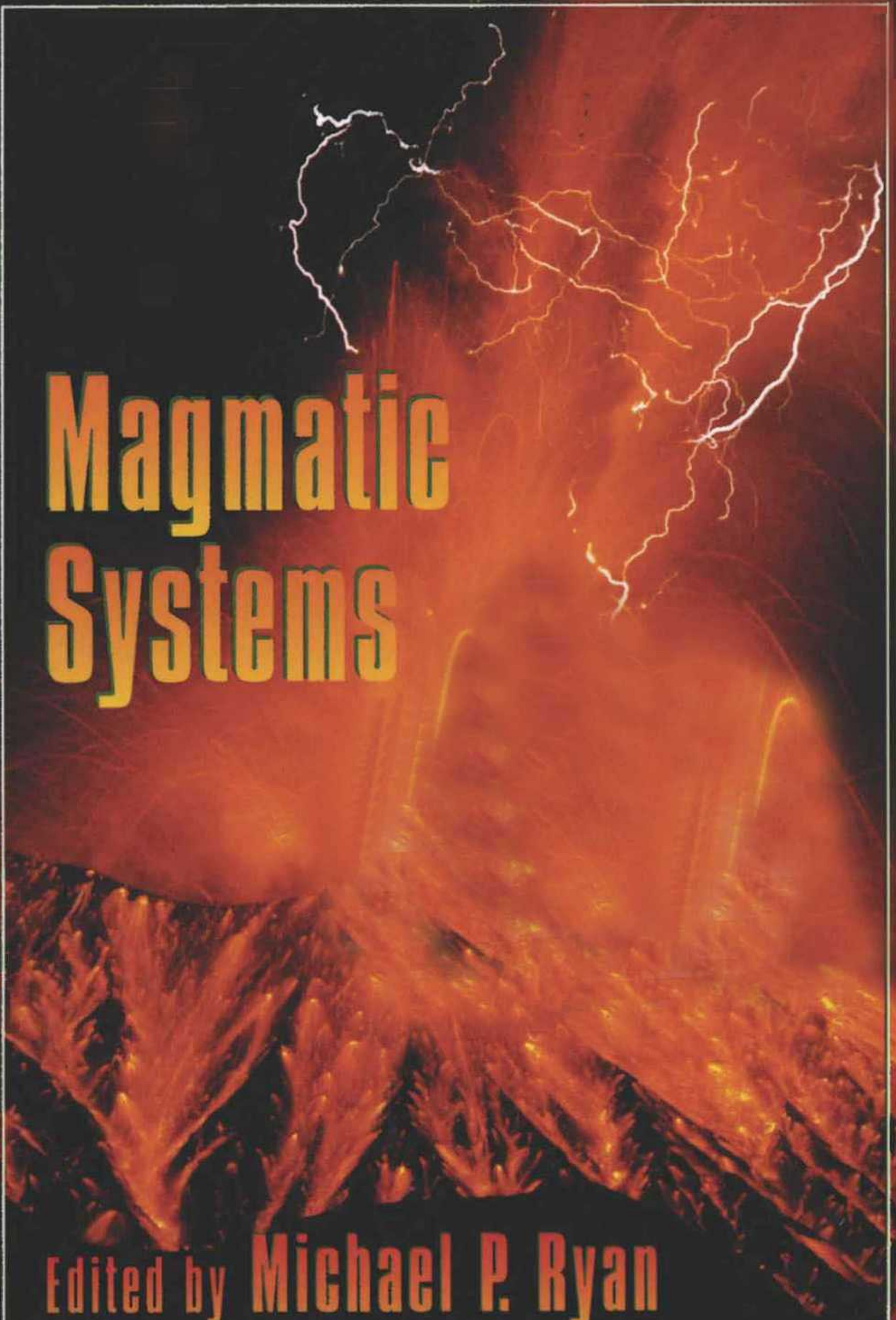
Magmatic Systems



Edited by Michael P. Ryan

Magmatic Systems

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The eruption of the Krafla central volcano, northeast Iceland during September 4–18, 1984. (*Top*) 06:00 hours on September 5th. Silhouetted against dawn's light, the coalescing plumes from seven en-echelon-arranged eruptive fissures rise over the Gjastykki fissure system. Fountain heights during these first hours of eruption averaged 50–75 m and had flow rates that tended to be maximized over an individual fissure's center. Prior to the eruption, magma was stored within Krafla's reservoir located beneath the caldera floor (right margin of photograph). (*Bottom*) 21:30 hours on September 11th. Within 72 hours the eruption had localized at this northernmost vent, shown here in the process of building a large spatter cone. In this eastward view, the fountain heights ranged from 30–40 m above the cone top. Collectively, magma flow at Krafla illustrates a number of dynamic patterns and processes: lateral injection at depth along the horizon of neutral buoyancy, laminar flow during crack migration, turbulent flow above surface fissures, and thermally constricted flow beneath volcanic vents. U.S. Geological Survey photographs by Michael P. Ryan.

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Edited by

Michael P. Ryan
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Cover photo: Sakurajima volcano, Kyushu, Japan, in eruption at Minami-Dake (the southern crater) during the early morning hours (03:09) of February 17, 1988. This remarkable photograph was made possible through the use of an automated system that continuously records atmospheric pressure. The expanding atmospheric shock wave generated during the eruption outbreak triggered the camera at the Sakurajima Volcanological Observatory, 5.5 km from the summit. The integrated intensity of the resulting Strombolian bombardment has been recorded by the time-lapse photographic process. Incandescent volcanic bombs are seen to follow both steep and low-angle trajectories, blanketing the upper flanks and rupturing on impact. Bomb rupture produces secondary showers of fragments down paths revealed by their bright comet-shaped trails on the volcano flanks. High in the ash plume, lightning strokes discharge buildups of static electricity and usually emanate from, or terminate in, the higher conductivity incandescent plume core.

Sakurajima is a tightly coalesced pair of pyroxene andesite and dacite stratovolcanoes that have grown within the Aira caldera during the last 13,000 years. The formation of the Aira caldera itself was associated with the great eruption of the Ito pyroclastic flow about 22,000 years ago, which covered much of southern Kyushu with some 150 km^3 of rhyolitic ejecta. The base of Sakurajima today rests about 125 km above the Wadati-Benioff zone, and the dynamics, mechanics, thermal structure, and deep hydrology of the subduction zone influences the generation, the segregation, and the ascent of Sakurajima magma. Photograph by T. Takayama, and courtesy of the Sakurajima Volcanological Observatory of Kyoto University, Professor Kosuke Kamo, and Dr. Kazuhiro Ishihara.

This book is printed on acid-free paper. ♾

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To

Herbert and Virginia Ryan
OF EATON RAPIDS, MICHIGAN

and

Tsuneo and Ayako Eguchi
OF KAMAKURA-SHI, KANAGAWA-KEN, JAPAN

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The volume has been designed to address perceived needs that relate to both research and to graduate teaching in Earth Sciences. All chapters have been invited to fill specific niches within the overall physical processes scope. Aspects, however, of selected chapters have also been presented at the Symposium on the Generation, Segregation, Ascent and Storage of Magma at the 29th International Geological Congress, Kyoto, Japan. In this connection, I am indebted to Professor Ikuo Kushiro of the Geological Institute of the University of Tokyo for the invitation to convene the Symposium and for his kind support. Professor Kosuke Kamo and Dr. Kazuhiro Ishihara of Kyoto University provided logistical support and gracious hospitality as did professors Toshitsugu Fujii and Yoshiaki Ida of the Earthquake Research Institute of the University of Tokyo, and Yoshiyuki Tatsumi of the School of Earth Sciences of Kyoto University.

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Prologue

The full title of this volume is *The Dynamics and Mechanics of Magmatic Systems*, but the contraction to *Magmatic Systems* serves as a useful shorthand. This book focuses on the core problems of igneous petrology and volcanology: magmatic heat and mass transport processes in the Earth's mantle and crust. In preparing this book, I have tried to combine viewpoints that represent the three principal scientific perspectives: the theoretical, the experimental, and the observational. These perspectives represent the three principal means of study, and together they blend into a powerful way of understanding Nature's plan for the regulatory mechanisms that control the movement of melts and thus the cooling and differentiation of our planet. The scope is devoted to physical processes and to the physics of magmatic systems in the Earth's interior and the subvolcanic environment.

The chapters present new research results within a surrounding framework of review material that summarizes the theoretical approach, the experimental technique, or the relevant physical environment. This provides a useful background for professional research workers, graduate students embarking on research in magma transport, and the general interest reader seeking a greater familiarity with the issues and concepts of this new field. The primary tools are continuum mechanics, analytic and computational fluid dynamics, and computational heat transfer. Summary results from high-temperature and high-pressure experimental geophysics and seismic tomography complement the theoretical studies.

The volume begins with studies of decompression melting in ascending mantle plumes and thermal diapirs and the rheology of basaltic partial melts. Next are studies of the kinematics of mantle flow beneath mid-ocean ridge spreading centers; the geologic field relations of intrusives within these centers; the three-dimensional magma buoyancy zonation structure of the magma reservoir; the sheeted dike complex; and the accreting oceanic crust. Island arc magmatism is studied from the perspectives of geophysical constraints on melting domains beneath the volcanic front, the kinematics and thermal structure of flow in the descending slab, and the melt generation—H_2O migration region of the recirculating mantle wedge. Studies of buoyancy-driven magma fracture and melt-filled crack interactions are presented next and have a general applicability that extends across specific tectonic settings. Magmatism in the continental interior is studied from the perspectives of generalized regions of partial melt within the subcontinental mantle and the mechanics of basaltic underplating; assessments of the relative roles of convective and conductive heat transfer and the rheology of partial melt in regions of silicic magma generation; two-component viscous segregation processes during concurrent silicic–basaltic magma flow; and the thermal and fluid instabilities in flow regimes that accompany surficial lava movements and may participate in deeper magma migration.

In Chapter 1, Olson discusses the fundamental process of decompression melting in ascending upper mantle thermal plumes and in rising thermal diapirs. Univariant melting that includes the effects of latent heat absorption and melt buoyancy is treated in a self-consistent approach. The chapter treats both solitary plumes and continuously driven plumes that rise beneath and then impact upon the base of thick (continental) lithosphere or, alternatively, the relatively thin lithosphere of the oceanic basins. The finite-difference solutions determined reveal a generally lens-shaped region of partial melt enrichment conformable with the basal topography of the lithospheric keel. The length of the terminal portion of the ascent pathway—as allowed by the thickness of the lithosphere itself—interacts strongly with the melting process and thus largely determines the overall volume of melt for a given class of plume. Therefore, solitary plumes are able to produce $\approx 10^6$ km^3 of magma over a few million years (Myr) beneath lithosphere of normal thickness, while thin lithospheric thicknesses promote correspondingly greater melting path lengths and are associated with $\approx 10^7$ km^3 of magma production over comparable time scales. These results accord with current estimates of the continental and oceanic plateau basalt volumes.

At the microscopic level, melting commences along the grain boundaries within the ascending lherzolite. Here, spreading melt may initiate the development of microporous networks and episodes of grain-scale fluid flow and thus assist in the attenuation of transiting seismic waves. In a highly original series of high-temperature, beam-bending experiments, Gribb, Zhang, and Cooper (Chapter 2) have induced alternating states of tension and compression in samples of synthetic olivine–basalt partial melts. Microporous flow of melt within the samples is thus experimentally induced via the production of transient gradients in the dilational stress. Application of the linear viscoelastic Burgers model to the rheology of this two-phase, liquid–solid system provides relationships for the aggregate shear viscosity and for the bulk viscosity.

Both hydrolytic weakening and melt phase enhanced grain boundary diffusion processes affect the rheology of rocks in regions of magma generation. Deformation experiments conducted by Kohlstedt and Chopra (Chapter 3) on synthetic basalt and olivine aggregates have thrown light on the important interactions between these two mechanisms of weakening. In unmelted mantle peridotites, distributed water-derived species within the framework of the crystalline silicates promote hydrolytic weakening and thus reductions in aggregate viscosity. The infrared spectroscopy portion of this study has revealed that ample amounts of a grain boundary melt may deplete the matrix olivine of hydrous species due to the relatively strong H_2O partitioning into the adjacent melt phase. Thus, while the presence of melt dramatically affects the rheology via creep strength and viscosity reductions (e.g., about a factor of 5 in strength reduction for $\approx 8\%$ basaltic melt), it tends to "dry out" the matrix olivines, reducing the *hydrolytic* component of aggregate flow regulation. As a result, the rheology of partial melts will depend on the H_2O partitioning into the grain boundary melt phase as well as the bulk permeability—both functions of the overall melt fraction.

The fluid mechanical richness of a mid-ocean ridge substructure is partially the result of the concurrent and differential flow of the deforming peridotite matrix and the intercrystalline melt phase. This flow is inherently three-dimensional, reflecting the offset or en-echelon arrangement of spreading center segments in plan view—an organizational pattern that further increases the complexity of the flow. Sparks and Parmentier (Chapter 4) have applied the mass balance and force balance equations for concurrent matrix and melt flow in a deforming mantle in three-dimensional simulations of the melt migration process. Combined with the energy equation, the determination of characteristic length scales for the solidification region has helped identify where in the system the permeability reduction due to solidification promotes enhanced melt pressures and a resulting matrix dilation. An intriguing result has been that melt focussing occurs in the decompacting (dilating) boundary layer that roofs the melting region. Melt enrichment and permeability enhancement in this *magmatic canopy* thus allows magma to migrate upslope toward the ridge axis, assisted by positive buoyancy forces. Geophysical evidence for this type of focussing in Iceland, where the magma-rich canopy lies at the top of the asthenosphere and dips symmetrically away from the neovolcanic zone axis, has been summarized by Ryan (1990).

The availability of relatively large volumes of magma near the top of the asthenosphere, combined with the steep thermal gradients and rapidly varying stress states associated with the divergent mantle flow below the Mohorovičić discontinuity, promotes diverse modes of magma fracture beneath an active ridge. Mapping campaigns in the Oman ophiolite conducted by Nicolas, Boudier, and Ildefonse (Chapter 5) combined with careful petrofabric analyses have defined the nature of these modes and their relationships to the flowing asthenosphere and the accreting lithosphere. A *first generation* of indigenous gabbro and pyroxenite dikes and veins crosses melt-impregnated peridotites while a *second generation* of microgabbro and diabase dikes has intruded into cooler crustal rocks and is regionally organized in patterns that mimic the strike of the reconstructed ridge itself. Diverse intrusive orientations that range from dikes to sills reflect the lithospheric and asthenospheric stress fields respectively, and sill-forming injections have been spatially linked with the strongly divergent asthenospheric flow fields at the very top of subridge diapirs. Thus, detailed studies of the Oman ophiolite open windows into the roots of mid-ocean ridges and illuminate their magmatic machinery.

Gravitational equilibrium and the quest for its periodic reinstatement are fundamental to the operation of magmatic systems. Until recently, the functional maintenance of this equilibrium state in active volcanic systems was thought to generally require the movement of magma completely through the lithosphere and its emplacement as lava on the Earth's surface. Lithospheric densities were generally regarded as always greater than magma density and *states of universal positive buoyancy* were believed to characterize the oceanic and continental lithosphere. These views have been widespread and pervade the geophysical and volcanological literature. The assumption of *complete fluid continuity* from the magma source region to the eruption site (now known to be generally false) complemented the universal positive buoyancy assumption and permitted the balancing of lithostatic and magmastatic pressures over great columns of virtually lithospheric dimensions. Existence criteria for mid-ocean ridge magma reservoirs were ascribed to be almost wholly the result of the initially assumed and then numerically modeled ridge thermal structures: robust development for high spreading rates, negligible development for low spreading rates. The detailed density states of mid-ocean ridges as the combined functions of the relevant range in magma compositions, suspended mineral phases, and the vertical succession of the nonlinear *in situ* density structure of the oceanic crust itself were not of general interest. These views, with few exceptions, characterized the period following the inception of plate tectonics to at least the mid-1980s, and to some extent remain today. That *states of positive magma buoyancy are, in fact, routinely complemented by states of neutral and negative buoyancy in active basaltic systems* was first demonstrated by Ryan (1987a) for Hawaii, and then again for Hawaii and Iceland with hypothesized extensions to the East Pacific Rise by Ryan (1987b). The recognition of the widespread role of neutral buoyancy states in the shallow subvolcanic environment has, I think, profound implications for how magmatic systems work. In these terms, the importance of the neutral buoyancy concept is three-fold: (a) an internally consistent existence criterion for shallow magma reservoirs; (b) a new tool for the quantitative understanding of the upward (and lateral) evolution of the reservoir; and (c) a powerful means of understanding magma dynamics in intrusion episodes within stratified reservoirs as well as in the sheeted-dike complex. In Chapter 6, I have reviewed several aspects of the neutral buoyancy structure of mid-ocean ridge magma reservoirs. The compositionally averaged horizon of neutral buoyancy (HNB) for the East Pacific Rise occurs at a depth of ≈1000 m to ≈3000 m beneath the rise axis (at 9°N latitude). Fractional crystallization and elastic crack stability criteria suggest that this generalized HNB should be subdivided into a deeper picritic horizon (≈1400 to ≈3000 m depth) and a shallow tholeiitic horizon (≈600 m to ≈1400 m depth). During the fractional crystallization that transforms a picritic melt and olivine mixture into tholeiitic melt, parcels of magma must elevate themselves to maintain gravitational equilibrium. In ophiolite complexes, the uppermost isotropic gabbros are correlated with the picritic HNB, whereas the sheeted-dike complex corresponds to the tholeiitic horizon of neutral buoyancy. These relations are consistent with the dominantly tholeiitic nature of the sheeted dikes as well as the paucity of ocean floor picrites. The combined tholeiitic and picritic HNB is, in addition, in virtually a 1:1 correspondence with the inferred sheeted-dike complex and the compressional wave velocity minima region (i.e., the magma-rich portion of the reservoir) for the East Pacific Rise as determined by seismic reflection surveys and by tomographic inversions of P-wave travel-time residuals. The dynamics of magma injections within the sheeted-dike complex are suggested to be analogous to their counterparts at Kilauea volcano, Hawaii, and to the Krafla central volcano, northeast Iceland, during, for example, the 1975–1984 intrusion-eruption episodes. [It is important to recognize that the present erosion levels in Hawaii and Iceland do not sample the heart of the tholeiitic HNB (centered at ≈3 km local depth) and thus contain components of vertical flow.] From an evolutionary perspective, as lithosphere is created at mid-ocean ridges and spreads laterally, the horizons of neutral buoyancy and negative buoyancy ride with it, and they are suggested to significantly influence the ascent of off-axis magma to about 30 Myr and provide the means for shallow off-axis storage as well.

Recent advances in the seismic resolution of mid-ocean ridge magma reservoirs have refined their images, considerably tightened their geometric extents, and have laid the basis for a new generation of numerical models that yield kinematic insights on how ridges work. Phipps Morgan, Harding, Orcutt, Kent and Chen (Chapter 7) have reviewed the results of seismic reflection experiments over the East Pacific Rise, suggesting that the magma reservoir comprises a relatively fluid-rich upper chamber (width: ≈1 km; thickness ≈50–200 m) that crowns a progressively crystal-rich mush where melt contents average 3–5%. Kinematic modeling of the two-dimensional structure of the flow field induced by steady-state lithospheric lid translation has used the conservation equations in conjunction with McKenzie's finite deformation formulation. The deformation results accord nicely with textural observations in ophiolite crustal sections: steeply dipping foliations high in the gabbros, with progessive increases in strain and considerable foliation flattening with depth.

About 439 of the world's 442 active andesitic volcanoes occur in regions of oceanic plate subduction (Gill, 1981). Frequently arranged in great sweeping island arcs, their magma generation systems, segregation mechanisms, and ascent networks remain shrouded behind a veil of complex rheology, often sluggish magma migration kinetics, and largely aseismic ascent pathways. Because so much of the inner workings of these systems remains unknown—even in outline—they comprise a great and relatively uncharted frontier for research in magma transport. Their petrologic diversity, violent eruptive behavior, and shear number underscore the great need for intensely focused and highly coordinated research in this area. A parting of this veil and an initial illumination of an arc system interior has made use of the velocity dependence of compressional seismic waves resulting from rock composition, temperature, regional structure, and the presence and distribution of included domains of fluid. Hasegawa and Zhao (Chapter 8) have employed a three-dimensional velocity model that explicitly incorporates the locally complex shapes of the Mohorovičić and Conrad discontinuities to refine the velocity structure of the northeast Japan arc based on least-squares inversions of P-wave travel-time residuals. The magma-impregnated low velocity zones revealed in their study are inclined, and they dip parallel to the dip of the Pacific Plate but are found at least some 30–60 km above the plate's upper surface. Produced by velocity contrasts of 2–6%, they are continuously distributed from the upper crust (shallow magma ascent regions) to a depth of 100–150 km within the mantle wedge (the magma generation and segregation regions).

The *refrigeration* of the mantle produced by the subduction of oceanic plates leads naturally to the paradox of prolific arc magmatism directly above a mantle wedge that is cooled by conductive heat transfer to a juxtaposed downgoing slab. Building on the theoretical work of McKenzie (1969) and Toksoz, Minear, and Julian (1971), the experimental studies from the laboratories of Burnham, Green, and Wyllie, and the geochemical studies of Tatsumi (1989), J. H. Davies (Chapter 9) addresses the *why* and *how* of this paradox by combining thermomechanical modeling with an incremental mechanism for water transfer from the slabs' upper surface well into the wedge interior. The model produces finite element solutions to the advection–conduction energy equation in response to the kinematically driven flow field of the subducting slab. The steady-state thermal structures of the wedge and slab as functions of the subduction velocity reflect the slow secondary wedge flow and set the stage for the H_2O migration mechanism. Water is released from amphibole at depths near 80 km, and in a cyclic series of dehydration (H_2O release) amphibole reformation stages, rides the downward streamlines of the wedge flow field in steps that, in inchworm fashion, carry it both laterally and downward into melt generation depths. These positions within the wedge are consistent with the roots of island arc magmas and the location of the volcanic front above.

The processes of linear elastic brittle fracture, creep rupture, and stress corrosion cracking occupy portions of a continuum of failure phenomena associated with the migration of magma by cracks. Within the oceanic and continental lithosphere and within the crust above subduction zones, the fracture mode of magma ascent, emplacement, and lateral intrusion is one of the great workhorses of magma migration. Without it the galaxy of veins, dikes, sills, sheets, fissure eruptions and shallow basaltic-to-andesitic magma reservoirs would not exist. Heimpel and Olson (Chapter 10) have used gelatine gel-based analogue experiments to study the mechanics of positive buoyancy-driven, fluid-filled fractures. In contrast with dry remotely loaded fracture processes which induce large amounts of elastic stored strain energy just prior to fracture and are associated with catastrophic crack growth, the *locally loaded* buoyancy-driven cracks suggest a set of dynamical constraints on the fracture process when the fluid-filled crack is imbedded in viscoelastic media. Thus, the coupled processes of time-dependent external stress relaxation and internal fluid flow that accompany increments of crack extension modulate the crack propagation velocities and, by analogy, may significantly influence the magma migration process.

The development and function of well-trodden magma migration conduits, as well as the nucleation of shallow magma reservoirs, all owe a great debt to the phenomena of magma fracture coalescence. Takada (Chapter 11) has used Westergaard stress functions and complex variables to compute the nature of the displacements and stress fields near two parallel offset fluid-pressurized cracks in a search for crack coalescence criteria. Complementary gelatine gel-based experiments on fluid buoyancy-driven cracks have revealed that magma-filled cracks *can* coalesce and undergo a resulting magma volume increase as long as there is an available *range* in crack sizes and ascent velocities. The coalescence process is further enhanced by small differential stress states in horizontal sections and by concomitant large magma supply rates.

The continents have been the birthplace of igneous petrology and most subdisciplines of geophysics, yet after the inception of plate tectonics, much of the energy and attention in these fields of research has been understandably directed offshore, toward the problems—and the promise—of the ocean basins. Perhaps the time is now ripe, however, for a rejuvenation of work within—and beneath—the continental interiors. Sato and Ryan (Chapter 12) have estimated generalized temperature profiles and degrees of partial melt in the upper mantle beneath the western United States. The study makes use of seismic velocity data for partially melted peridotites and published anelasticity data for the regional scale upper mantle. Experimental measurements of the compressional wave velocity and elastic wave attenuation in spinel lherzolites show a homologous temperature dependence: families of Vp, Qp^{-1} data for a variety of pressures plot as a single band in terms of the experimental temperature normalized by the sample melting temperature (T/T_{m}). Thus, a knowledge of the solidus as a function of pressure allows the estimation of temperature as a function of pressure—and hence depth in the mantle. Therefore, both Vp and Qp^{-1} are of use in estimating $T(Z)$ for various regions of interest. In addition, empirical plots of melt fraction versus (T/T_{m}) allow *in situ* melt fractions to be estimated once T_{m} and T have been determined. This procedure has produced generalized temperature-depth profiles for major regions of the western United States, and they cover the depth range 50–300 km. At shallow (crustal) depths they are comparable with conductive geotherms, while at depths greater than 200 km they are compatible with the adiabatic temperature gradient. Partial melt contents estimated for the intermountain and western margin regions cover the range $\approx 3\% \leq \varnothing_{\mathrm{m}} \leq 10^{+}\%$, when regionally averaged. These melt contents occur over the 120–200 km-depth range, and transitions from porous media melt flow to vein and dike flow are expected over these depth intervals. A review of elastic fracture stability theory within the context of subcontinental magma ascent reveals the fundamentally disconnected nature of the ascent pathway: the finite strengths of fluid-weakened mantle peridotites at high temperatures mandate, in turn, finite height magma-filled fractures. Deep dike swarms are thus suggested to be the ascent mode for the deepest levels of basaltic underplating along the crust–mantle boundary. The crust–mantle interface itself, reflecting changes in both mineralogy and potential melt content, may be treated as a bi-elastic material boundary, and the morphology and mechanics of dikes that penetrate such an interface depend on the ratios of effective elastic moduli on either side, as well as the fluid pressure loading conditions within the fracture.

The shear viscosities of single-phase natural silicate melts span an extraordinary 13 orders of magnitude and the *melts* of the continental interiors must routinely encompass this entire spectrum. For regions of basaltic underplating and of the secondary generation of silicic crustal magmas, the single-phase contents of laboratory crucibles are but one end-member of a rheological continuum that includes melt-based suspensions, melt-weakened country rocks, and highly altered, but as yet unmelted, rock on all scales. The high-solids-fraction domains thus raise the aggregate effective shear viscosities to yet greater values. Accordingly, the migration kinetics of ascending magma in the continental crust cover a time range that extends far beyond the realm of human experience and renders much of the generation, ascent, emplacement, and replenishment process of silica-rich magmas aseismic. Like the pathways for magma above Wadati-Benioff zones, the continental *interior* regions of silicic melt generation remain heavily shrouded and thus deserving of carefully focused and well-coordinated research. Bergantz (Chapter 13) reviews aspects of continental magmatism around the general theme of basaltic underplating. Finite volume solutions of the conservation equations have employed the spatial and temperature dependence of viscosity, density, heat capacity, and thermal conductivity in a model of basaltic underplating that considers the progress of crystallization in the basaltic substrate as a function of partial melting in the overlying crust. Three questions are of interest: How does convection influence the timing of partial melting in the crust, and what is the style of convection? How does variable viscosity (as a function of melt composition and crystallinity) influence convection? What are the overall heat transfer rates from the system relative to those expected from conduction only? Nusselt (Nu) number computations during the evolution of the melting region compare the strength of the overall heat transfer components and suggest that for critical melt fractions over $0.3 \leq \varnothing_m \leq 0.5$, the amount of melt generated was indistinguishable from that produced during conduction only. This is broadly consistent with the notion that the rheological conditions associated with the onset of crystallization control the subsequent dynamic evolution of the body. Thus the *early* stages of underplating appear to be largely conductive, and multiple basaltic intrusions are required to thermally mature a deep crustal section and permit widespread regional melting episodes in the crust above.

Magma reservoirs may be viewed as great mechanical capacitors that, during magma influxes, slowly accumulate potential energy. This stored energy occurs by virtue of the vertical displacements of their roof rocks and caldera floors and by the compression of the immediate surroundings, including the magma. Conceptually, these are akin to compressed springs that are coupled in parallel. Rupture of the reservoir walls suddenly releases magma into the surrounding country rocks in dike-forming injections—a process that relaxes the conceptual springs but works against the environment by virtue of the crack wall displacements and the work-of-fracture (atomic bond breaking) at the advancing crack tip. Importantly, the energy dissipated in the high shear boundary layers of the near-wall dike interior represents a significant resistance term in the overall process of fluid flow. Inherently repetitious, the overall magma recharge—discharge cycle maximizes its efficiency by (1) maximizing the overall potential energy reductions, and (2) simultaneously minimizing all the associated work done in the dike formation episodes. Thus a globally integrated *least work* principle lies at the heart of the magma storage and fracture process. In regions of *mixed* magma storage, Nature also has a trick up her sleeve that helps in the effort to minimize the work done in moving fluids and thus enhance the efficiency of the magma injection process. Carrigan (Chapter 14) has derived the lubrication equations for the two-component flow of a power-law fluid in a dike-like geometry. The solutions describe the process of the hydrodynamic encapsulation of the high viscosity (interior) phase by the low viscosity (exterior) fluid. Importantly, the outer (low viscosity) phase occupies the high shear—and energy dissipating—boundary layers at the dike wall. The overall flow process is analogous with the *lubricated pipelining* process of industrial settings. It describes the means of providing a least work solution to the problem of mixed magma transport in settings as diverse as Long Valley, California, and southeast Iceland, for example. A substantially more realistic magma withdrawal model has also evolved from the work, wherein two or more layers of differing composition (and viscosity) can be *simultaneously* withdrawn without invoking the rather special set of circumstances inherent in the *draw-up-depth* parameter or in the *overtaking* requirement of other approaches. Overall, the model represents a significant step forward in advancing our understanding of this important class of problems.

The simultaneous attempts to achieve both thermal and mechanical equilibrium within regions of high temperature magma flow, lead to a number of thermomechanical feedback processes. Familiar examples relate to the potential for either dike wall solidification or meltback, depending on the flow rates, magma temperatures, dike widths and the ambient thermal environment (Bruce and Huppert, 1990). Other examples include the role of the evolving conduit geometric aspect ratio in flow localization during the course of an eruption (Delaney and Pollard, 1982). Whitehead and Kelemen (Chapter 15) explore, theoretically and experimentally, a new class of dynamic feedback phenomena. Gravity-driven laboratory flow experiments, for example, reveal the potential for interplay between fluid pressure, environmental and fluid temperatures, temperature-dependent viscosity fluctuations, and the resulting flow rates. These effects include flow choking, episodic pressure buildups, and transitions in flow rates that correlate with the radially inward growth of high viscosity 'walls' during environmental temperature drops. Additional effects have been modeled theoretically, and include oscillatory pressure–time ($P-t$) and fluid velocity–time histories that may have either sawtooth or sinusoidal $P-t$ signatures, and are correlative with pulsatile fluid flow behavior. These types of relationships hold the potential for further application to the throttling of magmatic and volcanic flows through regions with high spatial gradients in environmental temperature and conduit geometry. For surficial volcanic process considerations, laboratory simulations by Whitehead and Kelemen (Chapter 15) of horizontally spreading flows have used paraffin as the working fluid. These show transitions from smooth perimeter radial flow regimes to finger flow regimes as a function of the solidification rate and temperature-dependent viscosity. Experiments with lateral spreading flows from line sources have charted a morphological continuum of surface textures depending on the ratio of the solidification to advection time scales. These forms range from pillows through surface ripples to flat sheeted flows.

In a direct way, this volume complements the book *Magma Transport and Storage* (M. P. Ryan, ed.), John Wiley and Sons, Ltd., 1990. While some authors have returned to write new chapters for this book, there is no overlap, and each chapter is a fresh, new and complementary effort, quite separate and distinct from the work cited above.

Increasingly, scientists with diverse backgrounds that have traditionally been spread out over several of the subdisciplines of geophysics, igneous petrology and volcanology have found that the subject area of magma transport offers an exciting and unifying process-oriented framework for study. Within this framework lies great cohesion yet remarkable room for individual and team research initiatives. It is my hope that the present book will further this process of unification by providing fertile points of departure for research as well as offering stimulating areas of discussion for the classroom and for the seminar hall.

Finally, detailed author, geographical and subject indices complete the volume and promote accessibility and cross-referencing.

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