram using differential scanning calorimetry (DSC). It has been our experience that students learn better from laboratory exercises that let them generate their own data. Hands-on activities that allow students to build knowledge for themselves have a clear advantage with respect to developing critical thinking skills (Tsui, 1999) and grasping difficult science concepts (McConnell *et al*, 2005). Labs also allow for work in cooperative groups, giving students a more accurate perception of how scientific research is typically pursued and greater satisfaction with the learning experience (Lord, 2001). Finally, lab exercises give students much-needed opportunities to practice quantitative skills such as measurement, calculation, and graphing (Manduca *et al.*, 2008).

To develop this exercise, we have drawn upon techniques commonly practiced in the undergraduate physical chemistry laboratory (Garland *et al.*, 2003). We have chosen the well-characterized chemical system naphthalene (N)–phenanthrene (P) (Gallus *et al.*, 2001), and present this system as a model for geological behavior, as it is analogous to the system diopside–anorthite (Bowen, 1915). The diopside–anorthite phase diagram represents a simplified model for crystallizing basaltic magma and is a favorite for teaching petrology students. It has been our practice to administer the lab exercise following an introductory lecture on thermodynamics (enthalpy, geologic systems, compositional components, and the phase rule) but before a detailed discussion of the diopside–anorthite system and then more-complex binary and ternary systems of geologic importance. While the focus is igneous at this point in the semester, knowledge of phase equilibria applies equally to metamorphic systems studied later in the same course.

We have found thermal analysis via DSC to be a robust, precise, and intuitive method well suited for use by

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undergraduate science majors (D'Amelia *et al.*, 2006). Operation of the calorimeter is straightforward, and success is readily achieved provided sufficient care is taken in sample preparation and instrument calibration. The exercise requires that students acquire data over a wide range of composition, compare the behavior of pure samples and physical mixtures, and ultimately build the phase diagram. This process gives them a chance to explore the phase diagram in its entirety, all the way from pure component N to pure component P and from solid to melt (Fig. 1). The exercise guides students toward expanding their understanding of temperature and melting point. While these quantities are intuitive in principle, their precise measurement is practically and conceptually challenging. The preparation and analysis of samples affords students exposure to modern analytical instrumentation and some of the challenges inherent to quantitative microscale work. Students leave the exercise with an appreciation for the quantitative nature of geoscience, and an enhanced understanding of the nature and utility of phase diagrams and how they are grounded in thermodyamics, which, in turn, facilitates their ability to use these diagrams to conceptualize possible origins for different rock types.

BACKGROUND

Geological phase diagrams may be constructed by melting samples of crushed rock containing different proportions of minerals. Once equilibrium is established, the samples are quenched and then analyzed for the relative proportions of crystallized minerals and vitrified melt stable under the experimental conditions. If samples representing a broad range of component mixtures and temperature regimes are analyzed, stability fields (e.g., total solid, melt + crystal N, melt + crystal P, and total melt) may be constrained and reaction curves (e.g., liquidus and solidus) delineated for a given pressure, resulting in a phase diagram (Fig. 1). While the exploration of rocks as teaching examples would be ideal, the extreme pressures and temperatures required make this technique poorly suited for the undergraduate laboratory. Using lower temperature systems as analogs for rocks and observing phase changes with heating or cooling is a good alternative. Darling (2000) created an exercise in which construction of a phase diagram is based on phase changes as synthetic H_2O–KCl fluid inclusions of known composition are warmed on a microscope heating stage. In another approach, Brady (1992) described an exercise in which students delineate the liquidus for the system H_2O–NaCl by recording saturation temperatures upon adding halite to brine solutions of known composition.

Phase diagrams may also be constructed via thermal analysis techniques. When a given substance is heated and begins to melt, heat is absorbed (enthalpy of the reaction or latent heat of melting), while formation of crystals from a cooling melt releases heat (latent heat of crystallization). Thus, solid–liquid phase transitions may be identified by monitoring temperature as a sample is warmed or cooled [e.g., Fig. 2(a)]. Sharp changes in the slope (dT/dt) of the temperature curve signal melting or crystallization and can be used to map the liquidus and solidus curves. Once

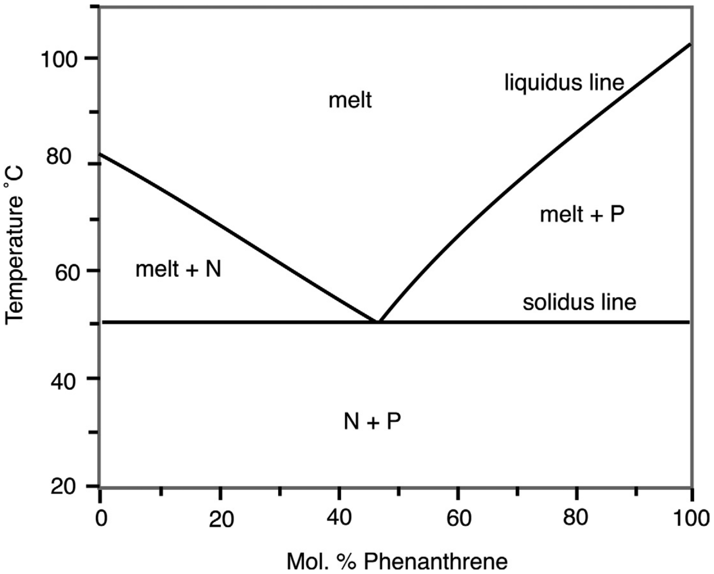

FIGURE 1: Binary phase diagram for the system naphthalene–phenanthrene (after Gallus *et al.*, 2001).

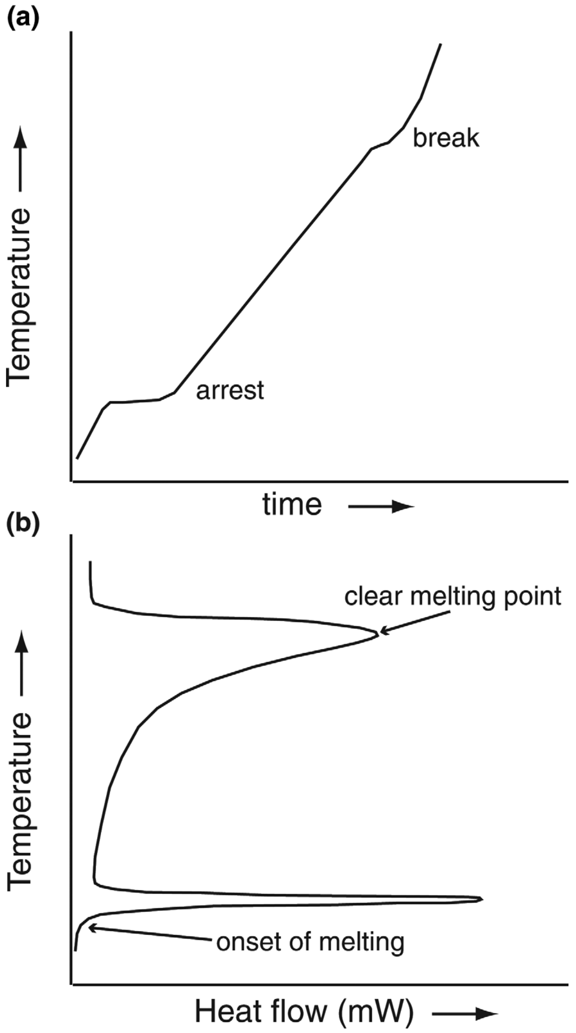

FIGURE 2: (a) Hypothetical heating curve for a two-component system (after Garland *et al.*, 2003). Thermal arrest correlates with solidus temperature; thermal break marks the liquidus. (b) Hypothetical thermogram for melting in a two-component system. Onset of melting delineates the solidus; the clear melting point marks the liquidus.

again, precise measurement of temperature under geologic conditions is demanding, making low-temperature analogs attractive. Elders (1967), Barker (1969), Berry (1973), and Boardman and Youngblood (1975), describe lab exercises in which students use temperature curves to construct phase diagrams for the systems lead–bismuth, salol phenyl salicylate–thymol, P-nitrophenol–acenaphthene, and diphenylamine–naphthalene, respectively. Alternatively, with DSC instrumentation it is possible to measure heat flow rather than temperature. The thermogram [Fig. 2(b)] is a more sensitive probe of phase transitions than is a simple temperature curve (breaks in slope can be difficult to identify), and represents a visual record of changes in heat flow that correspond to reaction curves and points (liquidus, solidus, and eutectic) on our phase diagram. A list of published exercises designed for teaching phase equilibria, and a summary of advantages and drawbacks is presented in Table I.

CREATING A BINARY PHASE DIAGRAM WITH DSC ANALYSIS

In our experiment, we use a power-compensated DSC, which consists primarily of two independent pans set atop individual heat sources and temperature probes (Fig. 3). A chemical compound or mixture is sealed in an aluminum crucible and centered in the sample (S) pan. An empty aluminum crucible is similarly positioned in the reference (R) pan. Heat is supplied according to a program that maintains a fixed rate of temperature increase, with power delivered independently to the two pans to keep the sample and reference at the same temperature. During warming, the DSC monitors heat flow to the two pans, which will differ unless the reference and sample have the same heat capacity. Using a power-compensated calorimeter, heat flow is actually a measure of differential power (the net rate of energy supply) between the sample and the reference. Differential power (heat flow) is plotted versus

TABLE I: Advantages and drawbacks of published exercises for teaching phase equilibria.

Exercise	Data/Observations	System	Behavior
Brady, 1992	T vs %NaCl	Water, sodium chloride	Eutectic, peritectic
Boardman and Youngblood, 1975	T vs t	Diphenylamine, naphthalene	Eutectic
Darling, 2000	Visual	Water, potassium chloride	Eutectic
Gallus *et al.*, 2001	T vs t	Various	Eutectic
Kim and Musfeldt, 1991	Heat flow vs T	B-napthol, acetamide	Not well characterized
Current study	Heat flow vs T	Naphthalene, phenanthrene	Eutectic

Exercise	Advantages	Drawbacks
Brady, 1992 Temperature is monitored as ice is added to various H_2O–NaCl solutions. Temperature is recorded when a steady value is reached.	Student preparation of samples Experimental acquisition of data Inexpensive Nontoxic reagents	No ΔH_{fus} information Liquidus only
Boardman and Youngblood, 1975 Cooling curves are generated for naphthalene, phenanthrene mixtures. Break, arrest temperatures are determined.	Student preparation of samples Experimental acquisition of data Visual, tactile confirmation of crystallization	No ΔH_{fus} information Hazardous reagents
Darling, 2000 A microscope with heating and cooling stage is used to monitor crystallization and melting in H_2O–KCl inclusions.	Visual observation of crystallization and melt observations relevant to geologic samples Nontoxic reagents	Specialized sample preparation Prefabricated samples Specialized microscope No ΔH_{fus} information
Gallus *et al.*, 2001 Cooling curves are generated for binary liquid mixtures of various reagents. Break, arrest temperatures are determined.	Student preparation of samples Experimental acquisition of data Visual, tactile confirmation of crystallization	No ΔH_{fus} information Hazardous reagents Not adapted for geosciences
Kim and Musfeldt, 1991 Thermograms are acquired for melting B-napthol, acetamide mixtures. Analysis of thermal events yields solidus and liquidus temperatures.	Student preparation of samples Experimental acquisition of data Peak area proportional to ΔH_{fus} Distinct features for onset and clear melt Nontoxic reagents	Requires DSC instrumentation Phase diagram not well characterized Scan time (50 min/sample) Not adapted for geosciences
Current study Thermograms are acquired for melting naphthalene, phenanthrene mixtures. Analysis of thermal events yields solidus and liquidus temperatures.	Student preparation of samples Experimental acquisition of data Peak area proportional to ΔH_{fus} Distinct features for onset and clear melt Reduced scan time (5 min/sample) Well characterized phase diagram	Requires DSC instrumentation Hazardous reagents

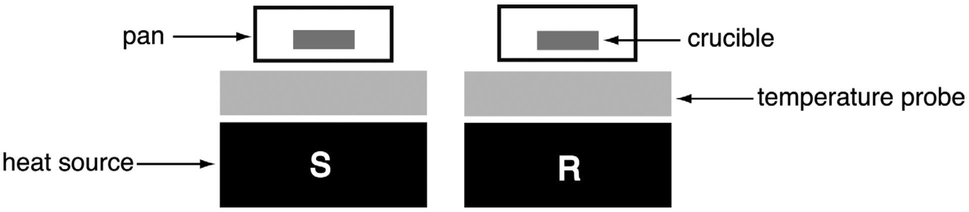

FIGURE 3: Schematic diagram of the DSC apparatus.

temperature to form a thermogram [e.g., Fig. 2(b)]. Once melting begins, a feedback loop in the calorimeter control circuitry sends more power to the sample pan to equilibrate the sample and reference temperatures. The resulting spike in differential power produces a peak on the thermogram that indicates the temperature of the phase transition. The area under the peak can be used to calculate the latent heat of melting.

In this exercise, samples containing different proportions of naphthalene ($C_{10}H_8$ – mol. wt. = 128.17 g/mol) and phenanthrene ($C_{14}H_{10}$ – mol wt. = 178.23 g/mol) are prepared and melted. We have chosen to melt rather than crystallize our samples to avoid nucleation issues and supercooling, as these effects may complicate thermogram interpretation. For samples consisting of 100% N or P, melting begins at the melting temperature of the pure end member (80.4°C and 99.4°C, respectively) and continues, at a fixed temperature, until the solid is gone. The result is a single peak on the thermogram. For the one-component system, the phase rule for isobaric conditions $F = c\text{-}p+1$ (degrees of freedom = number of components – number of phases + 1) indicates zero degrees of freedom when the two phases, solid and melt, are in equilibrium, explaining why the temperature remains fixed throughout melting. For the unique eutectic mixture of 47% P and 53% N, behavior is similar, and melting proceeds at a single temperature (48.6°C, Gallus *et al.*, 2001) until complete, again forming a single peak on the thermogram. For all other mixtures of the two components, the thermogram is characterized by two peaks. Melting begins at the eutectic temperature, forming an initial peak [Fig. 2(b)] on the thermogram that correlates with the thermal arrest on the heating curve [Fig. 2(a)]. As melting continues at fixed temperature, the solid is depleted in eutectic proportions until one of the phases (N or P depending on sample composition) is lost. The loss of a phase adds a degree of freedom, and the sample temperature rises as the remaining solid melts. When the second solid phase is lost, heat is no longer consumed for melting, resulting in a change in heat flow that forms the descending edge of the second thermogram peak [Fig. 2(b)], which correlates with the thermal break on the heating curve [(Fig. 2(a)]. This second peak marks the clear melting point of the sample and occurs at the liquidus temperature for the given mixture.

Interpreting the thermograms is straight forward despite variations in thermogram shape. For bulk compositions near the eutectic, most of the melting occurs at the eutectic temperature, resulting in a low temperature peak that is larger than the high temperature event. The opposite is true for bulk compositions approaching purity. Peak separation also varies with composition. A gradual increase in heat flow between the low and high temperature features [Fig. 2(b)] reflects univariant liquidus melting following the loss of a phase at the eutectic. However, for small increments of liquidus melting, this sloping portion of the thermogram may be obscured by the baseline. Despite these variations, the relationships between the low temperature peak and the onset of melting (eutectic), and between the high temperature peak and the clear melting point (liquidus) are robust.

By analyzing a number of sample mixtures, the solidus and liquidus lines can be defined. The eutectic composition can be estimated by extrapolating the liquidus curves down toward the eutectic temperature. If desired, the eutectic composition can be determined more accurately by calculating the latent heat of melting at the eutectic (proportional to the area beneath the first thermogram peak) as a function of bulk composition (Brown, 2001). Plotting all of the student-produced data after three administrations of this lab exercise illustrates the effectiveness of the technique for delineating the phase boundaries in the N–P system (Fig. 4). The temperature of the eutectic, 50°C on average with a standard deviation 0.9, as well as the clear melting points of the pure end members, are highly reproducible. Comparison with the published eutectic temperature of 48.6°C (Gallus *et al.*, 2001) indicates accuracy within ± 1°C. In contrast, liquidus temperature data, particularly on the P-rich side of the diagram, are less precise. Considering the well-defined liquidus on the N-rich side,

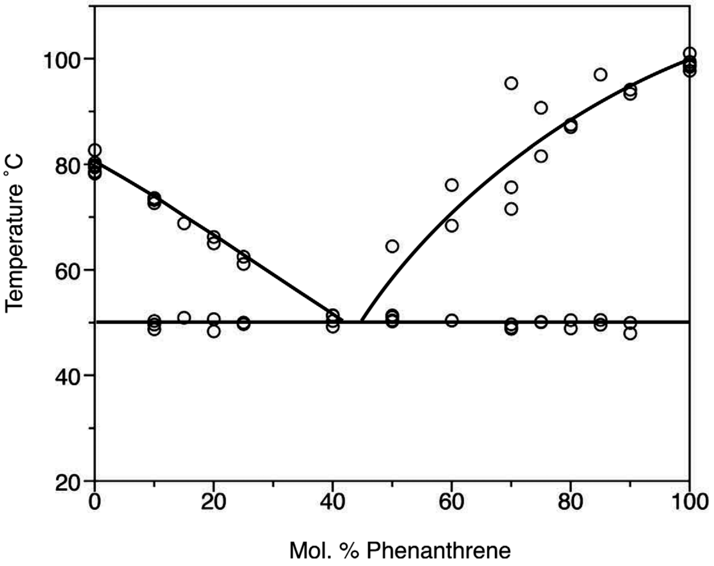

FIGURE 4: N–P phase diagram based on data collected by students in 2007, 2009, and 2010.

reproducibility issues on the P-rich side are probably related to inconsistent sample preparation. A common source of error is sample inhomogeneity resulting from inadequate grinding with mortar and pestle, which can result in spurious events in the thermogram. Fortunately, these thermogram anomalies are recognizable, and fresh samples can be prepared. It is most likely that the spread of liquidus values is a consequence of sample weighing error. Despite such errors, students have had little trouble creating phase diagrams with analysis of as few as six to seven samples.

MATERIALS AND PROCEDURE

We have conducted this laboratory exercise using a Perkin Elmer DSC 7, which is a power-compensated instrument. Since alternate instrumental designs yield similar thermograms, any calorimeter that operates at ambient pressure between 40° C and 100° C should be applicable. We have settled on a 5 min scan rate (from 25 °C to 110 °C at 20 °C/min). Higher scan rates enhance instrumental sensitivity but decrease resolution (i.e., result in thermogram peaks that are taller, but also broader). An indium sample was analyzed for calibration. The instrument should be calibrated at the experimental scan rate. In addition to the DSC and sample materials, necessary supplies include aluminum crucibles, forceps, a nitrogen tank with regulator and bubble meter, a microbalance, a hot plate, and mortar and pestle. Because our lab sessions are only two hours long, we devote one session to sample preparation and the second to operation of the DSC. Our students typically work in teams of two or three. The exercise can be streamlined by assigning a few samples to each team and compiling the data for use by the entire class.

For safety, students wear laboratory goggles and gloves during sample preparation, and melting and grinding of samples is conducted in a fume hood. We have conducted this exercise within one of the University chemistry laboratories, as our geology lab spaces are equipped with only one small fume hood, each. Napthlanene and phenanthrene are carcinogens: skin contact, eye contact, ingestion, inhalation, and open flames should be avoided. Consult the materials' safety data sheets before conducting the laboratory. Reagents and mixtures should be stored in sealed containers when not in use.

The laboratory procedure is summarized below. A copy of the complete laboratory execrise is provided as a supplement to this article

1. Prepare samples by weighing amounts of phenanthrene and naphthalene to yield six samples of 0.5 grams, each. The desired mixtures, in molecular % naphthalene, are 0 (pure phenanthrene), 15, 30, 50, 70, and 100 (pure naphthalene). As a homework assignment, students converted these molecular proportions to wt.% before class. When preparing mixtures, it is crucial to record actual weights measured so that the exact compositions of the mixtures can be plotted on the phase diagram.
2. Melt each sample on a hotplate, continuously mixing with a spatula. Once the sample is completely melted, remove from heat and continue to stir as it crystallizes.
3. Grind the sample thoroughly with a medium mortar and pestle. Afterward, transfer a portion of the sample to an agate mortar and pestle, and grind again.
4. Tare a sample pan on the microbalance. The sample size of the mixture should be between 2–5 mg. Seal the pan. Reweigh the pan, and record this value.
5. Load sample into a calibrated DSC and scan from 25 °C to 110 °C at 20 °C/min.
6. Once the run is complete, identify the peaks on the thermogram and record their temperatures. For most mixtures, with the exception of the eutectic composition, two thermogram peaks will be observed [(Fig. 2(b)]. The eutectic temperature corresponds with the onset of melting, which is indicated by the temperature at which the first peak on the thermogram begins to form. Points on the liquidus curves can be determined by measuring the clear melting points of the samples. The clear melting point corresponds approximately to the apex temperature of the second peak.
7. Repeat steps 1–6 for all samples.
8. Print representative thermograms for reference in a lab report.

Many, if not most, chemistry, polymer-science, or material-science programs have DSC facilities available for research purposes. In our case, geology students gained access to the instrumentation as a result of collaboration between the departments of geology and chemistry. However, if a dedicated calorimeter is desired, used equipment is widely available. We have chosen an inexpensive system that accommodates a wide array of scan rates (from 1 °C/min to 20 °C/min) and sample sizes (2 mg–10 mg) at ambient pressure. An analytical balance (0.0001 g precision) may be substituted for the microbalance with minimal impact. The total start-up cost including purchase of a used DSC 7 and a new analytical balance is approximately $6500. This includes the purchase of sufficient consumables to prepare 400 samples. The consumables cost is one dollar per sample.

STUDENT LEARNING AND ATTITUDES

Upper level geology majors have conducted this experiment as part of the lab component for an introductory class in igneous and metamorphic petrology at the University of Southern Indiana during the spring semesters of 2007, 2009, and 2010. Working in teams, students prepared and analyzed samples. Data produced by all of the student teams was then compiled, resulting in a more comprehensive set. Using this community record, each student was asked to plot the data to produce a phase diagram. All of the students successfully created phase diagrams for this system, with a eutectic temperature of approximately 50°C and eutectic composition, extrapolated from points on liquidus curves, at approximately 50% phenanthrene. In addition, each student submitted a lab report including a discussion of thermogram interpretation, phase diagram construction, and error analysis.

The laboratory exercise was designed to improve student understanding of phase diagrams. Upon completion,

TABLE II: Rubric for assessing of student learning from lab reports and excerpts of student work scoring 4.

Outcome	4	3	2	1
Terminology	Correct usage of all relevant terminology	Correct usage of most relevant terminology	Correct usage of some relevant terminology with significant mistakes	Minimal use of relevant terminology or replete with mistakes
Thermal features	Correctly identified and thoroughly discussed	Correctly identified with minimal discussion	Identified with significant mistakes	Features not identified or discussion replete with mistakes
Procedure/skills	Thorough and reproducible, no mistakes	Marginally complete or significant mistakes	Marginally complete with significant mistakes	Minimal coverage or replete with mistakes
Error discussion	Thorough and reasonable error analysis	Thorough analysis with some trivial error sources	Marginally complete or significant mistakes	Minimal coverage or replete with mistakes

students were expected to have (1) mastered relevant, critical terminology such as eutectic, liquidus, and solidus; (2) recognized the thermal events associated with melting, and distinguished the melting behavior of pure substances versus mixtures; (3) developed the procedural skills needed to generate their own data sets using modern instrumentation; and (4) developed the analytical skills to evaluate data quality. Since each student submitted a formal laboratory report, our assessment of student learning is based largely on this product. Using 21 lab reports produced by students during the spring 2009 and 2010 semesters (while a total of 25 students have completed this lab exercise, the rubric was not yet developed in 2007, which was the year we first implemented the exercise), the authors independently assessed student learning using a four-point rubric (1 — poor, 2—fair, 3—good, 4 —excellent) with categories corresponding to the four learning objectives (Table II). Overall, the results were quite positive. The average cumulative score (average of the scores for the four learning objectives) was 3.3. Within a category, each evaluator's average score was within 10% of the group mean. A plot of cumulative scores, separated by scorer for 21 lab reports (Fig. 5), illustrates the quality of student performance and the consistency of the scorers.

Additional assessment of learning was based on questions in an opinion survey administered in spring 2009 and 2010, two weeks after the lab was completed. Opinion questions (Fig. 6) included "This lab improved my understanding of melting" (95% agreed), "This lab exercise improved my understanding of crystallization" (47% agreed), and "This lab improved my understanding of phase diagrams" (95% agreed). Several students indicated that this was their best experience using analytical instrumentation; preparing samples, analyzing them, and then using the data to generate a diagram similar to the one (diopside–anorthite) discussed in lecture seems to have been a satisfying process for them. When asked what they liked most about the exercise, several students commented on the "hands-on" nature of the exercise. One student wrote "I believe learning by doing is a better approach to help students understand concepts and theory learned in lecture." Student complaints related to crowding around the instrument, precision required for measuring samples, and time consumption. Other student comments are included below:

- "It was good to actually see how eutectic melting worked, rather than simply hearing about it."
- "Being able to see how liquidus and solidus lines are calculated [was what I liked most]. Kind of enjoyed getting to do something different."
- "Phase diagrams and how things are plotted on the binary phase diagrams were a lot more clear after the lab."
- "The ability to see the thermograms and the actual melting temperatures where melting took place."

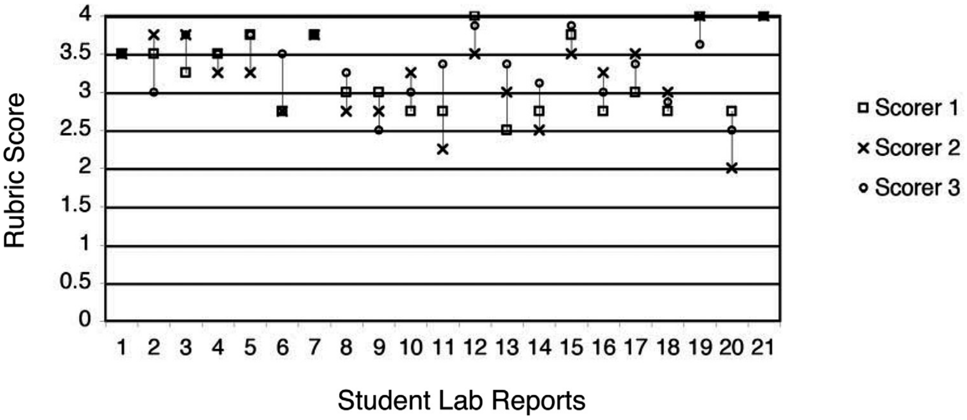

FIGURE 5: Cumulative scores (averages of scores on the four rubric categories) separated by scorer for student lab reports.

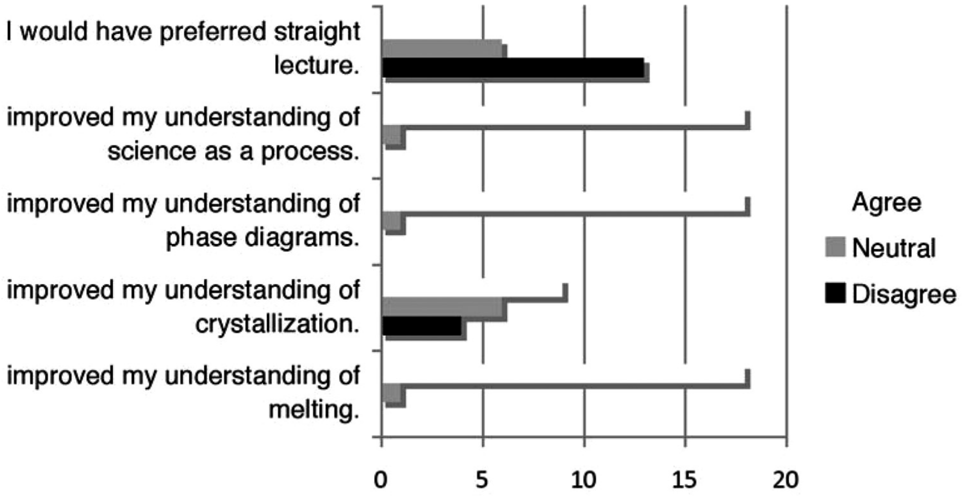

FIGURE 6: Student response to opinion survey.

CONCLUSIONS

The laboratory exercise described here gives students the opportunity to deepen their understanding of phase equilibria by generating their own data sets and then using this data to construct a phase diagram. Unlike other hands-on exercises designed around construction of a phase diagram (Elders, 1967; Barker, 1969; Berry, 1973; Boardman and Youngblood, 1975; Brady, 1992; Darling, 2000), this DSC exercise focuses on heat flow during phase transition, making it necessary for the student to think about and understand the thermodynamic principles underlying the phase change. The exercise exposes students to modern instrumentation and allows them to experience scientific inquiry. In contrast with exercises that yield results that can be automatically applied to a given problem like pieces of a puzzle, the DSC produces thermograms that must be interpreted. Students are prompted to ask themselves questions such as—Does my thermogram make sense? What does this peak mean? Was my mixture sufficiently homogenous? I wonder if the peaks will look similar for the next mixture?

Assessment of student learning, based on lab report quality, yielded an average score of 3.3, with a score of 4 corresponding to mastery of the desired learning outcomes. These scores, as well as teacher observation of students in the lab, indicate that this hands-on introduction to phase equilibria helps solidify concepts that most students found rather abstract beforehand. Student responses to opinion questions indicate that most enjoyed the lab and preferred it to straight lecture as a teaching delivery method. Many mentioned an appreciation of the hands-on nature of the lab, and the majority agreed that it improved their understanding of phase diagrams, helping to prepare them for deeper discussions of more-complicated phase diagrams later in the semester.

Quantitative assessment of the exercise as a teaching tool, regardless of the assessment rubric, is difficult given the small number of students that take this course (the number of students is insufficient for statistical validity). Nevertheless, there is no question that this exercise gives students the opportunity to practice many quantitative skills, including calculation (students converted molecular % to weight % before weighing out sample mixtures), graphing (students used Microsoft Excel to graph their phase diagrams), and assessment of error (students calculated standard deviations when reporting data and included a discussion of sources of error in their lab reports). Finally, this exercise helps to dispel the view that geoscience is largely qualitative (Manduca *et al*., 2008).

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