BULLETIN DE L'ASSOCIATION MINERALOGIQUE DU CANADA

THE CANADIAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL ASSOCIATION OF CANADA

Canadian Mineralogist
Vol. 29, pp. 611-613 (1991)

QUANTITATIVE METHODS IN PETROLOGY
AN ISSUE IN HONOR OF HUGH J. GREENWOOD

PREFACE

"Every one of his papers has made a difference to the way we do things"
D.M. Carmichael, personal commentary, 1983

One sunny afternoon in 1965, Hugh Greenwood burst into his laboratory in the basement of Guyot Hall, stopped briefly to drop a guitar score on his desk, and immediately launched into a tutorial on the complexities of the Greenwood apparatus for studying mixed-volatile equilibria. There followed an hour of intense instruction, complete with reference to meticulous engineering drawings and rapid-fire derivations of thermodynamic theory at the blackboard. Then he paused, glanced at his watch, and vanished as rapidly as he had appeared. A somewhat dazed graduate student remained standing in the suddenly peaceful laboratory and watched the artist – engineer – theoretician – experimentalist – geologist professor sprint away, to coach the Princeton rugby team. This was my introduction to the eclectic interests, scientific integrity and inexhaustible energy that characterize Hugh's work and play.

Now, in 1991, a letter from the *Almucantar*, at anchor off Baja California, outlines a typical day for Hugh and Sylvia: up and breakfast dishes washed by 7:30; short-wave radio sched; row ashore for a four-hour botanical expedition with cameras and equipment; back to do the laundry by hand; then ship's maintenance (including two hours with elbows in the bilge with hammer and wrenches... *déjà vu* of the experimental lab?); dinner fresh from the sea; an hour-long snorkel dive to harvest the next day's meal; forty-five minutes of guitar practice; and even some reading, all by 9:00 p.m.

Some things haven't changed in 26 years! What *has* changed, as so aptly summarized by Dugald, is the way we do things in the quantitative study of rocks. It is in recognition of Hugh's profound and lasting contributions to petrology, as well as our personal regard for him, that this issue of *The Canadian Mineralogist* has been assembled. The contributed papers have been grouped according to the following personal selection and classification of Greenwood's Greatest Hits.

Algebraic methods

Until the *n*-dimensional tie-line problem was formulated and solved (Greenwood 1967a, 1968), most petrological thinking was constrained to two- or three-dimensional relationships that could be easily visualized or plotted. Hugh not only removed this limitation by expressing the problem in algebraic terms, he solved it using linear programming, thus providing the inspiration for a number of applications

of numerical optimization in petrology, an area of research that continues to flourish. To help those who might falter along the path to algebraic salvation, Greenwood (1975b) showed how matrix techniques could be used to project the multidimensional world of nature into the more familiar world of two-dimensional graphics. Since these seminal papers, algebraic methods have become essential tools in petrology, and new applications continue to be devised.

Theoretical and experimental studies of mixed-volatile systems

Inspired by Thompson's celebrated 1955 paper, Greenwood (1961, 1962) developed the thermodynamic theory and experimental techniques required to analyze equilibria involving a mixed-volatile phase. A number of important papers followed, including a definitive (and at one point, explosive) study of the system $MgO–SiO_2–H_2O–CO_2$ in which theory and experiments of mixed-volatile equilibria were elegantly portrayed in now familiar $T–X(CO_2)$ diagrams (Greenwood 1967b). A brief glance through the figures in this issue will reveal more than a few such graphs, testimony to the lasting value of the careful analysis originally provided by Hugh. Having established the theoretical methodology, Hugh applied his experimental flair to obtaining the precise P–V–T data required for accurate phase-equilibrium calculations. His literally painstaking measurements of the properties of $H_2O–CO_2$ mixtures (Greenwood 1969, 1973) continue to serve as reference values that any equation of state must honor.

Quantitative models of petrological processes

Hugh's interests have always extended beyond the equilibrium model to encompass the quantitative understanding of natural processes. One of the first experimental kinetic studies of dehydration equilibria appears in Greenwood (1963), whereas an analysis of both equilibrium and kinetic effects of order–disorder in aluminum silicates appears in Greenwood (1972). His paper on buffering of pore fluids (Greenwood 1975a) astutely reminded us that experimentally controllable variables may not always be separable in nature. This contribution still serves as an exemplary demonstration of the use of careful geological reasoning to extend the applicability of equilibrium data to models of the actual mechanisms of metamorphism.

Quantitative field studies

Hugh's early geological career included mapping in the Canadian Shield, and he has never allowed the elegance of theory and experiment to obscure the goal of understanding natural phenomena. In fact, he insisted that all petrology students be familiar with the trinity of theory, experiment and field. His presidential addresses reminded us to always "*be guided by those natural observations that demand explanation*" (Greenwood 1979), and that no matter how mathematically sophisticated, our models must have "*necessary and testable consequences*" (Greenwood 1989). This philosophy is evident in his work on wollastonite (Greenwood 1967c) and studies with students and others on metamorphic rocks in British Columbia (*e.g.*, Fletcher & Greenwood 1979, Pigage & Greenwood 1982, Greenwood *et al.*, in press).

There are many other papers, some coauthored with students and colleagues, others which clearly could not have been written without Hugh's unselfish sharing of his ideas and data. But rigor in science is only one aspect of his personality. As shown by the many individual statements of appreciation in this issue, Hugh's influence extends far beyond the maps, microscopes, crucibles and computers that define our professional lives. To all of us, Hugh has been a demanding yet inspiring teacher, a challenging yet supportive colleague, and a warm and generous friend. Hugh's qualities have helped shape the environment of mutual respect and genuine camaraderie that uniquely characterizes the community of metamorphic petrologists in Canada and the world.

This collegiality was very much in evidence at a two-day symposium in Hugh's honor held during the Geological Association of Canada – Mineralogical Association of Canada meeting in Vancouver in May, 1990. Many of the participants had been part of Hugh's immensely successful MAC short course (Greenwood 1977). This time, we gathered to wish Hugh and Sylvia *bon voyage* as they began to sail the oceans of the world. It takes little imagination to picture the Greenwoods in Samuel Morison's depiction of an explorer and sailor who "*enjoyed long stretches of pure delight such as only a seaman may know, and moments of high, proud exultation that only a discoverer can experience*". To Hugh and Sylvia, our sincere thanks for the many ways you have enriched our lives, and our best wishes as you continue to experience all of the long stretches of pure delight and moments of high, proud exultation you so justly deserve.

REFERENCES

FLETCHER, C.J.N. & GREENWOOD, H.J. (1979): Metamorphism and structure of Penfold Creek area, near Quesnel Lake, British Columbia. *J. Petrol.* **20**, 743-794.

GREENWOOD, H.J. (1961): The system $NaAlSi_2O_6$–H_2O–argon: total pressure and water pressure in metamorphism. *J. Geophys. Res.* **66**, 3923-3946.

_____ (1962): Metamorphic reactions involving two volatile components. *Carnegie Inst. Washington Year Book* **61**, 82-85.

_____ (1963): The synthesis and stability of anthophyllite. *J. Petrol.* **4**, 317-351.

_____ (1967a): The N-dimensional tie-line problem. *Geochim. Cosmochim. Acta* **31**, 465-490.

_____ (1967b): Mineral equilibria in the system MgO–SiO_2–H_2O–CO_2. *In* Researches in Geochemistry II (P.H. Abelson, ed.). John Wiley & Sons, New York (542-567).

_____ (1967c): Wollastonite: stability in H_2O–CO_2 mixtures and occurrence in a contact-metamorphic aureole near Salmo, British Columbia, Canada. *Am. Mineral.* **52**, 1669-1680.

_____ (1968): Matrix methods and the phase rule in petrology. *23rd Intern. Geol. Congress* **6**, 267-279.

_____ (1969): The compressibility of gaseous mixtures of carbon dioxide and water between 0 and 500 bars pressure and 450° and 800° centigrade. *Am. J. Sci.* **267A**, 191-208.

_____ (1972): Al^{IV}–Si^{IV} disorder in sillimanite and its effect on phase relations of the aluminum silicate minerals. *Geol. Soc. Am., Mem.* **132**, 553-571.

_____ (1973): Thermodynamic properties of gaseous mixtures of H_2O and CO_2 between 450° and 800° centigrade and 0 and 500 bars. *Am. J. Sci.* **273**, 561-571.

_____ (1975a): Buffering of pore fluids by metamorphic reactions. *Am. J. Sci.* **275**, 573-593.

_____ (1975b): Thermodynamically valid projections of extensive phase relations. *Am. Mineral.* **60**, 1-8.

_____, ed. (1977): Application of Thermodynamics to Petrology and Ore Deposits. *Mineral. Assoc. Can., Short Course Handbook* **2**.

_____ (1979): Some linear and non-linear problems in petrology. *Geochim. Cosmochim. Acta* **43**, 1873-1885.

_____ (1989): On models and modeling. *Can. Mineral.* **27**, 1-14.

_____, WOODSWORTH, G.J., READ, P.B., GHENT, E.D. & EVENCHICK, C.A. (in press): Metamorphism. *In* Geology of the Cordillera in Canada (H. Gabrielse & C.J. Yorath, eds.). *Geol. Surv. Can., Geology of Canada* 4 (also *Geol. Soc. of Am. Decade of North American Geology* **G-2**).

PIGAGE, L.C. & GREENWOOD, H.J. (1982): Internally consistent estimates of pressure and temperature: the staurolite problem. *Am. J. Sci.* **282**, 943-969.

THOMPSON, J.B., JR. (1955): The thermodynamic basis for the mineral facies concept. *Am. J. Sci.* **253**, 65-103.

T.M. Gordon
University of Calgary

ACKNOWLEDGEMENTS

The symposium on Quantitative Methods in Petrology, referred to above, was organized in honor of Hugh J. Greenwood by T.M. Gordon, with the help of T.H. Brown and J.K. Russell, of the University of British Columbia, and G.B. Skippen, of Carleton University. The timely publication of such a voluminous thematic issue as this requires the collaboration of all participants, the authors, the five associate editors to whom I sent papers (T.M. Gordon, C.V. Guidotti, S.E. Haggerty, L.S. Hollister and C.M. Lesher), the reviewers they consulted, and Vicki Loschiavo, Managing Editor. I thank them all sincerely. On behalf of the Mineralogical Association of Canada, I acknowledge with gratitude the award of a grant in aid of publication of this issue by the Geological Survey of Canada.

R.F. Martin
McGill University