INSTRUCTIONAL RESOURCES FOR TEACHING THERMODYNAMICS ACROSS THE GEOSCIENCE CURRICULUM

Thermodynamics makes the world go round. It drives global geochemical cycling from the solid Earth, through the hydrosphere, atmosphere, and biosphere. Through approaches like thermobarometry and pressure–temperature–time (*P–T–t*) paths, it provides insights into many of Earth's processes, such as phase transitions and melt reactions; such insights allow us to interpret plate tectonics and the evolution of the Earth system. These facts are precisely why ALL geoscience students should gain a firm understanding of the principles and applications of thermodynamics in their pre-professional training. A single exposure to thermodynamics in an isolated course is not enough. Thermodynamics must be practiced early and often. Opportunities abound to engage thermodynamics across the geoscience curriculum and at all instructional levels.

Extensive collections of online teaching resources have been developed to support teaching and learning about thermodynamics. They include class-ready teaching activities, laboratory exercises, visualizations, links to related websites, recommended reading lists, and related resources on teaching methods and assessments. Most of these resources have been developed, organized, and reviewed by geoscience faculty through the *On the Cutting Edge* program for faculty professional development (http://serc.carleton.edu/1573) or through other community-based projects sponsored by the U.S. National Science Foundation. The instructional activities in these collections are focused on student learning, and all employ active, experiential learning approaches using a variety of teaching methods (see *Elements*, volume 3, number 2, April 2007, and a bibliography of teaching strategies at http://serc.carleton.edu/17525). Beyond gaining a mastery of the concepts of thermodynamics, complementary learning goals include the development of quantitative skills, the use of authentic data to solve geologic problems, and the use of modeling and visualization programs to represent and explain Earth phenomena. Here is a sampling of the online instructional resources that can serve as an instructor's companion to this issue of *Elements*.

For the application of thermodynamics to the solid Earth (Powell and Holland 2010 this issue) with a focus on igneous and metamorphic petrology, there is a comprehensive curriculum entitled "Teaching Phase Equilibria" (http://serc.carleton.edu/19562). This module includes tutorials for students and teaching activities for faculty. It starts with Gibbs' phase rule and progresses to topics such as phase diagrams, mineral compositions and chemographic projections, an introduction to thermodynamics, the Clapeyron equation, the method of Schreinemakers, types of igneous and metamorphic reactions, activity models, thermobarometry and *P–T–t* paths, and worked examples using advanced modeling programs such as TWQ, Perplex, Melts, and ThermoCalc (http://serc.carleton.edu/19573). A good example of the type of exercise is Sumit Chakraborty's "Learning Thermodynamics and Using Spreadsheets" (http://serc.carleton.edu/25381). In addition to the use of internally consistent thermodynamic databases, instructional activities have been developed using the American Mineralogist Crystal Structure Database in activities such as Kent Ratajeski's "Crystal Structures as Geobarometers" (http://serc.carleton.edu/7399).

A collection of animated PDFs of binary and ternary igneous phase diagrams (Fig. 1; http://serc.carleton.edu/19564), developed by Dex Perkins and John Brady, demonstrate the use of the lever rule to determine the state of numerous common rock-forming systems as a function of temperature (always a challenge for students to master, but made significantly easier through the use of these visualizations). Other visualizations include topics like Dave Hirsch's "AFM Projection 3D Movie" (http://serc.carleton.edu/6661) and Roger Powell's QuickTime movies of metamorphic AFM diagrams and the NCFM system over a range of physical conditions (http://serc.carleton.edu/17552).

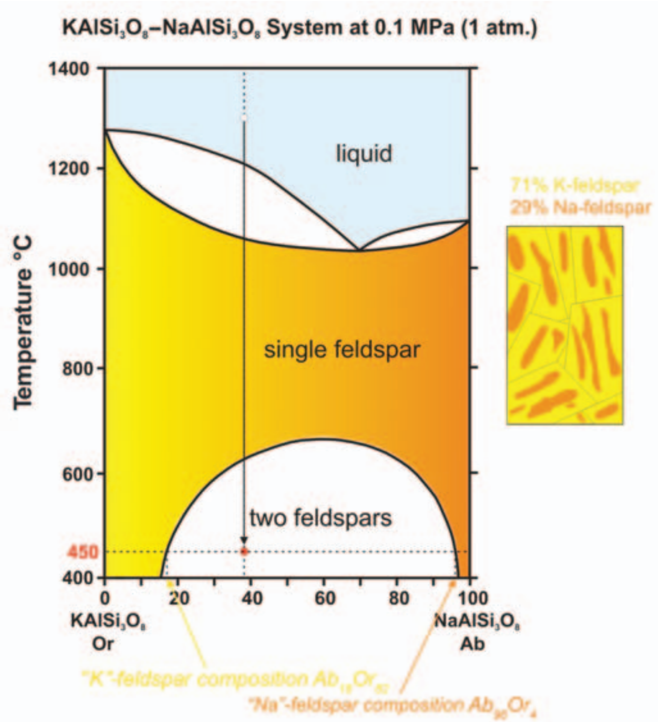

Figure 1 The binary alkali feldspar temperature–composition (*T–X*; isobaric) phase diagram at low pressure, developed as an animated PDF by Dex Perkins. This phase diagram represents a closed system at equilibrium conditions (essential information required to appropriately interpret this diagram). The vertical line represents the starting bulk composition of the system (arbitrarily picked to be 38% albite and 62% orthoclase). The dashed line shows the isotherm at 450 °C. At equilibrium, the state of the system is constrained to contain two solid phases that have compositions of $Ab_{18}Or_{82}$ and $Ab_{94}Or_{06}$ in relative proportions of 71% and 29%, respectively, based on the "lever rule."

Water–rock interactions (Zuddas 2010) are represented in activities such as Andy Knudsen's "Introduction to Equilibrium Thermodynamics: Salt Dissolution" (http://serc.carleton.edu/26805) and Barb Dutrow's "Timing of Mineralization in the Palm of your Hand: Cross-Cutting Relations, Copper Minerals and Ore-Forming Hydrothermal Fluid Evolution" (http://serc.carleton.edu/24565), in which the evolution of the fluid that developed alteration in cross-cutting veins is explained using activity–activity diagrams. Thermodynamics applied to atmospheric science (Bott 2010) is demonstrated in Tony Hansen's "Atmospheric Vertical Structure and the First Law of Thermodynamics" (http://serc.carleton.edu/36975), and thermodynamics applied to the ocean system (Millero and DiTrolio 2010) is demonstrated in Paul Quay's "What Is the Fate of CO_2 Produced by Fossil Fuel Combustion?" (http://serc.carleton.edu/36976).

Other thematic collections of resources have been developed to promote instruction about mineral physics and Earth's deep interior (Saxena 2010; see http://serc.carleton.edu/31415 and the Understanding Deep Earth website, http://serc.carleton.edu/36598), and to complement the 2008 MSA/GS short course and RIMG volume 69, *Minerals, Inclusions and Volcanic Processes* (Richet 2010; see http://serc.carleton.edu/28510). In addition, all of the original teaching activities published in the *Teaching Mineralogy* volume [1997, Brady, Mogk and Perkins (eds.), published by MSA] are now available online, with activities such as Dave Bailey's "Heat Capacity of Minerals: A Hands-On Introduction to Chemical Thermodynamics" (http://serc.carleton.edu/23863). There is also a "primer" on geochemical instrumentation and analysis, which introduces students to the methods used to acquire geochemical data (mineral, whole-rock, isotopic) that can then be used in thermodynamic modeling of the Earth system (http://serc.carleton.edu/18410).

Although we've made a good start, we need help in building these collections of instructional resources on the applications of thermodynamics to Earth systems. Please contribute additional teaching activities or recommend websites or articles you use in your own classes by submitting to: http://serc.carleton.edu/7074. If all the academic readers of *Elements* were to contribute just one teaching activity or resource, just imagine what a rich collection of teaching materials we would be able to share for the benefit of all!

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