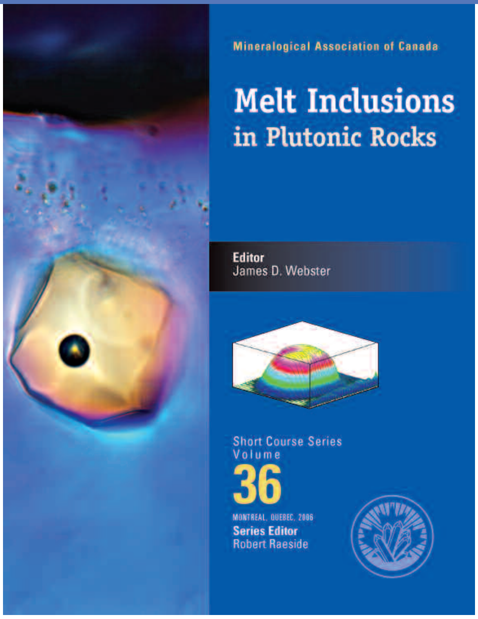
Melt Inclusions in Plutonic Rocks*

The study of fluid inclusions—gas, liquid, melt—saw an impressive renaissance after the Second World War, mainly through the efforts of E.W. Roedder in the West and N.P. Ermakov in the former Soviet Union. The use of inclusions as a tool to solve geological and geochemical problems has advanced from simple aqueous–salt systems, to rapidly quenched glass inclusions in extrusive environments, and now to melt inclusions in plutonic rocks. This advance has more or less followed the development of fluid inclusion analytical instrumentation and experimental research designed to elucidate the physicochemical understanding of the inclusions. In 1984, Roedder (in *Fluid Inclusions*, Reviews in Mineralogy, volume 12, 644 pp) briefly discussed melt inclusions in intrusive rocks and recognized some of the inherent problems: difficulty of recognition, problems with phase interpretation, and the lack of appropriate instrumentation or techniques.

The Mineralogical Association of Canada Short Course Series volume 36, *Melt Inclusions in Plutonic Rocks,* presents a historical perspective and details the current state of knowledge and potential future developments for this useful petrologic tool. The editor, James D. Webster, has brought together a very well-balanced, well-illustrated group of papers that will be useful to the student as well as the dedicated inclusion worker. This volume shows that the study, interpretation, and use of melt inclusions to understand intrusive rocks has come of age.

R.J. Bodnar and J.J. Student, in chapter 1, provide an excellent discussion of the history of melt inclusion study. They provide details of the fundamental petrographic and interpretative bases, explain what to do if you find inclusions in your intrusive rocks, and conclude with an example from porphyry-type deposits. SIMS (secondary ion mass spectrometry), an analytical technique that allows in situ elemental analysis with low sample destructivity, has been successfully applied to melt inclusions. In chapter 2, G.D. Layne describes the use of this technique for the determination of traditional and non-traditional, light stable isotopes in silicate melt inclusions. Layne clearly describes the technical details of the Cameca IMS instrumentation as well as specific techniques and applications. Chapter 3, by T. Pettke, provides an excellent mini–short course on in situ



laser-ablation ICP–MS analysis of melt inclusions. Pettke also provides a very important discussion of the statistical relevance and relative strengths of data sets generated by LA–ICP–MS, SIMS, and electron microprobe analysis. He concludes with a section on the potential for this technique to help understand subduction zone magmatism. Some sort of magmatic immiscibility (unmixing) is inevitable during the evolution of most magmas, and V.S. Kamenetsky, in chapter 4, discusses various types of magmatic immiscibility: silicate–silicate, silicate–aqueous saline, silicate–hydrosaline (or salt), silicate–carbonic, and non-silicate melt pairs. This discussion is excellently illustrated with clear and well-documented photomicrographs.

Chapter 5, by I.V. Veksler, provides a very comprehensible and detailed discussion about how crystallized melt inclusions can provide answers to problems concerning melt evolution, magma mixing events, local compositional perturbations, and liquid immiscibility in gabbroic magma chambers. Veksler illustrates these uses with examples from the Skaergaard and similar intrusions. Carbonate–silicate immiscibility provides a fertile environment for using melt inclusion observations and analysis to obtain an understanding of carbonatite petrogenesis. I.V. Veksler and D. Lentz, in chapter 6, not only provide a comprehensive summary of fluid inclusions in carbonatites but also summarize the phase relations most relevant to understanding coexisting silicate–carbonate melts. In chapter 7, W.E. Halter and C.A. Heinrich use their study of porphyry-type environments in the Farallón Negro volcanic complex, Argentina, to illustrate an integrated approach using laser-ablation ICP–MS to help understand magmatic processes and volatile phase generation. The authors focused their work on heterogeneous inclusions, both silicate and sulfide, in this andesitic system. In Chapter 8, J.D. Webster and R. Thomas provide a concise review and synthesis of silicate melt inclusions in felsic plutons. They discuss studies in the context of the problems and challenges recognized by inclusion workers. The authors discuss chlorine and water in petrogenetic models involving crystallization and degassing.

R. Thomas and J.D. Webster, in chapter 9, present a comprehensive discussion of a felsic pluton's more water-rich offspring, pegmatites. They review pegmatite petrogenesis in light of evidence from melt and fluid inclusions, petrography, mineralogy, and phase chemistry. In chapter 10, B. De Vivo, A. Lima, V.S. Kamenetsky, and L.V. Danyushevsky discuss fluid and melt inclusions in subvolcanic systems near Naples, Italy, including Vesuvius, Campi Flegrei, and Ponza and Ventotene Islands. They point out that studies such as theirs are undertaken for more than academic interest—millions of Neapolitans live near these volcanic systems. The results of years of inclusion studies are well illustrated and summarized. The role of magmatically derived hydrosaline chloride and/or sulfur-rich fluids is emphasized and used to discuss the significance of bradyseismic (slow vertical Earth movement) events.

The collection of references in this volume is also very valuable; in spite of the current Google milieu, the authors provide well-researched, concise, and relevant bibliographies. This short course volume is an educational bargain. It is a very good companion to Mineralogical Association of Canada Short Course Series volume 32, *Fluid Inclusions: Analysis and Interpretation*. The really lasting contributions to fluid inclusion research are not necessarily the scientific interpretations (which can come and go), but the discovery of new inclusion phenomena, either natural or synthetic, backed up by accurate analyses of carefully collected and documented samples. This volume represents a significant step towards using melt inclusions to understand the characteristics and origins of plutonic rocks.

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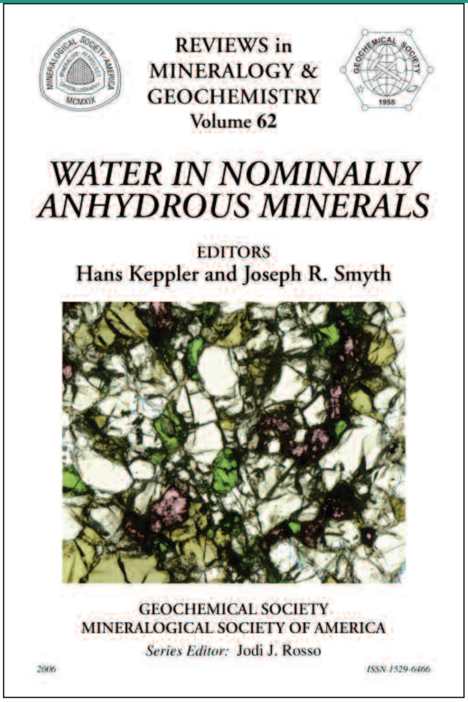
Water in Nominally Anhydrous Minerals*

We all know that water is essential to all aspects of life on our planet. Life probably evolved in the oceans, and plants and animals rely on water to flourish. Our hydrology lectures introduced us to the water cycle on Earth. If I recall correctly, water evaporates from the oceans, clouds form, cloud particles collide, grow, and fall out of the sky and eventually, rain distributes water all over the land masses. Having moved to Edinburgh recently, I can report on the latter from much personal experience.

However, over the last few decades, we have learnt that almost all minerals occurring in the Earth's mantle and crust contain small amounts of hydrogen, even minerals which were previously thought to be 'bone dry', or 'nominally anhydrous'. This may seem unimportant at first sight, but because of their huge mass, the Earth's mantle and the mantles of other planets may store much more hydrogen than the oceans. *Water in Nominally Anhydrous Minerals* is volume 62 of the much-admired and much-thumbed Reviews in Mineralogy & Geochemistry series, now produced jointly by the Mineralogical Society of America and the Geochemical Society. It provides an up-to-date summary of what is known about the hidden water in deep parts of the crust and the mantle.

The book is divided into nineteen chapters of approximately equal length. The first chapters focus on recent advances in analytical and experimental techniques used for analysis of hydrogen in minerals. In the first chapter, G. Rossman presents detailed information about analytical methods, most of them modern in situ microanalytical techniques. He discusses the pros and cons of each technique and gives a good and comprehensive summary of our current knowledge. Other chapters by E. Libowitzky, A. Beran, J.R. Smyth and K. Wright give detailed and well-researched information about various structural aspects of hydrogen and hydroxyl incorporation in minerals based on both spectroscopy and modelling.

Review articles by H. Skogby, A. Beran, E. Libowitzky and E.A. Johnson focus on our current knowledge of the hydrogen budgets of nominally anhydrous minerals in the mantle and crust. Here we learn that mantle olivines and pyroxenes can incorporate several hundred parts per million of water. Matters are complex, however, and one gets the impression that the last word on hydrogen substitution and concentration has not yet been spoken. Chapters by H. Keppler,



N. Bolfan-Casanova, S. Kohn and K.J. Grant deal with thermodynamic aspects of water solubility and the partitioning of hydrogen among minerals, fluids and melts. The authors show that the solubility of water in minerals is a complex function of pressure, temperature and the chemical composition of phases. An excellent chapter by J. Ingrin and M. Blanchard reviews the current knowledge on hydrogen diffusion in minerals. Chapters by D. Frost and T. Kawamoto are on the stability of hydrous minerals in the Earth's mantle and in subduction zones. Hydrous phases, such as amphiboles and serpentine group minerals, have been experimentally proven to be stable to enormous depths in subduction zones and may be important carriers of hydrogen from the surface back into the mantle.

The final chapters deal with the consequences of water in nominally anhydrous minerals and rocks for equations of state, rheology and geodynamic processes. S. Jacobsen explains how hydrogen in major mantle minerals may affect their equations of state in ways which are crucial for our interpretation of seismic data. E. Ohtani and K.D. Litasov review the effect of water on phase transitions in the deep Earth. The latter could be important because wadsleyite and ringwoodite in the transition zone may store large amounts of water in their structure, which would significantly expand their stability fields. S. Karato explains how one could use geophysical methods in remote sensing to explore hydrogen in the Earth's interior, and D. Kohlstedt investigates how water influences the rheologic properties of rocks. The latter is probably of crucial importance as even very low amounts of water weaken rocks dramatically during deformation. B. Marty and R. Yokochi discuss the origin of water on the Earth based on isotopic constraints and, in the final chapter, K. Regenauer-Lieb discusses the effect of water on tectonic processes on a global scale. Regenauer-Lieb's article nicely explains how small amounts of water in the Earth's mantle can explain different tectonic styles on Earth and, by extension, on our neighbouring planets Venus and Mars.

Water in Nominally Anhydrous Minerals has been extremely well researched and produced with remarkable care and attention to detail, and there are numerous literature references for the reader who craves further detail. This is an excellent issue of the Reviews in Mineralogy & Geochemistry series, well written and highly accessible to a wide audience of geoscientists. It will also appeal to post-graduate students interested in mantle geochemistry and to advanced university undergraduates seeking good background reading during their last years of study. At only US$40, with discounts available for members of the Mineralogical Society of America and the Geochemical Society, it is extremely good value.

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