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Artificial Magma Program: Report on Workshop Held in Oak Ridge, Tennessee on March 29–30, 1994

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Environmental Sciences Division
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Environmental Sciences Divison

ARTIFICIAL MAGMA PROGRAM: REPORT ON WORKSHOP HELD IN OAK RIDGE, TENNESSEE ON MARCH 29–30, 1994

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ACRONYMS AND ABBREVIATIONS

AMP	Artificial Magma Program
atm	atmosphere
3-D	three-dimensional
DOE	U.S. Department of Energy
ISV	in situ vitrification
KPa	kilopascal
m	meter
m^3	cubic meter
MORB	mid-ocean ridge basalt
ORNL	Oak Ridge National Laboratory
PNL	Pacific Northwest Laboratory

ABSTRACT

A workshop was organized and conducted in Oak Ridge, Tennessee, on March 29 and 30, 1994, to evaluate the use of in situ vitrification (ISV) technology to produce large silicate melts that would serve as analogs for natural magmas for the study of magmatic properties and processes. Presentations and discussions focused on important scientific issues and problems concerning crustal magmas that require the generation of large silicate melts in a controlled and monitored environment. ISV technology would permit experiments to test hypotheses or provide new data that cannot be tested or obtained through bench-top experimentation or the study of natural systems. The scale of ISV melts is intermediate between that of natural lava lakes and laboratory crucible experiments, with melt volumes from 15 to 300 m^3 easily obtained. This approach permits investigation of dynamic processes which operate on scales difficult to simulate through bench-top experimentation and that are not amenable to direct observation or control in natural systems (e.g., degassing, convection, and crystal settling). Several aspects of the ISV process make it uniquely applicable for the study of magma systems. The process produces "containerless" silicate melts, which permits development of important analog components of natural magma systems including: partial melt zones, stoping, contact metamorphic haloes, and "hydrothermal" fluids. The lack of a melt "container" also enables use of standard field-scale geophysical instrumentation for studying the seismic and electrical properties of the melt and host materials. In addition, volatile and particulate emissions from the melt can be sampled using methods that avoid reaction with, and contamination by, host rocks.

The workshop was attended by twenty-five university, national laboratory, and research institution geoscientists and engineers from across the United States. This group represented a wide diversity of expertise that included: representatives from the Battelle Pacific Northwest Laboratory engineering staff responsible for development of ISV for environmental restoration applications and geophysicists, geologists, and geochemists with interests in magmatic processes and properties and having expertise in theoretical, experimental, and field investigations. The consensus of the group was that the use of melts generated by ISV technology provided unique opportunities to advance the understanding of magmas and magmatic processes and warranted development of a proposal.

Introduction

A workshop was held during March 29–30, 1994, in Oak Ridge, Tennessee, to discuss the use of large artificial melts to investigate petrologic and geophysical aspects of magma evolution, migration, emplacement, and solidification. As analogs to natural magmas, artificial magmas (volumes up to 300 m^3) of specific bulk compositions can be produced using equipment developed for the in situ vitrification (ISV) of contaminated soils. These melts provide a unique experimental testbed for hypotheses related to petrologic and geophysical characteristics of magmas. Twenty-five scientists and engineers participated in the workshop to discuss the capabilities of the ISV equipment, features of the melts produced, and hypotheses that are amenable to testing with such an experiment. This report summarizes the discussion of scientific issues that could be studied using ISV melts. Recommendations were proposed for development of a program to use ISV-generated melts for the study of magmatic processes.

Recommendations

- Assemble a bibliography of publications reporting results of ISV-related studies.
- Evaluate and analyze pertinent existing data and samples
- Develop and test a melt sampler as soon as possible
- Plan tests with multiple objectives
- Piggy-back preliminary or mini–Artificial Magma Program (AMP) experiments on current or planned ISV demonstrations

Artificial Magma Program

An opportunity exists to advance the understanding of magmatic processes through the use of multidisciplinary experiments on large-scale artificial melts. Large melts created by joule heating provide the opportunity to design field-scale experiments that permit investigation of magmatic processes and properties in dynamic systems at scales large enough for gravity-dependent phenomena to operate (e.g., convection, crystal settling), but with constraints that permit excellent characterization and monitoring of the system before, during, and after melting. These large-scale experiments provide opportunities to advance our understanding of processes associated with magma evolution, and crystallization. Most specifically, AMP experiments can address scale-dependent phenomena and processes such as convection, crystal growth, and fracture of glassy and crystalline rocks that are impossible or impractical in bench-scale experimentation and direct observation of natural systems.

Time- and temperature-dependent melting or crystallization dynamics, accompanied by convection and crystal fractionation are coupled processes that are difficult to quantify in natural systems, and are not amenable to typical bench-scale experimentation. Evaluation of many of these processes and key parameters is possible through study of large-scale artificial melts produced under controlled and monitored conditions. In conjunction with investigations of melting or crystallization, the thermal energy flux associated with these processes can be monitored by three dimensional (3-D) instrument arrays within and around the magmatic environment. This type of experiment will also allow investigation of the processes by which volatile and trace metal components are released into the atmosphere from melts, and how they are transported to host rock surrounding a magma body. This knowledge will permit a better understanding of volcanic halogen and trace element emissions to the atmosphere, as well as geothermal systems and the processes controlling chemical transport. The large-scale melts are also well suited to the development, testing, and refinement of techniques for improved geophysical imaging of natural magmatic systems that would permit better understanding of magma chamber geometry and the process of magma migration within the earth's crust.

Knowledge of magmatic processes and the physical and chemical properties of magmas is gained largely through studies of fully-cooled, solidified igneous rocks or through controlled laboratory experiments. Although important, studies of igneous rocks are fundamentally indirect because only the final evolutionary stage of the system is preserved. Therefore, use of individual natural igneous rock bodies to address questions concerning processes that occur during magma genesis and magmatic evolution is complicated and uncertain. One approach to overcome this problem is direct observation and sampling of natural silicate magmas in lava lakes and lava flows. However, except in a few cases (Helz 1987), sampling of lava is possible over only a restricted range of temperature and crystallinity. As a consequence, time-dependent processes, such as crystal growth rates, proportions of crystals and melt, and compositions of crystals and melt at different evolutionary stages are difficult to quantify reliably from analysis of most igneous rocks or lava flows. Furthermore, observations of only the rock composition and texture may provide little information concerning the process by which the melt was generated. These and other limitations have been the impetus for high-temperature laboratory experimentation with analog chemical systems. However, small laboratory experiments are designed to address specific processes and/or parameters and cannot provide an analog for the total magmatic system, including the dynamics of large-scale convection, solidification and crystal settling, or degassing processes.

Geophysical investigations of magmatic systems are hampered by some of the same problems. For example, laboratory experiments conducted to correlate seismic velocity with magmatic properties must confront serious limitations because of problems associated with container walls and resolution (for wavelengths that can be transmitted in natural systems). Geophysical studies of natural magma systems face equally limiting problems because important acoustic parameters for melts and melt-host rock interactions are not quantified. The lack of knowledge concerning the interaction of acoustic waves with complex geologic environments containing magma bodies leads to uncertain interpretation of observational data, which is exacerbated by the large scales of natural systems.

Investigations of volatile species emitted in volcanic plumes and volatilization mechanisms within natural systems are difficult because of the complex nature of gases and particulates released from active volcanoes. Difficulties arise from the harsh and/or hazardous conditions encountered during sampling of volcanic gases near sources, and the related problems of extreme dilution and chemical reaction that have altered gases and particulates sampled far from a vent. Furthermore, gas sampled from a fumarole, which in many cases is the only source of magmatic gas, may be influenced by interactions with both wallrock and local meteoric water. In these circumstances the gas composition does not necessarily represent that released directly from the magma. These problems are difficult to address experimentally at a bench-top scale because of the complex nature of volatile interactions during exsolution and transport, and the scale-dependent processes of bubble nucleation, coalescence and migration.

The inability to observe and quantitatively monitor magmas on a large-scale impedes advances in understanding of many dynamic magma processes. This limitation includes restrictions on acquiring new data and the testing of hypotheses and numerical models in sufficiently constrained environments. A program of integrated experimentation using large-scale artificial melts as analogs for magmas provides a means to investigate fundamental scientific issues concerning magmatic processes. This approach permits investigation of dynamic processes that operate on scales difficult to simulate through bench-top experimentation and that are not amenable to direct observation or control in natural systems (e.g., gravity- dependent processes, which include convection and crystal settling). A program using large-scale artificial melts would be capable of addressing a broad range of magma physics and chemistry topics in a manner that can accommodate flexibility in experimental design.

ISV technology, developed for remediation of contaminated waste sites, offers unique opportunities for studying many magmatic processes under controlled conditions and at scales generally unavailable to earth scientists. ISV technology produces large bodies of silicate melt in a manner that permits extensive monitoring of a melt during both melt generation and solidification. Parent material, melt, and solidified products can be characterized before, during, and after vitrification experiments, respectively, to quantify chemical and physical parameters important to understanding igneous processes. The scale of ISV melts is intermediate between that of natural lava lakes and laboratory crucible experiments, with melt volumes from 15 to 300 m^3 easily obtained. The size of these artificial melts permits investigation of dynamic processes (e.g., degassing, convection, crystal settling) which operate on scales difficult to simulate through bench-top experimentation, and that are not amenable to direct observation or control in natural systems. Several aspects of the ISV process make it uniquely applicable for the study of magma systems. The process produces "containerless" silicate melts, which permit development of important analog components of natural magma systems including: partial melt zones, stoping, contact metamorphic haloes, and "hydrothermal" fluids. In conjunction with investigations of melting or crystallization, the thermal energy flux associated with these processes can be monitored by 3-D instrument arrays within and around the magmatic environment. The lack of a melt "container" also enables use of standard field-scale geophysical instrumentation for studying the seismic and electrical properties of the melt and host materials. The large-scale melts are also well suited to the development and testing of innovative techniques for improved geophysical imaging of natural magma systems that would permit better understanding of magma chamber geometry and the process of magma migration within the earth's crust. In addition, volatile and particulate emissions from the melt can be sampled using methods that avoid reaction with, and contamination by, host rocks. This knowledge will permit a better understanding of volcanic halogen and trace element emissions to the atmosphere. ISV has been developed by DOE since 1980 and is commercially available (for treatment of hazardous waste sites). Over 50 melts of the size required for these experiments have been generated. The unique features of ISV technology relevant to AMP were exploited at Oak Ridge National Laboratory (ORNL) during a field-scale test of ISV. The results obtained from this test are illustrative of the opportunities large artificial magmas can provide for geological investigations (Jacobs et al. 1992; Dunbar et al. 1993; Dunbar et al. in press). Indeed, use of ISV with an emphasis on geological investigations would provide opportunities for greater success because tests would be specifically designed to address geological problems. Research directed specifically at the geoscientific application of ISV would benefit not only the earth science community, but would advance the understanding of the ISV technology relative to its original application.

Workshop Summary

Gary Jacobs introduced the AMP concept to the participants and outlined the objectives for the workshop. John Tixier then described the ISV process (Buelt et al. 1987). Equipment is available for conducting artificial melt experiments ranging in size from engineering-scale (<1 m^3) to full-scale (300 m^3). More than 200 tests at these scales have been conducted since 1980, and ISV is currently being used to stabilize non-radioactive, hazardous waste sites by Geosafe, Inc. Pacific Northwest Laboratory (PNL) is working with several DOE installations to implement ISV for the stabilization of radioactive sites. Capabilities and limitations of existing field-scale ISV equipment are listed below.

Capabilities

- Large-scale experiments can be designed to include extensive instrumentation (e.g., temperature, pressure, heat flux, seismic, electrical).
- The bulk composition of the melt can be controlled with selection of either natural material (crushed) or mixtures of materials (natural, slags, commercial glasses, and dopants) to simulate a desired magma composition.
- The bulk composition can be designed to meet test objectives requiring either chemical and/or physical analogs to natural systems. For example, a bulk composition having the viscosity corresponding to that of a hydrous melt at high pressure might be simulated by a melt at 100 kPa by compositional modification to achieve a specific viscosity for seismic tests.
- Equipment for generating ISV melts is portable.
- Melt generation of maximum size can be achieved in 1–2 weeks, followed by periods of controlled time-temperature changes required to meet the objectives of a specific set of experiments.
- Melt temperature can be controlled to produce hyperliquidus to near solidus conditions by altering power levels to the melt.
- Samples of gases and particulates can be obtained from directly above the surface of the melt (avoiding contamination with wall rocks and minimizing dilution with the atmosphere. Atmospheric dilution can be quantified using the off-gas hood and measurements of flow rate through the system.
- Containerless melts for geophysical investigations.
- Seismic sensors can be configured in 3-D arrays surrounding the melt.
- The solidification products can be excavated to conduct detailed sampling and analysis.
- Chemical tracers can be introduced to investigate volatility, convective mixing, and crystallization processes using volatile, semi-volatile, conservative, and compatible vs incompatible tracer additions.

Limitations

- Methods for obtaining samples of melt during operations that will provide spatial and temporal samples of an evolving melt system have not been implemented and tested.
- The direct effects of high pressure on magma processes can not be studied.
- The solubility of water and other volatile compounds is limited by a 1 atm operating restriction.
- Oxygen fugacity is not controllable, but may be measured.

The next portion of the workshop was spent reviewing the research performed during a 1991 test of ISV at ORNL. This test, although emphasizing applied environmental restoration objectives, supported scientific inquiries related to petrologic and geophysical issues. The results provide an example of what can be accomplished with artificial melts even though practical limitations were imposed on experimental monitoring and sampling activities by the presence of radioactive material in the melt (Spalding et al. 1992; Jacobs et al. 1992; Dunbar et al. 1993; Dunbar et al. in press). Gary Jacobs provided background information on the test which was performed in collaboration with PNL. Mike Naney discussed the thermal and physical features of the melt that were observed during the ISV test. Nelia Dunbar described the mineralogical features of the ISV rock and chemistry of the volatiles that were sampled from the surface of the melt. Rick Williams presented the results of geophysical studies of the ISV melt. Brian Spalding then briefed the group on plans to apply ISV to a formerly used liquid radioactive waste seepage pit at ORNL.

A field trip to a partially excavated ISV rock body was conducted during the afternoon of the first day. This artificial rock was formed in 1987 during an ISV test with no radioactive materials present (Spalding and Jacobs, 1989). The solidified melt was partially excavated so that detailed sampling could be accomplished and geological relationships with the host rock could be observed. Participants collected samples and discussed features of the body, such as the sharp contact zone, distribution and nature of spherulites, vapor cavities, and fracture geometry.

The second day of the workshop began with a presentation by Sue Goff on the TerraKore concept, a technology for creating the equivalent of rotary-drilled boreholes by melting. The TerraKore concept is not new; it is being reinvestigated for application to environmental characterization and restoration activities. The concept uses heating elements to create boreholes via melting. One of the unique features of these boreholes is that the walls are sealed by quenched glass. Some applications of the tool may be beneficial for use in investigations of artificial magmas.

George Bergantz discussed magmatic fluid structures and macrosegregation. The three issues important to these rheologic problems are melt chemistry, geometry, and transport properties. George deferred discussing melt chemistry to Mark Ghiorso later in the morning. George explained how melt geometry adds a degree of freedom to analyses of magma dynamics and manifests itself in fluid structures. For artificial magma tests, consideration of the boundary conditions and geometry of the system is critical. The transport properties of melts (e.g., viscosity and density) are significant in the development of fluid structures and macrosegregation. Although models for the viscosity of melts are quite good, information on crystal-bearing systems is sparse and models are largely untested. Small-scale laboratory measurements are generally not applicable for model development because of scaling issues. One challenge for an artificial magma test would be to obtain ISV measurements of viscosity or other parameters that could be used to estimate viscosity. George emphasized that pretest numerical modeling and analog testing would be important for developing experimental constraints and boundary conditions for an artificial magma test to maximize the benefits from the test.

Bruce Marsh described results from some recent experiments in his laboratory (Hort et al. 1994) on water–alcohol systems and their implications for determining the "convective liquidus." His results suggest that convection diminishes rapidly upon cooling as the temperature reaches the liquidus. He pointed out several key differences between tests with such simple analog systems and tests that could be conducted using the AMP concept. The multicomponent nature of an artificial magma might result in behavior different from that of simple binary systems as a result of differences in thermodynamics, crystallization kinetics and transport properties. For artificial magmas, it would be important to know both the liquidus temperature and crystal–liquid physicochemical properties well. The scale of the artificial magma system and the reactive sidewall boundaries are important factors that more closely simulate natural systems, than experiments with simple binary systems. It is important to note that there are minimum melt sizes required to properly analyze the dynamics of convection and crystallization in magma systems; these sizes are achievable with artificial magmas generated by ISV technology.

Mark Ghiorso discussed the model MELTS (Ghiorso and Sack 1993, 1994), which simulates the crystallization of a broad range of natural melt compositions. MELTS is a potentially useful tool for planning artificial magma tests. For example, "designer" melt compositions with special crystallization features (i.e., cotectic crystallization at liquidus temperatures vs sequential saturation at subliquidus temperatures) could be developed and evaluated to aid selection of a melt composition that would provide maximum potential for achieving test objectives. In addition, artificial magma tests could be used to test hypotheses that would verify or aid refinement of MELTS. For example, temperature–enthalpy relationships could be determined and, with measurement of the proportion and chemistry of crystals, would provide a validation of MELTS. Mark postulated that the Oxygen fugacity variations in an ISV melt might be large and could be determined and related to convection and diffusion properties of the melt. In addition to requiring accurate and precise temperature measurements throughout the melt, such studies would necessitate a device capable of obtaining melt samples at known positions and temperatures within the melt with minimal alteration of the sample during retrieval, and cooling.

George Bergantz then led a discussion of hypotheses related to magma dynamics and chemistry that might be testable with an artificial magma. These are discussed in the following section on issues. Key data to be collected include temperature (extensive axisymmetric monitoring grid), convection rates of the melt, samples of melt, density, and heat flux. These parameters are discussed in more detail in the section on issues. Phil Ihinger pointed out that crystal nucleation and growth, together with quench effects could be significant in trying to obtain samples of melt. He suggested that crystal size distribution analysis methods be used to extrapolate to conditions of no quench effects. Significant discussion centered on what bulk composition should be considered for the first test. The consensus was that a mid-ocean ridge basalt (MORB) was the logical choice. A MORB composition would be geologically relevant, even at low total pressure and low water content. A well–characterized Columbia River basalt would provide an alternative that could be obtained locally at Richland, Washington, thus eliminating the need to transport the ISV processing equipment.

Mike Naney presented some concepts related to assimilation and magma mixing that would be amenable to testing via an artificial magma. While the effects of pressure and fluids cannot be studied in an ISV melt, the large size and controlled nature of the system makes it amenable to the investigation of macroscopic heterogeneities (compositional layering, crystal size, and fractures) during assimilation of enclave blocks or magma mixing that is not possible with standard laboratory methods.

Ken Grossenbacher summarized processes and parameters that influence the formation of cracks during the cooling of lava flows. He highlighted differences in fracture development during conductive cooling vs convective (liquid–vapor) cooling, and discussed how AMP tests might be useful in testing hypotheses related to this process. Such tests would also provide insight for predicting fracture network geometry in natural systems.

Rick Williams discussed possible objectives for geophysical studies. Using results from his previous work on the 1991 ISV test, he addressed the issue of which petrological questions are most amenable to study using geophysical methods. Details of his presentation are incorporated into the discussion of the geophysics issues.

Nelia Dunbar discussed some of the unique features of AMP melts that make them amenable to the investigation of volatile behavior. Phil Ihinger pointed out that large masses of glass samples would be available for determination of water solubility in melts at essentially 1 atm, a determination that is not possible with standard experimental methods. In addition, D-H fractionation could be determined from such samples.

Issues Amenable to Study via AMP

Petrology - Melt Chemistry and Crystallization

Issue Time- and temperature-dependent processes such as crystal growth cannot be reliably quantified from analysis of most igneous rocks. Similarly, mineral-melt composition and proportions as functions of time and temperature cannot be quantified from field observations of natural systems. Crystallization accompanied by melt convection and crystal settling are additional complexities making it difficult to quantify crystallization processes in natural systems, and that are not amenable to typical bench-scale experimentation. Most quantitative crystal nucleation and growth data has been obtained from experimental study of simple silicate systems. Extrapolation to natural systems is difficult because laboratory experiments are typically conducted at large undercooling and/or high cooling rates relative to those of natural systems. Other complicating factors (Kirkpatrick 1981) are variation of nucleation and growth rates with changing composition, multiple-phase crystallization, convective heat transport, crystal settling or floatation, and the effects of multiple intrusion.

Objective Obtain 3-D, time-dependent thermal data and corresponding samples from a large convecting melt system to analyze liquid-crystal equilibria/fractionation and crystal growth rates that may be used to calibrate models of magma chemistry evolution and crystallization.

Approach Monitor indicators of crystallization events with in situ (thermocouples) and ex situ sensors (heat flux sensors), in combination with syn-test and post-test sampling and petrologic/geochemical characterization. Instrumentation and sampling would be designed to measure key parameters, (e.g., melt temperature, "host rock" temperature, melt and crystals proportions and compositions during active melting and solidification).

Control melt temperature and cooling history via variation of ISV power levels to impose a time-temperature cooling path, or to impose "marker" thermal events that will provide physical and chemical indexes in the solidification products (e.g., impose isothermal periods to promote crystal growth at a measured temperature and for a known duration to permit growth of identifiable zones in crystals.

Expected results An analysis of the effects of scale and fluid dynamic processes (convection, mixing, bubble migration) on liquid-crystal chemical evolution and crystal growth. Development of a data set on a large melt body that will provide a basis for calibration of crystal growth models, and thermodynamic models such as MELTS (Ghiorso 1993, 1994).

Unique data set (liquid-crystal chemistry, crystal nucleation density, crystal size as functions of temperature and time) providing rigorous characterization of crystal–liquid fractionation and textural development in a well constrained system large enough to develop convective flow will provide a basis for comparison with theoretical model predictions and model development. The proposed experiment will provide in situ measurement of melt temperature and melt-crystal fraction.

Magma Dynamics - Convection

Issue Knowledge of convective processes in magma systems is of great importance for understanding the thermal energy balance, and both the chemical and physical evolution, of magmas. A controversy currently exists concerning the physical state of magmas when convection ceases. A widely accepted model is that magma convection proceeds until a large fraction of the magmatic liquid crystallizes (e.g., 50%). In contrast, experiments with some binary systems used to model magma solidification indicate that convection ceases at near liquidus temperature (Brandeis and Marsh 1989; Marsh 1989). Some of the reasons this controversy exists and will persist are: (1) convection of magma is difficult to quantify in natural systems because of significant logistical and experimental constraints (e.g., lack of access to crustal magma bodies, hazards associated with active lava lakes, slow cooling that limits temperature-dependent measurement, and the extreme demands of instrument size, installation and operational life); and (2) bench-scale experimental measurements focus either on analog chemical systems with properties that may not scale to those of magmas, or natural compositions in volumes that are not large enough (minimum dimensions 2×2×2m, ~$8m^3$) to yield a Raleigh number ($R_a = ag\Delta TL^3/dK$) of $> 10^3$ needed to achieve convection (Brandeis and Marsh 1989; Marsh 1989). Therefore, advances in understanding dynamic magma processes driven by convection requires careful measurements in a large volume of silicate melt having the composition and/or physical properties of a natural magma in which key parameters can be either monitored or controlled. The data from such an experiment must be appropriate for the needs of rigorous testing and further model development.

Objective Evaluate and test contrasting models of magma cooling and convection that have important implications for magma evolution.

Approach Monitor and map convection in a silicate melt closely simulating the composition of a natural magma (i.e., MORB) as a function of spatial position within the melt at temperatures ranging from hyperliquidus to the glass transition. Instrument and sample artificial magmas to measure key parameters [e.g., convective flow rate, geometry of convective "cells", melt temperature (the period and amplitude of oscillations recorded from a 3-D array of thermocouples may be used to monitor melt dynamics) (Jacobs et al. 1993), "host rock" temperature, 3-D heat flux from cooling melt body, and melt and crystal proportions and compositions during active melting and solidification].

Challenges and Needs An important operational challenge for this experiment is the development of a melt sampling apparatus that permits extraction of melt from any position within the artificial magma body with simultaneous measurement of melt temperature and sampling cooling history. In addition, methods or instruments are needed to measure melt flow direction and flux.

Expected Results Unique data set (thermal history, chemical evolution) providing rigorous characterization of convective flow in a magma body that provides a basis for comparison with theoretical model predictions and model refinements. The proposed experiment will provide in situ measurement of convection, viscosity, and other variables as a function of melt temperature and melt-crystal fraction. Control of power input to the melt body permits investigation of convective flow patterns in the presence of known heat source geometry and power input.

Magma Dynamics - Thermal Arrest

Issue Thermal energy released during crystallization of large magma systems influences the crystallization history of the magma, hydrothermal systems associated with magma emplacement, and the thermal history of host country rocks. However, analysis of the thermal energy released during crystallization of magma bodies typically is ignored or addressed by modifying other system thermal properties (e.g., thermal conductivity). The release of heat (ΔH^{fusion}) during crystallization of silicate melt has the potential to significantly influence the cooling history of a magma body and the host country rock into which the magma is emplaced (Ghiorso 1991; Spear 1993, pp. 46–52), as well as evolution of hydrothermal systems associated with magma emplacement. Depending on the thermodynamic properties of the melt system, the thermal environment, and the physical environment of the magma, the enthalpy of fusion released by crystallization of constituent minerals from the melt may produce significant perturbations on the cooling history of a magma (Spear 1993, pp. 46–52). In some circumstances the energy released during crystallization may be sufficient to temporarily halt cooling of the magma or portions of a magma body. Consequences of such a "thermal arrest" include influences on crystal size distribution manifested in textural variation. *(Note - The following examples help to provide a perspective on the magnitude of thermal arrests: crystallization of a pure phase in capsule experiments may result in thermal arrests of a few seconds to a few minutes in duration; the 1991 ISV test conducted at ORNL experienced a thermal arrest lasting approximately 12 hours during cooling of the 4.5-*m^3 *melt volume; extrapolation to natural magmas may produce thermal arrests of several days to several months or years duration) depending on the size and geometry of the cooling magma body).* Propagation of this thermal energy away from the magma body will influence hydrothermal systems associated with a cooling magma and mineral reactions in the host country rocks surrounding an intruding magma. Hydrothermal fluid–host rock mineral reactions driven by this latent heat may be responsible for retrogressive metamorphism associated with the emplacement of batholiths.

Objective Quantitatively evaluate the effects of thermal energy produced during magma crystallization on magma cooling, crystal size distribution, textural development, mineral chemistry, and "host rock" chemical and mechanical effects.

Approach Monitor and map the evolution of latent heat in a silicate melt as a function of spatial position within the melt at temperatures ranging from hyperliquidus to the glass transition. Sample the melt during cooling to characterize the liquid and crystallization products. Monitor temperature and heat flux in "host rocks" surrounding the melt.

Expected Results Unique data set (thermal history, heat flux, chemical evolution, and textural development) providing rigorous characterization of physical and chemical response of a magma body to cooling rate variations that provide the basis for comparison with theoretical model predictions and model refinements. The proposed experiment will provide in situ measurement of temperature, heat flux and cooling rate as a function of time. Control of heat input to the melt body provides the opportunity to study magma cooling under conditions in which the system heat balance can be measured.

Magma emplacement - Cooling Crack Development

Issue Characterization of fractures and knowledge of the thermal and mechanical parameters that control fracture development in rocks formed from cooling magma is important for understanding crack geometry and for interpreting the cooling histories of magma. The ability to accurately model fracture distribution in solidified magma has important practical implications for predicting productive zones and estimating the longevity of geothermal energy fields, predicting the geometry of fractures artificially generated for the purpose of extracting thermal and mineral resources, and evaluating fracture distribution in igneous rocks that may be used as hosts for hazardous wastes. However, it is seldom possible to evaluate the geometry and spacing of cooling fractures in an igneous rock under conditions in which the thermal history of the rock is known. In a natural system, such an analysis would require the installation of a thermal sensor array capable of long-term (i.e., months or years) monitoring at known positions within a cooling magma, followed by careful 3-D excavation of the solidified body. This type of field-scale experiment is subject to a multitude of logistics problems, in a environment that is unlikely to be conducive to establishing the experimental constraints and monitoring rigor to conduct a truly quantitative experiment.

Objective Measure fracture geometry (network as well as individual cracks) in large artificial rock bodies with known size, shape, mass, and contrasting thermal histories dominated by either conduction or two-phase aqueous convection within the solidified rock.

Approach Instrument artificial magma with both vertical and horizontal thermal sensor arrays to record thermal history of a cooling magma body of known size, shape, and composition. Install 3-D geophone and seismic source arrays to monitor fracture development. Simultaneously, monitor radon flux inside the hood covering the surface of the melt as one measure of fracture evolution. Perform experiments to evaluate fracture development in a system dominated by conductive cooling (dry conditions), and in a system in which convective cooling is possible (i.e., with saturated boundary conditions). After cooling to ambient temperature, fracture and joint development in the artificial igneous rocks can be evaluated by excavating and sampling the products of the well-characterized, large-scale melts through core drilling and/or wire-saw slab cutting.

Expected results Spatial and temporal fracture evolution, together with resulting fracture geometry and fracture density will be recorded and measured in a magma body whose cooling history and thermal boundary conditions are well known. The experiments will produce unique data sets that provide rigorous characterization of the thermal fracture history of a magma body. Data from experiments performed under "dry" and "wet" conditions will permit model evaluation and testing of these hypotheses: (1) the fracture front is at the T_g isotherm (glass transition temperature) for both wet and dry conditions; (2) a dry experiment will produce a conductive temperature profile and joint spacing will increase inward from the magma body margin; and (3) a wet experiment will produce a fracture front with constant local thermal gradient and cooling rate, resulting in columnar jointing.

Geophysics - Seismic Imaging

Issue Hunting for magma chambers in the crust using either near-vertical incidence reflection techniques or wide-angle reflection/refraction methods is notoriously difficult. Seismic reflection profiling is commonly hampered both by problems of difficult access to natural magmatic systems, and by formidable image reconstruction (migration) problems associated with the possibly complicated shapes and rapid velocity changes that can occur in their vicinity. Refraction methods where a relatively sparse distribution of sources and widely spaced receivers are used may lack the resolution to map, or even detect, magma chambers. The usual problems of seismic imaging are compounded when the uncertainties in the shape and other characteristics (e.g., state of crystallization, stratification) of natural magma chambers are considered.

Objective Obtain comprehensive seismic data sets for well-characterized artificial melts that simulate critical features of natural magma chambers. Use these data to evaluate different seismic imaging methods for possible application to natural magmatic systems.

Approach Conduct seismic reflection and wide-angle reflection/refraction profiling along the surface above silicate melts that resemble magma chambers. Scale the seismic profiles to simulate possible data acquisition in the search for real magma chambers at crustal scales. Obtain a comprehensive data set, and use subsets of it to determine which data acquisition and processing strategies are likely to prove most effective in actual field studies.

Expected Results Improved strategies for hunting magma using seismic methods. Reevaluation of the results from the 1991 ISV test, that (1) transmission tomography does not work well in these circumstances; (2) neither near-vertical nor wide-angle reflection profiling is likely to produce satisfactory images; (3) the maximum amount of information is obtained from "backscattered" reflections, using a dense array of receivers on the same side of the magma chamber as the shot, extending to large distances from the magma chamber. A better understanding of the important processes that can and should be imaged, such as convection, crystallization, stratification of the magma chamber, and degassing (bubble formation). Possible technologies for near real-time imaging of melt shape and depth that would contribute to predicting the eruptions of dangerous, closely monitored volcanoes.

Geophysics - Effects of Partial Crystallization on the Elastic Properties of Melts

Issue Knowledge of seismic P- and S-wave velocites of partial melts is of great importance, both in the application of seismic imaging methods to magma chambers, and to connect the results from petrologic models of melts to geophysical observations of magma chambers. Laboratory experiments conducted to measure the seismic properties of magmas or partially melted rocks are limited by difficult technical problems associated with working at high temperatures. Also, questions can be raised about the applicability of seismic properties determined from measurements on small-volume partial melts in the laboratory, because the laboratory-scale experiments generally do not fully reproduce the convection and crystalline textures that may occur in natural magmas.

Objective Determine P- and S-wave velocities and densities as they vary with temperature and crystallinity in crystallizing magmas.

Approach Produce 3-D images using P- and S-wave travel-time tomography of a silicate partial melt that closely simulates the composition and temperature of a natural magma, and in which the temperature, convective flow rate, and proportion of melt vs crystals is also determined. Instrument the artificial magma using arrays of ultrasonic transducers near or within the melt, obtain "cross-hole" data, and invert the data to map the distribution of P- and S-wave velocities in the partial melt.

Expected Results Data that characterize the seismic properties of the partial melt, including variations in the seismic properties due to changes in melt temperature, composition, and ratio of melt to crystals.

Geophysics - Monitoring the Electrical Resistivity of Partial Melts

Issue Because liquid magma is highly conductive and silicate minerals are highly resistive, numerous problems related to the process of melting and crystallization could be addressed via resistivity studies. In particular, the onset of crystallization and final solidification of a melt are marked by rapid changes in resistivity.

Objective Study the dependence of electrical conductivity on the crystallization of magma.

Approach Install a 3-D array of electromagnetic antenna operating in the kiloHertz to MegaHertz frequency range so that signals propagate through the artificial magma chamber. Monitor the attenuation of radio-frequency electromagnetic waves, which are strongly dependent on electrical conductivity, as the melt crystallizes, and interpret in terms of electrical conductivity and melt fraction.

Expected Results Remote monitoring of melt crystallization.

Volatiles and magmas

Issue Investigations of the sources of volatile species emitted in volcanic plumes and volatilization mechanisms within natural systems are difficult because of the complex nature of gases and particulates released from active volcanoes, difficulty of sampling volcanic gases near sources and the related problem of extreme dilution and chemical reactions that occur when gasses and particulates are sampled far from a vent. Furthermore, gas sampled from a fumarole, which in many cases is the only source of magmatic gas, may be contaminated by both wallrock and local meteoric water. These problems are difficult to address experimentally at a bench-scale because of the complex nature of volatile interactions during exsolution and transport, and the scale-dependent processes of bubble nucleation, coalescence and migration.

Of particular interest in the study of magmatic volatiles is the role of volatile species on the partitioning of trace elements between the melt and the vapor phase. This question is not only relevant to the impact of volcanic eruptions and passively degassing volcanoes on the earth's atmosphere, but also to understanding ore deposits that are related to magmatic systems. Specifically, how do the proportions of H_2O and CO_2 which make up the bulk of a vapor phase evolved from a melt affect trace element partitioning, and what role do Cl and F in the vapor phase play?

Furthermore, precise measurement of the isotopic composition and solubility of H_2O in a melt at atmospheric pressure is not possible using standard experimental techniques because the mass of dissolved H_2O is below the detection limit of analytical methods for bench-scale crucible experiments. The large mass of the ISV-generated melt would provide sufficient homogeneous material to enable extraction and precise measurement of these quantities.

Objectives

- To measure the effect of volatile phase composition, particularly with respect to H_2O, CO_2, Cl and F, on volatility of trace elements to elucidate the mechanisms of volatilization.
- To precisely measure the amount of H_2O soluble in a melt at atmospheric pressure.
- To measure the isotopic composition of H_2O soluble in a melt at atmospheric pressure.

Approach A number of different approaches will be taken to address the problem of trace element volatilization. The plume emitted from the melt will be continuously sampled using particle and base-treated filters in order to trap condensed trace elements and acidic gases (Finnegan et al. 1989). The CO_2 content of the plume will also be measured continuously using a CO_2 analyzer. This is possible because of the low CO_2 content of the atmosphere. Volatile tracers will be either introduced into the melt, or will be buried in the area to be melted, and their behavior will be investigated using the above-mentioned filter analysis. In addition, layers of more H_2O -rich or CO_2-rich rock would be buried in the area to be melted, in order to introduce more of these components into the melt. The isotopic composition of H_2O in the "starting material" would be measured. The output of these species would be monitored by the known melt depth, as well as by measuring the CO_2 content of the plume. The H_2O solubility and isotopic composition measurements would be made on large glass samples once the melt was cooled.

Expected Results Unique data sets that will enable comparison of uncontaminated trace element emission from an artificial magma with the trace element release from active volcanoes as a function of gas content and composition. Accurate measurement of the amount and isotopic composition of H_2O soluble in a melt at atmospheric pressure.

Benefits to ISV Technology

Issue Although ISV is being applied in both the commercial and DOE sectors, there are three issues that would significantly benefit from AMP. Improvement of our understanding of these issues would allow the technology to be used more effectively on a wider range of materials and sites.

(1) Melt shape and depth - Currently, melt depth is estimated during an ISV application using the self-feeding electrodes as "dip-sticks." This method provides reasonable results for depth, but does not provide any information related to the shape of the melt. The shape of a melt is critical when attempting to melt materials with either encapsulated volatiles or structures that may impede the gradual release of pressure from the boiling of water beneath the melt. In addition, without almost real-time monitoring of melt shape, ISV cannot be applied at sites where utilities or other critical structures are in close proximity.

(2) Release of volatile metals and radionuclides - A small percentage of semi-volatile radionuclides (e.g., ^{137}Cs) are volatized and collected by the off-gas hood. Although manageable, these quantities result in additional costs through increased handling, special engineering solutions, and disposal of secondary waste. AMP tests would provide opportunities, through the use of analog elements, to test various methods to minimize volatility and evaluate innovative solutions to the collection of these materials.

(3) Water and other volatiles (e.g., organics) - ISV is not being applied to sites with encapsulated volatiles (e.g., buried wastes, such as drums), or sites where underground structures prevent escape of volatiles around the base of the melt. The reason for avoiding such sites is twofold. First, only limited data are available to confirm that volatile organics are not pushed ahead of an expanding ISV melt front. Second, volatiles may collect under a melt causing pressure to build up until the volatiles are transported through the melt and released at the surface. These transient releases, even though not violent releases of pressure, can cause temperature-induced pressure increases under the off-gas hood that results in the loss of containment. Such loss is unacceptable for applications to hazardous and radioactive waste sites.

(4) Other issues - Data is needed on melt growth rate and heat transfer in fusion zone to improve models; Knowledge is needed on phase change and bubble generation - coalescence and absence of coalescence to mitigate melt eruptions; and Understanding is needed of melt displacement mechanism and bubble and water movement around melt.

Objectives An AMP test would provide an opportunity to investigate processes important to the three issues discussed above. Typical applications of ISV do not provide such an opportunity because the sites are generally unavailable for extensive instrumentation prior to the treatment. In addition, the presence of radioactive and/or hazardous materials limits effective access to the site, especially during active melting.

Approach Issue (1) would be addressed by refining geophysical methods tested during the 1991 ISV test at ORNL (Goldman and Williams 1993; Jacobs et al. 1992) to provide almost real-time imaging capabilities of the melt in three dimensions. Issue (2) would be addressed directly by the investigations described previously for elucidating the behavior of volatiles in volcanic systems. Engineering approaches to collect or reduce volatile emissions would be included via piggy-backed studies in AMP tests for minimal additional costs. Issue (3) would require special consideration of pressure and moisture sensors. Also, sources of volatiles with unique chemical and physical characteristics could be deployed around the melt for tracing behavior during melting. Some of this effort would address multiple objectives relating to the behavior of volatiles around magma bodies.

Expected Results For each of the issues, specific data will be obtained that will provide ultimate resolution of issues associated with the behavior of ISV-like melts that will directly benefit the technology and expand its effective application. Information to help resolve issue (1) will include optimal deployment of geophones, selection of sources frequencies, optimization of processing algorithms, and possible interferences by ISV equipment. Studies related to issue (2) will result in elucidation of the role of H_2O, CO_2, halides, SO_x, and other volatiles on the release of semi-volatile metals. Determination of physicochemical nature of volatiles will allow specific engineering solutions to be developed that minimize impact to ISV processing. Issue (3) will benefit from the collection of data related to pressure, moisture content, chemical tracers, and isotopes that are developed into a consistent conceptual model of volatile transport within and around an ISV melt. Such a conceptual model will allow an assessment of whether ISV can be applied to complex sites with the potential for transient volatile releases.

Recommendations:

- Thoroughly evaluate and analyze existing data and samples
- Plan tests with multiple objectives
- Develop and test a melt sampler as soon as possible
- Assemble a bibliography of publications reporting results of ISV-related studies.

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