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Preface

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This Special Issue includes 18 papers investigating aspects of the Extraction, Transport and Emplacement of Granitic Magmas. Many of the papers were presented at the symposium on the same theme held at the Geological Association of Canada's annual meeting in Ottawa, in May 1997. Forty-six communications were presented at the symposium by participants from Australia, Canada, France, Germany, Great Britain, the United States, Russia, Spain and Sweden. The abundant and stimulating discussions that punctuated the symposium testified to the strong interest of Earth Scientists in the nature of granitic magmatism. The symposium marked the 50th anniversary of the historic Origin of Granite conference held in Ottawa at the first annual meeting of the GAC, in December 1947 (Gilluly, 1948). Some of the topics debated by participants at that earlier conference have since been resolved. Others, such as the room problem for granite emplacement, remain subjects of much current research and debate.

The 1997 symposium was motivated by the desire to foster debate on the physical processes that control how granitic magmas are separated from their source regions, transported through many kilometres of the Earth's crust, and emplaced as large plutons and batholiths. In recent years, these have been key issues in vigorous debates on the fundamental nature of continental magmatism. Increasingly, structural and geophysical observations have become critical for the resolution of what were once mainly petrological issues. Accepted models are being questioned, either because they require apparently unrealistic rheological behaviours of rocks and magmas, or because they do not satisfactorily explain the available structural and geophysical data.

The collection of papers in this issue reflects the theme of the Ottawa symposium, as well as the diversity of views and approaches being adopted to address the many outstanding questions on the place of granitic magmatism in crustal evolution. The papers present much new data collected using modern and diverse geological and geophysical methods (e.g. remote sensing, and the mapping of fabrics in isotropic-looking granitic rocks using magnetic techniques), as well as new results from numerical modelling of magma-country rock systems and experimental studies of magma viscosities.

The first nine contributions deal with pluton emplacement at mid- to upper-crustal levels. The papers explore the important controls exercised by crustal structures, rheologies, strain rates and cooling rates on where and how plutons are emplaced, and on the internal structures of plutons.

Dehls, Cruden and Vigneresse use Landsat imagery, field mapping and gravity modelling to investigate the emplacement of the Archean Ulu leucogranite pluton in the Slave Province, Canada. The straight sides of the pluton in map view correspond to principal regional fracture lineaments. The gravity models suggest the pluton is a thin tabular body with narrow root zones that are also parallel to the regional fracture sets. These results lead to a model for fracture-controlled ascent and emplacement of the Ulu magma, with space being created for the pluton by vertical displacements on pre-existing fracture sets.

Hogan, Price and Gilbert investigate pluton emplacement during extensional tectonics within the

Wichita Igneous Province, Oklahoma. Their analysis begins with field observations of the geometries of intrusions, and a discussion of the petrological constraints on the physical properties of the magmas in question. Magmastatic calculations are used to explain why different magmas are emplaced at different depths, and why plutons adopt different shapes. Magmas can potentially ascend to depths where the magma driving pressure is negligible. Magmas are erupted if they maintain a positive driving pressure at the surface and if they have not been stopped by a crustal magma trap, such as a subhorizontal strength anisotropy in the crust. Pluton shapes are predicted to be a consequence of the relative magnitudes of the lithostatic load and the magma driving pressure. Subhorizontal sheet intrusions, such as the Mount Scott Granite, form when magma driving pressure greatly exceeds lithostatic load, thereby allowing the roof to be lifted. When magma driving pressure is approximately equal to the lithostatic load, steep sided plutons form and space may be made by stoping or floor depression.

Roig, Faure and Truffert apply structural mapping, quartz petrofabric and TEM studies, strain analyses and gravity modelling in an intensive investigation of the emplacement of granodioritic plutons in the Tulle antiform, Massif Central, France. The quartz *c*-axes fabrics and TEM analyses demonstrate the continuum in deformation of the syn-tectonically emplaced magmas, from the magmatic state through subsolidus conditions. The gravity models and strain analyses suggest the plutons are laccolithic bodies, emplaced within a constrictional strain field along a syn-folding décollement level during Variscan transpressional tectonics.

Corriveau, Rivard and van Breemen summarize the results of extensive regional mapping, geochronology and remote sensing studies in the Central Metasedimentary Belt of the Proterozoic Grenville Province, Québec. Using two distinct suites of intrusions they show that the distributions and map outlines of plutons may not be reliable indicators of the timing and style of tectonic events in deeply eroded orogens. Magmas of a younger, potassic suite are shown to cross-cut felsic gneiss complexes as dykes, and to intrude marble-rich wall-rocks as elliptical plutons. The distribution and form of the intrusions are controlled by the rheologies of the felsic gneiss (strong) and the marble (soft). An older, less alkaline magmatic suite is shown to be distributed uniformly across the various lithotectonic domains in the area. In both cases, consideration of the nature of the wall rocks is critical for understanding the emplacement mechanisms and tectonic significance of plutons.

Yoshinobu, Okaya and Paterson investigate the progressive construction of plutons from magma pulses emplaced along fault zones, where the creation of room for pluton growth would be controlled by fault slip rates. They use numerical modelling to investigate the fault slip rates that enable conductively cooled granite plutons to grow in such a way as to preserve homogeneous internal structure, rather than developing as sheeted dyke complexes. The results suggest that homogeneous plutons, if created by successive magma batches and not by one magma pulse, require very low rates of heat loss between magma pulses. This condition would be found where fault slip rates are fast, or where the wall rocks are very warm. One key conclusion from this work—that slip rates on faults where space is created for plutons may be very rapid—will surely stimulate field investigations of the internal structures of plutons and the deformation rates in spatially associated faults.

Continuing with the theme of pluton growth, Castro and Fernandez present an elegant case study of the Plasenzuela pluton in Spain. The overall pluton shape and internal fabrics appear to be concordant with the country rock structures. However, based on the foliation patterns in the country rocks and the presence of crenulations and shear zones in the wall rocks and the pluton margins, the authors argue for an initial crack-shaped opening that filled with granitic magma. As regional deformation continued the crack continued to open and was in-filled with more magma and rotated, with shear zones developing at the pluton margins. The magma composition and style of magma emplacement also changed with time giving rise to a zoned pluton. Several possible pluton geometries are predicted based on the model of magma emplacement within a deforming crustal fracture.

Two papers combine field and microstructural studies with detailed analyses of the anisotropy of magnetic susceptibility (AMS) fabrics in plutons. The magnetic fabric method is gaining wide acceptance as a standard tool for mapping of magmatic to high-temperature solid-state petrofabrics in granitoid plutons (Bouchez, 1997). Gleizes, Leblanc, Olivier and Bouchez use the AMS technique to map the foliation and lineation in the three plutons comprising the Cauterets–Panticosa complex in the Pyrenees. The magnetic fabric data, together with structural observations in the country rocks and microstructural observations in the granites, reveal that the plutons were emplaced during regional dextral deformation, in contrast with earlier conclusions that the plutons were emplaced after regional deformation had ceased. In some parts of the complex the foliation apparently retains information on magmatic deformation whereas the lineation in the same rocks has been reset and records regional post-crystallization deformation. The proposed emplacement model resembles that of Castro and Fernandez for the Plasenzuela pluton. It is interesting to note that the plutons studied by Castro and Fernandez and by Gleizes *et al.* both have rather uniform cores with large regions preserving magmatic foliations. This is the type of pluton which the modelling of Yoshinobu *et al.* suggests ought to be rare. Are published studies really representative of the true diversity of plutons in nature? Are sheeted dyke-type plutons grossly neglected and under-reported? Are emplacement-related strain rates much higher than considered normal?

Benn, Ham, Pignotta and Bleeker use the AMS technique to map the pervasive fabrics of the Archean Sparrow pluton, Slave Province, Canada. Microstructural study shows the fabrics record magmatic to high-temperature solid-state deformation. The patterns defined by the magnetic foliation and the magnetic lineation, and by scalar parameters of the AMS are all consistent with the regional D_2 phase of transpressive tectonics. The penetrative fabrics in the pluton are part of the regional syn-emplacement strain field and record transpressive regional deformation during crystallization and cooling of the granite. The study demonstrates how the penetrative fabrics in granite plutons can serve as markers of the strain field and kinematics associated with syn-magmatic tectonic events in multiply deformed metamorphic terranes.

Paterson and Miller investigate the magmatic fabric patterns around stoped blocks within the Mount Stuart Batholith, in the Cascades Crystalline Core, Washington. The magmatic fabrics do not preserve any record of block sinking, and therefore they must have formed once the blocks had been trapped in the partly crystallized magma. The magma yield strengths and/or the magma viscosities when the blocks were trapped must have been high (viscosities may have been from 10^{14} to 10^{15} Pa s). Since the fabrics in the pluton post-date trapping of the blocks, they must have formed within largely crystallized magma. In this case, the magmatic fabrics do not record the history of magma emplacement, but rather regional tectonic deformation of a largely crystallized pluton.

The next three papers present detailed studies of the internal mesoscale structures of several plutons, and the results have implications for pluton emplacement models and for the dynamics of granitic magma chambers. Weibe and Collins describe a wide range of diverse structures and textures in plutons that are related to input of mafic magma into a felsic magma chamber. Using examples of plutons and field relations in SE Australia and southern New Zealand they argue that some of these features can be used as way-up indicators. The relationships presented suggest that many plutons are constructed by mafic and felsic injections, with sequential deposition of mafic material (e.g. aggregations of mafic enclaves) on the transient floor of the chamber. Small-scale way-up structures indicate that the igneous stratigraphy starts out with a horizontal attitude and is subsequently tilted to steeper orientations as younger pulses are intruded into the active part of the chamber above. Space is made by tilting and downward sagging of the pluton floor and earlier intrusive layers in a similar manner to the cantilever mechanism for floor depression proposed by Cruden (1998). An important consequence of their observations and model is that many magma chambers may be constructed much more slowly than presently thought. At any one time the volume of magma in the chamber is relatively small, occupying a thin horizontal layer.

Everitt, Brown, Ejeckam, Sikorsky and Woodcock describe the internal structure of the late Archean Lac du Bonnet Batholith using surface mapping, drill hole and geophysical data at Atomic Energy of Canada Ltd's underground research laboratory at Pinawa, Manitoba. The granitic intrusion appears to be quite homogenous in flat, glaciated surface exposures, but it is shown to consist of a well-defined, metre- to decametre-scale lithostructural layering. Lithostructural domains in the pluton are defined based on the distribution and abundance of wall-rock xenoliths within a main phase porphyritic granite, concordant pegmatite sheets and discordant granodiorite dykes whose abundances vary with depth. The lithostructural layering has been folded to define open upright kilometre-scale domes. The batholith is markedly asymmetric in shape. The results are highly instructive because they show a well-documented three-dimensional view of a large granitoid complex, demonstrating that an apparently homogenous pluton, based on surface observations, is in fact a heterolithic body composed of subhorizontal sheets. Surface observations of plutons alone may be subject to a major sampling bias, particularly in areas of low relief.

There has been much activity by those working on mafic intrusions directed towards studying the origin of igneous layering. Ideas have progressed from the simple crystal settling models of the past, and it is realized that layering may form in response to a number of influences ranging from magma pulses through compaction to subsolidus recrystallization. Many granite plutons also contain layering on various scales and, although its occurrence is often reported, it is seldom studied. Clarke and Clarke report on a portion of the Late Devonian South Mountain Batholith where layering is prominant and well exposed. After describing the physical and petrographic aspects of the layering they go on to propose a numerical model to explain its development. A curious and key observation is the association of layering with dykes. Their model involves settling and growth of microphenocrysts left in the magma after flow through a partly crystallized and deforming adjacent part of the pluton—a form of porous flow driven by roof block subsidence. The model predicts layer development would take from 10 to 35 years. In view of the progress made in understanding layering in mafic magma, the contribution of Clarke and Clarke is timely and one hopes it will stimulate further work on the layering in granites.

Stoped blocks are commonly found within granitoid plutons emplaced at upper crustal levels, but accumulations of sunken blocks are not found on the floors of plutons. Clarke, Henry and White propose one explanation for the absence of 'elephants' graveyards' of stoped blocks on pluton floors with their detailed study of a $20\,\mathrm{m} \times 25\,\mathrm{m}$ mechanically anisotropic (bedded) xenolith of metasedimentary rock within the South Mountain Batholith. Thin (centimetre-scale) sheets of granitic magma were injected into bedding-parallel (mostly) and bedding-perpendicular fractures that formed in the block in response to thermal stresses. This resulted in the explosive disintegration of part of the block into centimetre-scale fragments. If the explosive disintegration of anisotropic stoped xenoliths is common it might explain why large blocks do not accumulate at the bottoms of granitic plutons.

Before emplacement at a higher crustal levels granitic magma has to be removed from its source region and transported upwards. The processes by which extraction and transport of granitic magma occur are a matter of some controversy—magma diapirs, dykes and channelling along shear zones have all been proposed (e.g. Marsh, 1982; Clemens and Mawer, 1992; Collins and Sawyer, 1996). Paterson and Miller document the geometry of highly elongate intrusive sheets that make up the Cretaceous Entiat pluton of the Cascades Crystalline Core, Washington. Where the ends of these sheets intrude host rock, they are emplaced parallel to the axial planes of local and regional folds. Field relationships suggest that these intrusions are not folded and locally cut across wall rock fabrics. Emplacement of the sheets was broadly synchronous with regional NW–SE shortening that caused the folding of the host rocks and the magmatic fabrics in the intrusive rocks. Measured aspect ratios of the sheets and the radius of curvature of their tips indicate a geometry between those predicted for dykes and diapirs. Emplacement of the sheets perpendicular to the regional σ_1 direction is used to argue they were not intruded as Andersonian dykes. The authors propose that the sheets formed by the ascent of diapiric ridges, which grew from the top of a larger magmatic body at depth. The ascent and form of the ridges were strongly controlled by the regional contraction and host rock anisotropy in ductile lower crust of the magmatic arc. The study emphasizes that magma ascent processes such as dyke transport, diapirism, fault-controlled and pervasive magma flow are end-member mechanisms leading to end-member emplacement styles. Ascent and emplacement of granitoid magmas may occur by a combination of these processes, in this case a hybrid between dyke transport and diapirism.

Brown and Solar examine a region of the Central Maine Belt of New England where granitic magma can convincingly be shown to have migrated up crustal scale high-strain zones in a convergent orogen. Magma flow was driven by buoyancy forces and tectonic stresses. They show that granitic magma has moved up the high-strain zone by percolative flow and also in fractures oriented parallel and subparallel to the foliation. The magma moved as discrete packets leaving dykes (sheets) of different composition. Further evidence of magma batches can be seen above the high-strain zone, as some plutons were built of sheets of different bulk composition that came from different sources.

Melt viscosity is one of the most important variables that control the mechanisms and rates of melt extraction from source regions, as well as the rates at which the melts are transported towards the final site of emplacement. Baker discusses the importance of temperature and volatile (especially H_2O) content in controlling melt viscosities. On the basis of new experimental data, he recalibrates an empirical model for granitic melt viscosities. The predicted viscosities are used to model the conditions under which melts may be extracted and transported large distances from partially melted regions above thick underplated basaltic sills.

Petford and Koenders consider self-organization of fractures and the development of fracture connectivity in the continental crust in response to rapid heating. A random graph model shows how isolated fractures formed during a thermal perturbation can rapidly combine together and form an isotropic fracture network with high estimated permeabilities. A physical model is then presented to explain the emergence of a vertical directionality in the permeable fracture network within a heterogenous medium. The connectivity within the fracture network and its directionality are crucial to allow the collection of melt and its buoyancy-driven transport from partially melted source regions. Such a fracture network may arise in response to the rapid heating of crustal rocks, for instance above a region of magmatic underplating.

Departing somewhat from the granitic magma theme, Collins, Van Kranendonk and Teyssier investigate the origin of the granitoid domes in the Pilbara craton of Western Australia. Using field data, and lineation trajectories in particular, they conclude that the domes formed by partial convective overturn of a predominantly solid, but thermally softened crust. In their model, which resembles that of Mareschal and West (1980), the greenstones between the granitoid domes represent zones of sinking and the domes regions of uprising. Using U–Pb dates they argue that thermal softening and subsequent diapirism occurred because a mantle plume lay beneath the Pilbara crust at about 3325–3310 Ma. Relatively minor amounts of granite magma, generated by partial melting of the crust, rose within the domes.

The reader has noticed from this summary that the assembled papers represent diverse approaches to investigating the physical processes associated with granitic magmatism, and also diverse opinions on how granitic magmas are transferred in the crust and assembled into plutons and batholiths. A consensus has yet to be reached on many of the questions addressed by the contributing authors, but the data they have documented and the ideas they have developed will certainly open new perspectives on granitic magmatism, and lead to a better understanding of the structures within plutons and their country rocks. It is hoped that this special issue will serve as a durable reference for a broad audience of structural geologists and tectonicists. Hopefully, it will also fuel more exciting research and debate on the place of granitic magmatism in the tectonic evolution of the Earth's crust.

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