



## Changing techniques and paradigms for the evaluation of magmatic processes

George W. Bergantz

Department of Geological Sciences, University of Washington, Seattle

**Abstract.** The study of magmatic processes is at a juncture. New continuum models for the complex physics of crystallization and melting with convection and crystal-melt segregation are now available, and the models are amenable to exploration by numerical methods. These models, which were largely developed in the fields of material science and mechanical engineering, will allow petrologists to consider a wide range of transport phenomena: crystal settling with reaction as fully multiphase flow, combined thermal and compositional buoyancy with realistic material property variations, open system and eruptive behavior and the appropriate system geometry and boundary conditions. The traditional notions of magma chambers as large vats of near liquidus material is being replaced by models where a substantial portion of the chamber may consist of a crystal-melt mush, subject to reintrusion or mobilization. Percolative flow and reaction in this mush, including contaminants, may be as important as near-liquidus processes in driving petrological diversity. Thus simple dimensionless numbers are of little utility in describing the vigor or style of magmatic processes. Melting of the crust following intrusion by basalt can be considered in light of two end-members: the large sill or tabular mafic magma body and intrusion of basalt as sequences of spatially and temporally overlapping dikes. Although more commonly cartooned, the large sill type may not be nearly as efficient as repeated diking in driving crustal melting, magma mixing, and mingling. The greatest challenge for those studying magma dynamics will be to key the models to well-constrained geological examples and to raise the sophistication of the content of these models in light of well-defined tests that have geological significance.

### Introduction

The purpose of this brief prospectus is to emphasize aspects of physical magmatism that I believe will be growth directions in the coming decade. For a recent literature review and thorough discussion of the state of the field, the reader is strongly encouraged to see *Cashman and Bergantz* [1991]. The emphasis here is on subsequent developments that I feel will best illuminate the geological and geophysical issues related to magmatism and petrologic diversity. Magma dynamics is usually considered in the context of volcanic eruptions, magma ascent, and magma chamber processes. Although all these phenomena are linked, they are usually considered separately and that is the spirit of the presentation given below.

Previous work on magma dynamics has been useful in illustrating a wide variety of possible processes in magmas, but there has been surprisingly little of that work that has appeared, in a quantitatively meaningful way, in petrologic reasoning. This is due in part to the inductive approach often employed in laboratory and numerical experiments [*Truesdell*, 1984 p. 478]. It is also a result of the "reductionist" approach which attempts to discover relationships that can be broadly generalized in complex systems. This has often resulted in end members for magmatic systems that are constructed on the basis of material and computational convenience. As a result, experimental materials and conditions typically reflect

nongeological states and the end-member behavior is difficult to integrate with the kinds of data that geologists have available. As stated by *Anderson* [1972 p. 393], "The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe." The point is that models for magmatic processes must attempt to include, at a minimum, the known types of interactions and degrees of freedom. Models of magmatic processes that fail to explicitly identify and incorporate the first order aspects of magmas will be a poor vehicle for understanding the complex nonlinear processes that attend magmatism. It is clear then that a productive approach must explicitly incorporate appropriately scaled physical properties and system geometry. This does not mean that a modified reductionist approach does not have a central place in the study of magmatic processes but rather that it is very difficult to provide much more than simple demonstrations from this approach; they are designed to this end. It is also difficult to anticipate, deduce, or explain the complex behavior of the real system from "demonstrations" when a number of processes are possible. For example, just as in the study of mantle convection today, few would consider models that did not include variable viscosity and phase changes to have much relevance.

The study of magmatic processes is at a juncture. Developments in the last 5 to 7 years in the fields of mechanical engineering and material science have led to sophisticated and formally correct transport models for solidifying systems. These models, which are discussed below, can successfully link the many scales of magmatic phenomena from the kinetics of crystal growth to the

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compressible flow of volcanic plumes. The proliferation of high power work stations, many tens of papers that explore aspects of the relevant physics, and available software will soon make the modeling of crystallization under geologically relevant conditions nearly routine. Petrologists will be able to explore a wide variety of phenomena such as reintrusion and magma mixing, kinetic models, time-varying boundary conditions, crystal settling with phase change, and different models of cumulate structure and intercrystalline flow. In addition, physical processes can be isolated and the importance of individual nonlinear terms can be established. One of the most attractive features of this approach is that one will no longer be limited to parametric estimates of magma dynamics derived from highly simplified, near-linear representations of the system which involve spatially averaged quantities.

### Crystallization

The petrologic diversity manifested in magmatic systems reflects the interplay of a variety of processes: thermal and compositional diffusion and convection, sedimentation, and distributed crystal growth. From a geological standpoint, a quantitatively useful continuum description of solidification requires that the physical processes occurring at the micro scale be reexpressed at the macroscale. The complex variety of processes that can occur in solidifying systems are inherently multiscale in both space and time. It is clear that dimensionless numbers developed on the basis of system wide length scales are inappropriate to use in establishing the degree of segregation of phases, the local convective state or heat transfer out of the system [Benyon and Incropera, 1987b; Oldenburg and Spera, 1991]. Both laboratory and numerical experiments have been used to model solidification and the utility and drawbacks of each method are discussed below.

### Laboratory Experiments

Laboratory experiments are particularly well suited to the exploration of phenomena where little is known about the timescale and length scale of self-organization of the system. They provide invaluable insight into the formulation of preliminary models for system behavior and can, perhaps most importantly, help guide the identification of constraints and tests of models. Experiments with salt solutions, paraffins, and other simple systems have effectively demonstrated that a variety of fluid instabilities may occur during solidification and in permeable, mushy regions and that the form of instabilities can change with time [McCay *et al.*, 1993; McCay *et al.*, 1989; Worster, 1992]. In the context of solidification, the review by Huppert [1990] provides an inventory of the many aspects of fluid flow and solidification. Much of the emphasis of recent laboratory experiments has been to elucidate the conditions associated with the onset of a particular type of instability and the fluxes of enthalpy and solute between different portions of a solidifying material. This is typically followed by a quasi-analytical treatment of the conditions leading to instability. The vehicle for this treatment is usually a substantial reduction in the complexity of the governing equations, often using spatially averaged quantities in dimensionless groups [Amberg and Homsy, 1993; Emms and Fowler, 1994; Worster, 1992].

Clearly, these kinds of experiments will continue to be a vehicle for demonstrating the variety of fluid instability that

might be significant in magmatic chambers. However, quantitatively extending the laboratory experiments discussed above to geological conditions is subject to large uncertainties. Changes in the microscale structure of the mush are intimately tied to the evolution of the permeability and hence to the fluid flow. For example, one has to decide a priori which porosity-permeability model is appropriate. The form of this assumption can have dramatic influence on the perceived nature of the flow, as discussed by Hopkins *et al.* [1993]. Hence it is very doubtful that the results of linear (or even nonlinear) stability analyses can illuminate the detailed feedback between crystal morphology, permeability, and reaction progress in a way that is useful to geologists. Nonetheless, they can provide some insights into the possible modes of convection that might occur at the onset of convection; a particularly nice example of this approach with geological relevance is that of Smith [1988], who explicitly includes variable viscosity of the fluid.

One drawback of trying to generalize the results of laboratory experiments is that some systems display what might be regarded as pathological aspects. An illuminating example of this bears on the recent work on the origin of "chimney" structures in crystallizing mushes. The  $\text{NH}_4\text{Cl-H}_2\text{O}$ ,  $\text{NH}_4\text{Br}$ ,  $\text{SCN-EtOH}$  (organic) systems have demonstrated the development of what have been called "chimney" structures, through which less dense fluid in the mush is efficiently and dramatically channeled upward. A number of recent papers present experiments that explore different aspects of chimney formation [Hellowell *et al.*, 1993; Tait *et al.*, 1992; Tait and Jaupart, 1992]. The assertion is that this mechanism may be important in the evolution of magma chambers, the Earth's core, or any system that can develop a "mushy" zone. The presence of chimneys in metals is suggested by local regions of solute-rich material referred to as "freckles." What is not emphasized is that chimney formation is usually not observed in the solidification of compounds other than those listed above or that even more remarkably, the addition of even a slight amount of contaminant (0.3 wt %) to the  $\text{NH}_4\text{Cl-H}_2\text{O}$  mixture can shut down chimney formation completely [Huppert and Hallworth, 1993]. As pointed out by Hellowell *et al.* [1993], it appears that the microscopic-structural aspects of the crystals are fundamental to the formation of chimneys: they are only predicted to occur in systems with nonfaceted, dendritic crystals. Thus, to generalize these kinds of experiments to complex silicate mixtures and nondendrites seems, at best, premature. In addition, the compositional buoyancy and viscosity in magmatic systems are highly variable, making the calculation of an averaged Rayleigh number within a mushy zone an ad hoc proposition.

Thus, although many laboratory experiments have been carried out, only a fraction of these have included what are widely known to be the important physical characteristics of magmas such as temperature and concentration dependent viscosity, multiple and suitable components, and realistic boundary conditions which rarely scale. In addition, no study to my knowledge has discussed the scaling difficulties and profound differences in the crystallization habit between  $\text{H}_2\text{O}$  solutions and silicate liquids, such as surface tension and crystal morphology, that will influence the topological aspects of crystallization. This will in turn have a direct influence on the evolution of the mushy zone and subsequent evolution of the system. The fact that other compounds, such

as paraffins, do not follow the scaling relationships developed for salt solutions and that there are even differences in salt solutions indicates that the reductionist formulations, while providing insights into some aspects of crystallization, are, at best, not yet complete. The problem is exacerbated by the fact that changes in surface tension that arise from the presence of very small amounts of contaminants can have a large effect on the porosity [Emadi *et al.*, 1993]. Anisotropic permeability in the mush region will also have a large effect on the evolution of the mush and the style and degree of macrosegregation as demonstrated by Yoo and Viskanta [1992]. In addition, with simple but elegant arguments, Hills and Roberts [1988a] remind us that within a region of mixed phase that is in equilibrium, the distribution of solid is arbitrary. Hence there is no theoretical justification for the commonly invoked assumption that relates solid fraction (locally) to permeability. Taken together, all this reflects the difficulty in finding experimental materials that are appropriate analogs to magmas and the limitations of the reductionist approach. As cautioned by Worster and Kerr [1994 p. 40], "The use of a mean Rayleigh number to determine the onset of convection in the mushy layer is rather crude since the solid fraction (and hence permeability) of the mushy layer can vary significantly with its depth." To apply this body of work to magmas without substantial consideration of the validity and the limitations of the experiments does little to illuminate the actual evolution of natural systems.

In my view, the role of experiments in the future will be largely to provide physical examples against which numerical experiments can be calibrated. This will bring substantial challenges to the current standard of laboratory modeling of magmatic processes, requiring careful attention to variable physical properties and relationships such as enthalpy-temperature-solid fraction. Ultimately, the goal is to combine laboratory experiments and numerical experiments which has been very successful in material science and engineering. As stated by Huppert [1990 p. 236],

There are clearly a number of fluid-dynamical aspects of this situation (crystallization) that need quantitative investigation. It would be fruitful to construct a numerical program that incorporates the strong convective flows in the melt, the dynamics of the mushy zone and behind the crystallization front and the possibility of compositional stratification in the solid product. Such an advance represents a challenging task for the future.

Such models were in common use in the engineering community when this comment was made and have evolved rapidly in the interim.

### Numerical Experiments

An alternative approach to laboratory experiments that is ultimately more flexible is to formulate the phenomena of interest in a continuum model that can then be solved numerically. Significant progress toward a unified set of transport equations has been made in the last 7 years with the application of both mixture theory and the volume averaging approach [Beckermann and Viskanta, 1988; Ganesan and Poirier, 1990] to the equations for mass, momentum, energy, and species conservation. These continuum models have been successful at predicting a number of the first-order features of crystallization demonstrated by laboratory experiments. An important feature of these mathematical models for

crystallization is that it is possible to write conservation statements for the entire region of solid, mush, and liquid without formally partitioning the computational domain. However, there has been debate as to which approach, mixture theory or volume averaging, more rigorously characterizes the micro-to-macro representation of solidification. An excellent review of the development of continuum models for solidification is that by Beckermann and Viskanta [1993], and the interested reader is urged to consult this reference for a very good introduction to solidification modeling.

The so-called mixture models for transport during solidification have been widely used [Bennon and Incropera, 1987a; Chiang and Tsai, 1992; Hills *et al.*, 1983; Oldenburg and Spera, 1991; Prescott and Incropera, 1991; Voller *et al.*, 1989]. The benefit of the mixture model is that it explicitly treats the multiphase solidification process as a single phase "mixture" which permits numerical implementation using standard one-phase computational fluid dynamics codes. Although convenient to implement, the mixture model has several drawbacks. The solid volume fraction is determined by the lever rule or Scheil equation, microstructural aspects in the mush can only be included in the expression for the permeability, and thermal and solutal nonequilibrium and other kinetic considerations are difficult to implement in the model. The development of an expression for momentum balance has been particularly problematic for mixture models. The momentum of the liquid is the basis for the equation for the determination of the mixture velocities; however, the stress in the solid phase has been modeled by using the solid momentum equation rather than a constitutive equation [Prescott and Incropera, 1991]. This precludes a complete statement of solid transport if the mush is moving or if there is equiaxed solidification. The mixture models of Voller *et al.* [1989] use a similar formulation for the momentum as Bennon and Incropera [1987a], but the domain is subdivided into zones where either there is a stationary mush or a well-mixed equiaxed region; a similar strategy was used by Oldenburg and Spera [1992]. Both of these approaches to modeling the mixture momentum are important steps forward but are fundamentally ad hoc.

The two phase model of Beckermann and Viskanta [1988] uses formal volume averaging [Hassanzadeh and Gray, 1979] rather than mixture theory to develop the set of equations governing transport during solidification. The advantage of the volume averaging technique is that the microscale equations are clearly and formally linked to the macroscopic conservation equations for enthalpy, species, mass and momentum. The extension of volume averaging to conditions where there is simultaneous columnar and equiaxed crystallization has been the basis of the two-phase model of Ni and Beckermann [1991]. The solid and liquid momentum equations have separate sets of conservation equations which can be linked with interfacial balances which permits the explicit consideration of kinetic effects related to interfacial area, undercooling or other microscopic effects. Sedimentation can also be included with explicit calculation of the number density of grains, an exciting prospect for the petrologist! Wang and Beckermann [1993] have extended the model of Ni and Beckermann to include yet another level of refinement to further model the kinetics of crystal growth where the three phases are identified: the solid, the interdendritic liquid, and the extradendritic liquid. Although this model has not yet been extended to include convection, it

is clear that the field of computational solidification is rapidly becoming very sophisticated. The difficulty in the practical application of the volume averaging approach is that it requires detailed knowledge of the heat and mass transfer coefficients between phases and of topological relations among the solids and the appropriate kinetic expressions. In addition, the numerical implementation of the volume-averaging approach may be prohibitively demanding of computer resources.

A formulation that combines many of the useful features of both the mixture model, such as the ease of numerical implementation, and flexibility and rigor of the volume-averaging approaches is that of *Ni and Incropera* [1995a,b]. This particular model for solidification allows for explicit expressions for the influence of kinetics, surface area of crystals, sedimentation, and reaction of crystals. The important difference is that the momentum equations for both the solid and melt are summed. A detailed discussion of this model is beyond the scope of this review; however, it is important to note that when the solid velocity is zero and the solid and liquid densities are assumed to be the same; the model of *Ni and Incropera* [1995a,b] reduces to that of *Prescott et al.* [1991]. The advantage of this model approach is that it permits one to explicitly consider a variety of model relationships and allows explicitly for the extension to conditions of geological relevance.

One of the problems in the numerical modeling of local crystal growth is the tracking of the interface, particularly if the growth habit is dendritic. A modeling approach that allows for the numerical treatment of the very detailed local balances in dendritic solidification is the phase-field method. The phase-field method provides a means of calculating complicated growth morphologies by introducing an additional variable whose value identifies the phase of interest and varies between 0 and 1. The phase-field method is well suited for the study of crystal growth where interfacial kinetics and capillarity are important [*Murray et al., 1993; Wang et al., 1994*]. The finite element method with front tracking has also been used to model dendritic growth, giving good agreement between calculated and measured dendrite tip velocities as a function of tip curvature [*Sullivan and Hao, 1993*].

However, there are difficulties in the practical implementation of these continuum models. For any system with more than a few components and many possible length scales, the computational demands are currently too great for routine work. This requires that the magmatic system be reduced to a subsystem of fewer components and phases and hence some meaningful projection of the composition space of the actual system be found. For example, *Oldenburg and Spera* [1991] reduced the basalt system to the subsystem diopside-anorthite. The greatest difficulty in this regard will be the modeling of the Fe-Ti oxides as they can have a profound influence on both the physical properties and the composition. One tool with which to explore the phase characteristics is the MELTS algorithm of *Ghiorso* [1985] and *Ghiorso and Sacks* [1995] which allows one to recover all the thermophysical properties (except thermal conductivity) for the individual phases and liquid under conditions of fixed or varying oxygen fugacity. For an example of the use of MELTS in a transport example, see *Bergantz and Dawes* [1994].

Another limitation for the routine application of continuum models of solidification is the computational "power" one can bring to bear on these complex, multiscale problems. An

extended discussion of the computational resources and strategies required for the numerical implementation of the models discussed above is given by *Dobran* [1993, section 6.5.1]. It is estimated that by the year 2000, various parallel architectures will routinely be able to achieve TerraFLOPS ( $10^{12}$  floating point operations per second) speeds; individual microprocessors are now available that have speeds measured in BIPS (billions of instructions per second). However, this level of performance is not needed for the modeling of the subdomains of a crystallizing system. Much valuable work has been done with existing hardware such as that by *Oldenburg and Spera* [1991].

Last, it should be appreciated that any model based on a continuum formulation with associated constitutive equations can only be used to study the interactions that are already understood or parameterized at some scale; they cannot be used to predict microstructural phenomena. For example, the models described here cannot predict which permeability model for the mush is appropriate. That must be determined empirically. The models can provide geologists a means of exploring the rich variety of nonlinear interactions that attend crystallization and a means of evaluating the likelihood of certain processes.

### Paradigms for Magma Chambers

Before modeling can begin, some notion of the initial and boundary conditions must be developed. The presumption that all magma chambers originate as vats of near-liquidus magma, instantly intruded into cold country rock is undoubtedly naive. The geometry of magma bodies and how they change with time is uncertain; some discussion of this is given by *Marsh* [1989a] and *Bergantz* [1991]. Intrusive mechanisms are discussed below. Magmatic centers can show a remarkable diversity of processes and compositions. Examples include *Katami* [*Hildreth, 1987*], where multiple magma plumbing systems coexist in close proximity, while others such as Mount Rainier, Washington, have a limited range of compositional variation throughout the life of the system. Thus trying to generalize the range of magmatic conditions in any simple model requires that specific geological conditions be understood and articulated. Hence the most useful way to study the geological processes in the context of simple crystal-liquid segregation is to study demonstrably simple systems, such as sills and lava lakes. This is discussed below.

As an illustration of the changes in the usual notion of magma chambers, consider how the classic "cartoons" of mid-ocean ridges and silicic systems have changed. The traditional model of a large, near-surface to Moho, mostly liquid magma chamber beneath a mid-ocean ridge has been replaced with a model where a melt lens just a few tens to hundreds of meters thick overlies a large, permeable, crystal pile [*Sinton and Detrick, 1992*]. Much of the compositional variation and kinematic fabric in the system reflects a balance between magma injection and lateral spreading. *Quick et al.* [1992, 1994] have documented the same kinds of relationships in the large mafic complex of the Ivrea Zone, northern Italy. One important aspect of this study is that a very similar style of magmatism may exist beneath both spreading ridges and extending continental crust. A similar picture of silicic magma chambers with a substantial volume of hot, but crystal rich material, comes from the teleseismic tomography of the silicic system in the Long Valley region [*Dawson et al.,*

1990]. It appears then that one challenge is to determine just what constitutes a magma chamber at any point in its history and the distribution of effective fluid and solid portions.

Petrological considerations have also provided some support for the view that chemical diversity involves the communication between a region of magma and extensive amounts of crystal rich mush. *Hopson et al.* [1987] provide a picture of silicic systems as rising out of their own crystal piles and becoming zoned upon ascent. *Hildreth and Moorbath* [1988] proposed the acronym MASH (melting-assimilation-storage-homogenization) to describe a magmatic system where much of the chemical diversity exhibited at eruptive centers is initially established in the deep crust. An important feature in all these paradigms for magma chambers is a volumetrically significant amount of crystal-rich material acting as a thermal and compositional buffer to the bulk of the liquid. *McBirney and Hunter* [1995] explain how many features in the Skaergaard Intrusion once thought to result from precipitation from a melt are due to percolative processes. Similar processes are required to explain the contamination in the large mafic complex of the Ivrea Zone, Italy [*Sinigo et al.*, 1994] and the formation of the Merensky reef in the Bushveld Complex [*Mathez*, 1995]. Although there are a number of candidate processes for driving this melt migration, quantitatively useful models are just now being developed. The important point is that the chemical data that are the mainstay of petrologic reasoning reflect the "superposition" of a number of processes that take place at elevated temperature.

Establishing the timescales for magma residence times and crystal growth is central to understanding the solidification histories of magmas. Isotopic studies and crystal size distribution studies yield linear growth rates from  $10^{-11}$  to  $10^{-14}$  cm/s, although the crystal sizes must be considered to reflect a minimum residence time. In the case of silicic systems, *Davies et al.* [1994] note that rapid cooling does not seem to take place as suggested by the parameterized calculations of *Sparks et al.* [1990]. Perhaps the thermal history of silicic magma bodies is more consistent with the cooling rates proposed by *Marsh* [1989b] where convection does not lead to rapid cooling. Rates for melt generation and eruption in arcs based on U series data have been reported: *Gill et al.* [1993] estimate a time of 200 kyr between slab dehydration to magma formation and eruption. Even more rapid rates of melt generation, differentiation, and eruption are suggested by *Sigmarsson et al.* [1990], who propose that the time for slab dehydration, mantle transit, differentiation, and eruption through the crust of southern Chile is less than 20 kyr! Thus the timescales over which petrologic diversity is established may be highly variable and may require a substantial revision of our notions of the rates of melt movement.

The challenge, then, is to combine the isotopic estimates of magma chamber evolution with geologically relevant models of magma chamber dynamics (see discussion of crystallization above). This will require that detailed geologic studies be made on carefully chosen systems to establish the kinetics, emplacement and crystallization history. An example where this kind of ongoing work is yielding continued insights and feeding into models of dynamics is the careful mapping of ophiolites [*Nicolas et al.*, 1994]. Similar models are being developed for the Ivrea Zone, Italy [*Bergantz and Barboza*, 1994]. Geophysical studies will also continue

to play a dominant role in determining the size and physical state of the thermal anomaly associated with magma chambers on both the continental crust and mid-ocean ridges [*Bergantz*, 1991].

## Geological Examples: Research Directions

### Crystal Settling

Crystal settling is one of the most often invoked mechanisms by which crystals are separated from liquid and the suggested mechanism by which many of the eye-catching features of layered intrusions are formed. Laboratory experiments designed to explore the feedback between the settling of nonreacting particles and thermal convection have been done by *Koyaguchi et al.* [1990] and discussed by *Sparks et al.* [1993]. They documented a very interesting time dependence with cyclic settling and convection that would lead to repeated overturn of the whole system. The experiments did not include crystal growth, multicomponents, variable properties, or coupled boundary conditions so the importance of this in magmatic systems remains to be established. In addition, there are geological examples where crystal settling and convection were demonstrably not important, usually in systems that are less than 500 m high [*Gibb and Henderson* 1992; *Mangan and Marsh*, 1992]. *Hort et al.* [1993] consider the role of oscillatory nucleation in the development of layering and cumulates and conclude that settling will not be effective in systems that are less than 100 m high. None of the available models includes all the relevant physics, but the potential for a variety of interactions has been demonstrated.

Numerical modeling of crystal settling has been successfully used in material science and does not inherently suffer the shortcomings of the laboratory models. The models of *Ni and Beckermann* [1991, 1993] allow one to include crystal growth or resorption, a variety of nucleation and growth rate functions, crystal-crystal interactions and the presence of thermal and/or compositional convection. Using their model, one can develop synthetic crystal size distributions for geologically relevant conditions and so evaluate magma chamber evolution during combined settling and convection. The student of crystal settling is strongly encouraged to study *Ni and Beckermann* [1993].

### Mush to Slurry Transition

One petrological issue that ties together the paradigms for magma chambers with the crystallization history involves the partitioning of crystallization. Clearly, magmas crystallize at both the margins and, perhaps, in a distributed fashion in the interior. The region of mixed crystals and liquid that forms a nearly rigid region at the margins of a crystallizing system is often called a "mushy" zone [*Hills et al.*, 1983]; that occurring in the interior a "slurry." In the metallurgical and material science literature these regions are usually called the "columnar" and "equiaxed" zones, respectively, reflecting the dominant crystal morphology in each region. The processes whereby crystallization is partitioned between that occurring at the walls and the interior are not well understood, despite the fact that it will exert the dominant control on fractionation processes.

There are currently two approaches to understanding the first-order distribution of crystallization between the margins and the interior. One is based of the rheological variations

and the related dynamics of crystal-rich plumes that are possible as crystallinity increases [Marsh, 1988]. The other focuses on the local and system-wide thermochemical balances such as the nature of the diffusional gradients around crystals and the dispersion of nuclei and crystal fragments during intrusion or convection. The first of these has been largely motivated by geological observations and models; the second has been motivated by experiments and modeling in metallurgical sciences. Both approaches no doubt can inform models of the mush-to-slurry transition, and we consider each below.

Observations that magmas do not typically erupt with more than about 50% crystals motivated Marsh [1981] to suggest that this crystallinity corresponds to a rheological limit of eruptibility. This notion of the connection between mixture viscosity and magma dynamics was extended by incorporating measurements from lava lakes, the crystal size distributions, and crystal chemical modes from intrusions. This has led Marsh and coworkers [Brandeis and Marsh, 1990; Marsh, 1989b; Smith, 1988] to models for magma chambers which subdivide the region of crystallization at the margins on the basis of mixture viscosity: a rigid crust which includes up to 50% crystals, a mush which is delimited by the isotherm corresponding to the point where the mixture viscosity is no more than 10 times that of the bulk mixture which is called a suspension. The subdivision between the mush and the suspension is based on an order of magnitude, or less, increase in viscosity. This has been substantiated by a number of numerical and laboratory experiments, most recently those of Davaille and Jaupart [1993]. It is clear then that rheological variations that occur during crystallization will have a profound effect on the evolution of the body and on the nature and style of thermal and compositional convection and sedimentation. Applications to models of magma ascent are discussed in more detail below.

In the casting of ingots and other metallurgical applications, it is commonly observed that there is a region extending from the margin of the casting wherein the crystals have a strong, growth induced anisotropy. The crystals typically develop with a long axis parallel to the cooling direction. This is called the columnar region of the casting. In the interior of this region, the crystals are more symmetrical; this is called the equiaxed region. The transition in crystal structure from the columnar to the equiaxed morphology has some features in common with the mush to slurry, or suspension, transition in magmas. The columnar to equiaxed transition (CET) has been the subject of many experiments, but only recently have multiphase continuum models appeared that included the effects of enthalpy and solute transport, undercooling, an explicit term for dendrite tip growth (and curvature) and the density of nuclei. Wang and Beckermann [1994] submit that the form of the nucleation law has little influence on the CET but that the equiaxed nuclei density is the most important factor in determining the position of the CET. As these models do not yet explicitly consider convection but give good agreement with experiments, one aspect of the CET would appear to be controlled by environmental conditions such as the number of intratelluric crystals and the rate of heat transfer out of the system as governed by the heat transfer to the surrounding country rock. One interesting result that may connect the observations of Marsh [1988, 1989a,b] with the CET models of metallurgists is the criterion developed by Brown and

Spittle [1989] that when the volume fraction of equiaxed grains ahead of the columnar front exceeded 49% by volume, columnar growth stopped. The notion of columnar and equiaxed morphologies is obviously not directly applicable to magmas; however, it provides a paradigm within which work in material science can possibly illuminate geological conditions.

To resolve the issue of the partitioning of crystallization, many approaches are required. One is to study the crystallinity and eruptive history of systems where both eruptive products and plutonic equivalents are available. Although there are few systems where this kind of connection can be unequivocally demonstrated, they may provide some measure of the relative importance of crystallization associated with pressure changes related to exsolution compared to those due to cooling and internal processes. Cognate xenoliths which are thought to reflect the early phases of crystallization, usually considered to have been removed from the "walls" of a chamber [Bacon, 1992], provide another vehicle for comparison of wall and interior crystallization. The rheological contrasts associated with the mush to slurry transition, or the geological equivalent of the CET, may be found by careful mapping and age dating of concentrically zoned intrusions. Thus careful field work combined with extensive age dating of related volcanic plutonic suites seems to be a required first step in developing a geologically relevant paradigm for the chemical and mechanical partitioning of magmatic systems.

Studies from lava lakes indicate that the transition is not associated with a single value of the melt fraction and that convection is weak in magma chambers being cooled strongly from above [Barth *et al.*, 1994]. Another avenue for exploration of crystallinity versus time is to do a field-scale test by creating a magma chamber and monitoring its chemical and dynamic evolution. This is not as far fetched as it may seem: the in situ vitrification of soil, an environmental remediation technique, yields substantial melt pools. The technology is currently available to create a magma with a "custom" composition that can have dimensions of tens of meters. The advantage of this approach over the study of lava lakes is that the experiment can be fully instrumented and the heat input controlled so that melting processes can also be considered. The careful study of the vitrification experiments that have already been done provides an invaluable view into the processes of both melting and solidification [Dunbar *et al.*, 1993; Jacobs *et al.*, 1992] where the interplay among crystallization kinetics, composition, and convection (or lack thereof) is readily demonstrated. They can also provide an invaluable means of calibrating numerical models of magmatic processes against chemical systems of geological relevance.

### Melting

Partial melting of crustal rocks is a potentially important process in the development of petrologic diversity [Bergantz and Dawes, 1994; Brown, 1994]. The evolution of the lower crust to midcrust and the mechanisms of heat and mass transfer from the mantle to the crust remain one of the least understood aspects of plate tectonics. Melting can be considered in terms of two rate limiting processes: melt generation and melt segregation. The available geological examples of melt generation and segregation are typically difficult to interpret as there are uncertainties about the composition of the protolith, the role of volatiles in the melt producing reaction,

and the degree of equilibrium between trace and major phases during melting [Sawyer, 1991]. In addition, rocks that demonstrate partial melting have usually experienced metamorphism and/or tectonism subsequent to the peak conditions of pressure and temperature, and the conditions of melting are difficult to interpret. The physics of melting is poorly understood as well. Crystal size and the spectrum of sizes have a large effect on the progress of melting and the degree to which equilibrium is maintained, as demonstrated by the in situ vitrification experiments [Jacobs *et al.*, 1992]. In addition, thermal and compositional buoyancy can be generated on many scales which are largely controlled by structural and compositional anisotropy.

The melting of geological materials is fundamentally different from solidification in that it may involve a dehydration reaction in the absence of externally derived free water, the so called "damp" melting. Significant amounts of melt can be produced in steps as melting advances through the dehydration peritectics, and the melt production can be sensitive to the modal composition of the protolith. The progress of closed-system melting can be estimated from laboratory experiments such as those of *Vielzeuf and Holloway* [1988]; however, one is required to assume equilibrium conditions and no melt removal [Bergantz, 1992]. Although these existing laboratory experiments are an invaluable aid in establishing the progress of melting under static conditions, much more experimental work needs to be done simulating open system conditions. The challenge in developing fully time-dependent models for melting is in choosing the right systems of reduced components and modeling the simultaneous changes in solid fraction and liquid composition. Clearly, the assumption that the system can be characterized by invoking a simple binary eutectic is inappropriate. One approach is to model the mixture as a solid solution with multiple peritectic points. This provides for the changing solid compositions and the important melt-producing steps. Another complication in the modeling of melting occurs if crystals of the protolith are zoned and diffusion in the solid is neglected. This requires a bookkeeping scheme so that the thermodynamic closure conditions at the crystal-liquid interface can accommodate the changing, local composition of the solid [Hills and Roberts, 1988b].

Melting is usually considered to occur in response to the intrusion of basalt. Two geologically motivated end-members for this process can be identified. The first is the "Ivrea type" where the mafic system forms a near-horizontal interface with the overlying country rock as described by *Quick et al.* [1994]. *Bergantz and Dawes* [1994] have summarized the features associated with this type of system; the important point is that large percentages of country rock melting do not occur and that the heat transfer is largely conductive. The interaction between the mafic system and the country rock is limited. This type of system provides an excellent opportunity to study the geochemical evolution of contamination in magmas that are largely crystal mushes [Sinigoi *et al.*, 1994] and where the chemical potential to drive melting is due largely to temperature differences. The other end-member, where dramatic amounts of country rock melting can occur as well as enhanced magma mingling, is the "Chelan Complex type." In this type, described by *Hopson and Mattinson* [1994], mafic magma repeatedly intrudes as a plexus of overlapping dikes. The time-integrated effect is to

locally generate substantial amounts of melt intimately associated with mafic magma. This is accompanied by a regional change in the strength of the crust and many scales of magma mobilization. In addition, changes in both composition and temperature provide the changes in chemical potential that drive phase change. The Chelan Complex type may ultimately be more important in driving the development of petrological diversity than the more often cartooned Ivrea type.

Models of melt segregation under crustal conditions have been even more difficult to develop and evaluate than models of melting itself. *Sawyer* [1994] provides evidence that melt can be continually drained away by the interplay of buoyancy and tectonic forces at low melt fractions. This occurs at what has been called the first percolation threshold. The important points are that rather large amounts of melt may leave the system while the source remains mechanically coherent, e.g., before the bulk critical melt fraction is reached, and that the degree of chemical equilibrium achieved will depend explicitly on the timescales of segregation.

Much more work remains to be done to fully articulate the geological constraints on melt segregation; modeling efforts are currently underway by our group to evaluate melting and segregation rates and the relative roles of buoyancy and shear [Bergantz and Barboza, 1994]. It is here that experimental chemical petrology will continue to play a significant role. The melting systematics of common rocks under wet and damp conditions is needed, with particular attention paid to the composition and textural evolution at low melt fractions. In addition, much more work needs to be done on the mechanisms of deformation and the development of constitutive relations for crystal-liquid mixtures at low melt fraction. Finally, more field work of the type discussed by *Sawyer* [1994] needs to be done to guide the development of continuum models for melt extraction.

### Open System Behavior

There is no question that many magma chambers are open systems. Magma mixing is often invoked in petrogenetic schemes, although the physical evidence can be ambiguous. Magma mixing can involve the bringing together of magmas with no common chemical source or can involve the "defrosting" of the walls and rejuvenation of previously solidified material in a single chamber [Mahood, 1990]. Petrographic measurements are often used to provide evidence of magma mixing; for a recent review, see *Hibbard* [1995]. Surprisingly, there has been little work done on the mechanics of magma mixing that is applicable to viscous, crystallizing fluids without a free upper surface. The work of *Oldenburg and Spera* [1989] provides a framework for the development of the systematics of mixing in a geological context. In addition, a number of works have recently appeared that describe the phenomenology of mixing and also provide a mathematical basis with which to evaluate mixing. The book by *Ottino* [1989] is recommended.

One of the difficulties in modeling magma mixing is that the driving forces and their time dependence are poorly understood. In particular, the role of volatiles remains to be elucidated. Although it is not difficult to imagine some mixing taking place during eruption or possible during rapid vesiculation in a shallow chamber, it is much more difficult to account for the apparently thorough mixing in mid-to-deep

crustal plutons required by geochemical models where the pluton may have always existed in a largely mushy state. It appears that a means of reducing the rheological contrasts and the diffusion length scale is required. One possibility was discussed above in the context of the Chelan Complex type system, where intruding mafic material is widely dispersed in a silicic host at all scales. This differs from the usual models of magma mixing in that it happens at the time of magma generation and the mafic magma is not assumed to have originated as a large sill or dike. Rather, the mafic material invades a section of crust on a wide front and in a distributed manner. This model is appealing in that it can effectively provide for a spectrum of mixing and mingling textures and the variability in enclave compositions. Further field work at this and similar localities will undoubtedly illuminate aspects of the origin of petrologic diversity and mixing features.

### Magma Ascent and Emplacement

There has been renewed interest in evaluating magma ascent with a recent flurry of literature on the mechanics of dike propagation and the kinematic analysis of granitoids; the reader is directed to the recent volumes edited by Ryan [1990, 1994a] for an introduction to current work in the field.

The recent work on diking is too voluminous and is changing too quickly to be usefully summarized here. However, a number of new and important paradigms for magma ascent will be continued areas of research. The notion that magma ascends to a level of neutral buoyancy has been repeatedly emphasized by Ryan [1994b] and has features that are testable using both geophysical techniques and volcanological observations. The proposal that magmas can "unmix" while flowing in a dike, where the lower-viscosity component encapsulates the higher-viscosity one has received extensive discussion by Carrigan [1994]. This model also has many features that are testable, and more laboratory work with fluids of variable viscosity and phase change might provide a rich field of geologically relevant models for magma ascent. One of the largest challenges in any model of diking is to include phase changes (or perhaps more appropriately, a glass transition) in the mechanical models.

The ascent and emplacement mechanisms of granites continue to be a field of active study, primarily using kinematic analysis of rock fabric by both direct observation and anisotropy of magnetic susceptibility (AMS). Despite literally hundreds of studies using kinematic data collected from plutons, no clear consensus has been reached on the connection between tectonism and magma emplacement. The hypothesis that crustal-scale structural features are linked to magma ascent is attractive as it provides for a convenient solution to the "room problem" [Bergantz and Dawes, 1994]. However, recent work by Paterson and Fowler [1993a,b] questions this connection. The traditional model of plutons being emplaced by a "ballooning" mechanism has also been recently called into question. Paterson and Vernon [1995] compare the evidence for ballooning from a variety of plutons considering a variety of evidence, and conclude that the dominant mass transfer process (MTP) must be some form of diapirism. This diapirism is not the familiar "hot Stokes" diapir but is the ascent of magma by stopping and some ductile flow; however, a detailed model remains to be found. They also suggest that plutons may be incrementally assembled and that many of the fabrics observed in plutons may be set late in the history of the system and reflect magma flow instead of

emplacement. One noteworthy aspect of this work is that their observations require some magma to be largely crystal-free, but without vigorous convection in the system as compositional domains are preserved and crosscut by later fabrics. Further work on this topic must involve combined thermal and petrological models. The exciting aspect of this is that it ultimately ties together many aspects of magma chambers: emplacement models, chemical evolution, and thermal and convection models.

### Volcanic and Eruptive Processes

Perhaps the most successful application of laboratory and numerical experiments has been to eruptive processes; rather simple models agree well with the evolution of both effusive and explosive eruptions. There is no attempt to present a complete discussion of all the recent developments in this field. The interested reader is directed to the review by Luhr and Williams [1991] and the comments of Fink [1995].

New models for effusive volcanism have recently been proposed. The mechanics of dome growth have been particularly amenable to laboratory and mathematical modeling, in part because of the relatively simple feedback between dome growth and rheological conditions. One longstanding conundrum in effusive volcanism is the mechanics of large lava flows that travel exceptionally long distances. New models for these flows are driven largely by field observations: lava tube systems can develop which can effectively act as "insulating pathways" [Chitwood, 1994] such as those described at Kilauea [Hon et al., 1994]. It is clear that despite extensive study, there is still much to be learned about the phenomena of lava flows.

Numerical models of volcanic phenomena are rapidly becoming more sophisticated and will very soon become the premiere way to explore the parametric aspects of both effusive and explosive eruptions. Early efforts to consider the general physics of eruption in a numerical model [Spera, 1984; Trial et al., 1992; Valentine and Wohletz, 1989; Wohletz et al., 1984] have demonstrated the utility of this approach. A consortium of earth scientists organized to assess the volcanic hazards of Italian volcanoes has extended this approach to a broader range of volcanic processes [Dobran, 1993; Dobran, 1994; Dobran et al., 1994]. These works are comprehensive in that they present an approach to volcanism that explicitly identifies the links between magma input, evolution, and eruption. Close attention is paid to the specific conditions of geological relevance, and the interested reader is strongly encouraged to consult these works. As an example, the utility of continuum models (numerical) in addressing multiphase flow during eruption is aptly demonstrated in a number of recent publications [Dobran, 1993, 1994; Dobran et al., 1993; Dobran and Papale, 1993; Papale and Dobran, 1993]. The value of these works is that they investigate the fully nonlinear and multiphase regime and are a demonstration of the kinds of models that are currently available. There is little question that modeling of this kind, when coupled with careful field work, will become the preeminent way that volcanic phenomena are modeled and understood and perhaps in the near future, predicted.

### Physical Properties and Thermodynamic Relationships

In order to employ any kind of model for magmatism, thermophysical and transport properties and thermodynamic



relationships must be reasonably well known. *Overfelt* [1994] provides estimates of the sensitivity of the solidification time for steel as a function of the uncertainty in the physical properties. For example, an error in the estimate of the density of 5% led to a 10% error in the estimated cooling time. The least sensitive property was found to be thermal conductivity where an error of 40% in the estimated value yielded only an error of 10% in the cooling time. Data are available for some simple mineral groups and liquids, but for many compositions of common interest, there are few measurements. For example, even the common assumption that viscosity (of the crystal free liquid) has an Arrhenian temperature dependence appears to be inappropriate, and there are a number of viscosity-temperature relationships as temperature decreases [Bottinga *et al.*, 1995]. The influence of isotropic solids or bubbles on bulk viscosity can exert the largest influence as cooling proceeds, this is discussed by Spera *et al.* [1988] and Bergantz and Dawes [1994].

Chemical diffusion data determined from experiments with natural compositions are consistent with a Fick's law formulation, however, Kress and Ghiorso [1995] caution that there is no simple model for predicting diffusion coefficients. More experimental data are needed before models for crystal zoning can be rigorously considered. Many more data are also needed for surface tension, the kinetics of crystal growth and dissolution, and the subsequent crystal morphologies under a variety of conditions. These data are particularly important for developing models of porosity-permeability relationships [Emadi *et al.*, 1993] which are key to understanding crystal-melt mush dynamics. Although undercoolings in magmas appear to be very small, the available kinetic models need to be evaluated for application to melting.

## Closure

One of the fundamental notions that will be dispelled in the coming decade is that petrological diversity originates in magma chambers that are big vats of liquid whose dynamics can be readily characterized by simple dimensionless numbers or length scales. The generality of that approach is easily disproven. Nonetheless, despite many years of discussion and model development, even the first-order dynamic conditions that attend petrologic diversity remain a source of controversy and speculation. The uncertainty in current models does not reside in their being "right or wrong" but rather in whether the model assumptions explicitly consider the specific character of magmas. In my view, an approach that begins with models or parametric assumptions and then attempts to find corroboration in the rock record is ultimately successful but rarely illuminating, as it usually represents a union of preconceived "truths" with the vagaries of the rock record. The raw material of the necessary constraints for critical tests of a hypothesis in magma dynamics must ultimately come from the geology. I do not mean tests of agreement; these are rarely conclusive, as the absence of evidence does not then inform the model. Rather, an approach is needed that looks for negative tests of models, as only one negative test is required. Those proposing models should state what negative tests might be found in the rock record that will allow some estimate of model applicability [Truesdell, 1984].

Perhaps the best news for those interested in magma dynamics is that there is a rapidly developing set of continuum models which are robust enough to accommodate the peculiarities of magmas: strongly variable transport

properties and a rich feedback between crystallization (including kinetics), convection, and relevant boundary and initial conditions. The repeated theme of this prospectus is to join evolving models of crystallization with carefully articulated geological constraints. Linking selected field studies to modeling efforts that can incorporate a number of physical processes is an exciting prospect and will be the dominant growth direction in the study of magmatic processes in the coming decades.

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G. W. Bergantz, Department of Geological Sciences, Box 351310, University of Washington, Seattle, WA, 98195. (e-mail: bergantz@u.washington.edu)

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