

CONTINUING ADVENTURES IN EXPERIMENTAL  
PETROLOGY; DIFFUSION KINETICS, BASALT  
CRYSTALLIZATION, AND MELTING OF PELITIC  
SCHISTS

FACULTY

John B. Brady, Smith College  
Samuel J. Kozak, Washington and Lee University

STUDENTS

Sean P. Flynn, The College of Wooster  
Kristopher Edwin Kerry, Amherst College  
Dana Kovaric, Smith College  
Ronald W. Niebo, Washington and Lee University  
Gillian Rosenstein, Smith College  
Hendra Sasmita, Beloit College

VISITOR

Jack Cheney, Amherst College

# **Continuing Adventures in Experimental Petrology; Diffusion Kinetics, Basalt Crystallization, and Melting of Pelitic Schists.**

Samuel J. Kozak, Department of Geology, Washington and Lee University,  
Lexington, VA 24450

John B. Brady, Department of Geology, Smith College, Northampton, 01063

## **Introduction**

The summer of 1994 marked the third experimental petrology project sponsored by the Keck Geology Consortium at Washington and Lee University. Participants included two faculty members, six students and one puppy from five different institutions. In many ways, the 1994 group benefited from the experiences and results of the 1990 and 1991 students. Some previous mistakes (see Brady and Kozak, 1992) were avoided and some previous successes (Mata McGuire) were continued. Nevertheless, students in the 1994 project chose to rediscover the relative strengths of metal, rubber O-rings, and human flesh, the importance of planning, the significance of checklists, and the persistence and success of water in finding otherwise undetectable channel ways. In addition, northern misconceptions that the "War Between the States" is over, that "fried green tomatoes" is just a movie title, and that open-toed sandals and a teething puppy are compatible were dispelled.

Project selection in 1994 was guided by the interests of the participants and of the faculty advisors as well as by the equipment available. Piston-cylinder presses provided the means to study processes at pressures of 0.5-2.0 GPa. High pressure is necessary for any experiment involving hydrous minerals or melts. Gas-mixing furnaces provided the means to study processes at one atmosphere pressure and controlled oxygen fugacity. These furnaces are ideal for working with dry magmatic systems.

## **Melting**

Based on the strong interest and support of Jack Cheney of Amherst College, our unofficial third participating faculty member, two students (Sean Flynn of the College of Wooster and Kris Kerry of Amherst College) undertook a study of the melting of pelitic schists. In some metamorphic terranes, temperatures are reached that exceed the solidus temperatures of the metamorphic rocks. Melting occurs and the results range from migmatites to separate bodies of "granite" and metamorphic "restite." When confronted with these rocks in the field, geologists would like to know how much melting has occurred, what the temperatures and pressures were that produced this melting, and how the chemical compositions of the remaining metamorphic rocks have been modified. One way to investigate these questions is to melt metamorphic rocks in the laboratory.

Surprisingly few studies have been published on the melting of schists. Perhaps the most relevant to this project is the paper by Vielzeuf and Holloway (1988). They partially melted powders of a high grade metamorphic

rock of a single bulk composition without adding any water. Previous melting studies have not focused on pelitic compositions or have melted rocks containing minerals that would not be present in a high-grade metamorphic rock. Two natural samples were selected for study. One, studied by Kris Kerry (Amherst), is a muscovite-bearing biotite-garnet-sillimanite-quartz schist from Maine. The other, studied by Sean Flynn (Wooster), is a muscovite-free biotite-garnet-sillimanite-cordierite-quartz schist from central Massachusetts. In each case melting was investigated "dry" and in the presence of excess water. Because the schists contain hydrous minerals (micas), the "dry" melting experiments were actually "dehydration melting." The loss of water from the micas is closely connected with the formation of melt. Dehydration melting and water-saturated melting are the extremes within which natural melting must occur.

### **Magma Mixing**

Evidence of contact between magmas of different compositions can be found in many parts of the world. See for example the papers in this volume from the Maine Project. When two magmas come in contact, there is potential for mixing on various scales. Typically, the temperature of contact is closer to the solidus of one magma than the other, so the more mafic magma may chill or quench against the more felsic magma. Solidified mafic magma, sometimes in the form of pillows, cannot mix with the felsic magma as if two liquids are being stirred. Nevertheless, there may still be potential for mixing on a small scale near the contact by diffusive exchange between the mafic pillow and the adjacent felsic magma.

The process of "diffusive mixing" of mafic and felsic magmas was explored in experiments by Gillian Rosenstein (Smith) and Hendra Sasmita (Beloit). The goal of their experiments was to bring dacite (Gillian) and andesite (Hendra) into contact with basalt at various temperatures and to quantify the diffusive mixing that occurred. To prepare for their experiments, they melted volcanic rocks of the appropriate compositions and quenched the melts to obtain glass. The glasses were ground and packed into capsules with the denser basalt on the bottom to prevent any convection. The samples were heated under pressure so that the effect of water could also be studied.

### **Magma Crystallization**

Much of the foundation of igneous petrology is based on crystallization studies of magmas. Bowen's (1928) classic work grew out of his crystallization studies at the Geophysical Laboratory. Most of these studies concerned simplified chemical systems that were considered analogs of natural magmas. More recently, experimental petrologists have undertaken similar crystallization experiments on more complex natural bulk compositions with interesting results. Dana Kovaric (Smith) explored the crystallization of a natural basalt from the Cascades. Because basalts are iron-bearing, the oxidation conditions during crystallization can have a significant effect on the process. Therefore, these experiments were conducted at 1 atmosphere pressure in the presence of a mixture of gases (CO and CO<sub>2</sub>) that buffered the oxygen fugacity. To maximize the contact of the gases with the sample and to minimize the contact of the sample with a container (avoiding Fe loss), a drop of basalt liquid was suspended from a Pt wire in the vertical tube of the gas-mixing

furnace. Each sample was cooled at a constant rate from a temperature above the liquidus to the temperature of the experiment. After a long anneal, the sample was dropped into a water bath to quench the high temperature assemblage.

### Oxygen Diffusion

Oxygen is the most abundant element by volume in most terrestrial minerals and magmas and with silicon forms the structural framework for these materials. The movement of oxygen in magmas is important in establishing isotopic equilibrium and in determining the redox state of multivalent ions which in turn influences the behavior of elements during crystallization and the compositional evolution of residual melts.

The most common technique used to determine the diffusion rate of oxygen in silicate melts is by tracer experiments. In these experiments a melt enriched in  $^{18}\text{O}$  is exposed to air for varying lengths of time. The change in  $^{18}\text{O}$  as a function of time can then be used to calculate the diffusion rate of the oxygen. A second experimental technique uses redox kinetics to monitor the diffusion rate of oxygen into or out of a melt. The latter technique is the one used by participants in the Keck projects. In these experiments, the chemical system under study is doped with a small amount of a multivalent ion such as iron. Doped samples are then equilibrated in a reducing atmosphere ( $\text{CO}_2$ ). Individual samples are exposed to a more oxidizing atmosphere for different lengths of time. Changes in the redox state of iron occur as a function of time, and permit the calculation of diffusion rates of oxygen into the melt.

The two different types of experiments on melts of similar compositions yield dramatically different results. Isotopic tracer experiments typically yield oxygen diffusion rates two orders of magnitude slower than those obtained by means of redox kinetics. The most likely explanation for this difference is that the oxygen which diffuses in trace studies is part of the polymerized structural network in the melt. Oxygen diffusing in the redox experiments involves, at least in part, unpolymerized "dissolved" oxygen in the melt and does not have to break the relatively strong oxygen-silicon bonds in the polymerized network. Ron Niebo (Washington and Lee University) elected to study oxygen diffusion by means of redox kinetics in a part of the system anorthite-diopside.

### Acknowledgments

A number of people contributed to the success of the Virginia Project. Jack Cheney (Amherst College) visited during the first week of the project and provided samples of pelitic schists used in two of the projects. Diane Smith (Trinity University) provided samples of the dacite and basalts used in the cation diffusion and basalt crystallization projects. We would also like to thank Robert Thren, Whitney Morris, Henry Schreiber, Mata McGuire, and Ann Davis all of whom helped in a variety of ways.

### References Cited

- Bowen, N.L.(1928) *The Evolution of Igneous Rocks*. Princeton University Press.
- Brady, J. B. and Kozak, S. J.,(1992) Oxygen diffusion, viscous magmatic flow, garnet synthesis and other adventures in experimental petrology, *in* *The Fifth Keck*

Research Symposium in Geology (Abstracts Volume); Washington and Lee University,  
Lexington, VA, April 1992.

Vielzeuf and Holloway (1988) Experimental determination of fluid-absent melting  
relations in pelitic systems: Contrib Mineral Petrol, 98, 257-276

# The Partial Melting of a Metapelite Under Wet and Dry Conditions

Sean P. Flynn  
Department of Geology  
College of Wooster  
Wooster, OH 44691

## Introduction

Most large-scale melting in the continental crust occurs near the level of the base of the crust at a depth roughly equivalent to a pressure of 10 kbar. For this reason, a large number of experiments have been performed on rocks of various compositions at the pressures and temperatures believed to exist in this region. The majority of these studies of partial melting in the lower crust emphasize the effects of water on the melting processes. However, it is now assumed that the majority of magmas in the lower crust are originally undersaturated with respect to water, indicating that the melting processes normally occur without water (Clemens, 1984; Vielzeuf and Holloway, 1988). In order to further the understanding of this process, the experimental melting of a metapelite has been undertaken between 750-1050°C at 10 kbar under both wet and dry conditions. Similar studies done under vapor absent conditions have resulted in several models for the anatexis of pelitic rocks (Thompson, 1982; Grant, 1985; Vielzeuf and Holloway, 1988). They did not, however, offer a comparison between melting with and without water.

The goals of the experiments of this study are to determine whether and to what extent melting occurs on the metapelite at various pressures and temperatures by studying the amount and nature of the melt which is generated along with the various mineral assemblages which remain. In order to do this, experiments were conducted using a piston-cylinder apparatus. The products of these experiments were studied via scanning electron microscope in order to determine the following: 1) The composition of the melt at different P-T conditions, 2) The mineralogical composition of the remaining rock, and 3) The proportion of melt as a function of temperature.

Normally experiments of this nature are run for several weeks in order to establish equilibrium. Due to time constraints, however, these experiments could only last for a few days each. Therefore, a series of experiments were conducted at 850°C for various lengths of time to determine whether or not it is reasonable to assume that equilibrium was established in the experiments.

## Methods

The experiments were run at 10 kbar using a NaCl piston-cylinder assembly. Runs were conducted at 10 kbar for one to four days at temperatures ranging from 750°C to 1050°C. Each run consisted of both a water-saturated (10% water by weight) and a water-absent sample. Before the piston cylinder apparatus could be constructed, the sample had to be ground into powder. This was accomplished using a ball mixer. Once the sample had been ground, it was placed inside a sealed capsule. Gold capsules were used on all runs except those conducted at 1050°C. Silver-paladium capsules were used in the runs done at 1050°C since these were less likely to melt, thus helping to insure that contamination did not occur.

Once the capsules had been filled, the sample assembly was constructed. The sample assembly was then wrapped in lead foil and inserted into the piston-cylinder apparatus with a thermocouple wire which monitored temperature. The endload was employed and the pressure was brought up to 3 kbar at room temperature. The temperature was then brought up to the target temperature at a rate of 100°C/minute while the pressure was gradually increased to 10 kbar. Thus, the target pressure and target temperature were reached at approximately the same time.

At the end of each run, the sample assembly was removed from the pressure vessel and the surrounding material was broken off until the graphite sample container was completely exposed. The container was then mounted in epoxy and sawed in half. The exposed halves of the sample were then polished to 1 micron and covered with a thin film of carbon in preparation for analysis using a scanning electron microscope. All run products were analyzed on a Zeiss scanning electron microscope using a Link energy-dispersive analyser. Modal percents of minerals and liquids were determined via X-ray mapping techniques. The photographs were made in electron backscatter mode. Natural garnet crystals were used as standards and results were normalized to 100%.

Although steps were taken during each stage of the experiments and analyses to insure that the results were valid, erroneous analytical results may still have occurred. One possible source of error is contamination. This would most likely have occurred during the grinding of the rock when it could have been contaminated by previously prepared samples or by the grinding apparatus itself. Calibration could also lead to erroneous analyses as the accuracy of all analyses depends upon the accuracy of the standards used in calibration. Errors could occur relatively