An appreciation of Daniel Robert Boyle, and an introduction to the special issue of *Geochemistry: Exploration, Environment, Analysis* in his honour

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BACKGROUND AND EDUCATION

Daniel Robert Boyle, our friend and colleague, died on 29 June 2000, in Ottawa, Canada, at the age of 52 after a courageous battle with cancer. Dan was a leader at the Geological Survey of Canada (GSC) in the application of lithogeochemistry, and groundwater geochemistry for the study of mineral deposit genesis, mineral exploration, environmental and health issues. He was the son of the (recently deceased: 5 August 2003) internationally renowned and respected geochemist Bob (Robert W.) Boyle, who was also employed at the GSC (Garrett 2004).

Growing up in the 1950s and 1960s, Dan spent many happy summers travelling with his family to places across Canada, notably New Brunswick and Nova Scotia, where his father's fieldwork took him. These experiences instilled in Dan and his sister Heather a love for the sciences and the outdoors that shaped both their future careers: Dan following in his father's footsteps as a geochemist, while Heather, the family radical, became a biochemist (Carleton University, Ottawa, Canada and Victoria University, Wellington, New Zealand).

Dan completed a BSc honours degree at Queen's University at Kingston, Canada, with a thesis entitled "Geochemical environmental study over a Cu–Mo porphyry deposit, British Columbia". He continued his education at the Imperial College of Science and Technology, University of London, London, UK. He graduated with a PhD in 1976, and his thesis was entitled "The geochemistry of fluorine and its application in mineral exploration". During his studies in the UK, he completed several mineral exploration consulting contracts in Spain, France, Ireland, Turkey, and Great Britain. During the latter part of his PhD studies, he became a member of the Mineral Industry Research Organization review board of Great Britain.

While at Imperial College, Dan became an associate professor, and later (1975) head of the mineral exploration research section of the applied geochemistry research group. During this time he taught graduate mineral exploration courses and supervised three PhD and two MSc research projects in different parts of the world.

Dan returned to Canada to work for the GSC, and during his 25 years there became recognized world-wide for his research in the area of geochemistry, particularly as it relates to the origin of metals in ancient ore deposits and modern natural environments. He focused on a broad variety of interests which included process studies, mineral exploration, mineral deposit studies, and environmental geochemistry. He possessed an incredible capacity to assimilate, integrate, and synthesize knowledge from diverse fields of interest. To quote our colleague and Dan's good friend Wayne Goodfellow (2003): "in this respect, he was a renaissance scientist of the old school, who looked at problems not from an overly specialized and narrow perspective, but from the viewpoint of someone who wanted to understand the complex interplay of different processes."

Dan divided his research time almost equally between groundwater hydrogeochemistry (including technology development and environmental research) and mineral exploration and deposit studies. His research on groundwater sampling, monitoring technology, and groundwater geochemical processes was aimed at solving many of the major problems

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associated with natural and anthropogenic contamination of water supplies, especially as they might affect human health and aquatic biota. Indeed, one can view Dan's work in this realm as trail blazing, as he was one of the first scientists of his time at the GSC to recognize the critical need for a better understanding of groundwater systems. Groundwater studies are now a research priority at the GSC. In addition he applied groundwater geochemistry and technology in mineral exploration to improve the efficacy of mineral deposit discovery. Using his broad background in mineral deposit studies, he strove to characterize the pre-glacial landscape of Canada, its economic potential, and the effects that pre-glacial weathering have on the selection of appropriate mineral exploration techniques in glaciated terrains and the interpretation of data gathered.

RESEARCH

Dan's research interests and contributions can be broadly grouped into three areas.

Mineral exploration and mineral deposit studies

Dan studied the mineralogy, geochemistry and genesis of a variety of mineral deposit types, including precious and base metal supergene deposits, uranium deposits, tin deposits, and titanium deposits.

Based on his early work at the Geological Survey of Canada, Dan became an authority on the geology, genesis and exploration of sediment-hosted uranium deposits of Cenozoic and Mesozoic age, the second largest class of uranium deposits in the world. This research led him to become involved with Atomic Energy Canada Limited, the International Atomic Energy Agency, and the US Department of Energy, where he served on working groups, served as advisor, authored papers, and gave presentations.

Dan later integrated the use of airborne radiometric and lithogeochemical techniques in Nova Scotia, Canada, to demonstrate that an integrated multidisciplinary approach to tin exploration is more effective than a single methodology approach.

Dan's work on the precious metal gossan deposits in the Bathurst base-metal mining camp of New Brunswick, Canada, focused on geochemical reactions which led to the genesis of the ore. This work was published in a definitive paper for which he received the Barlow Memorial Gold Medal from the Canadian Institute of Mining and Metallurgy (CIM) for the best economic geology paper in 1996. Together with D.T. Symons and M.T. Lewchuk he developed a technique for palaeomagnetically dating young residual ore deposits (gossans) developed over sulphide deposits; previously there were no other methods for dating these deposits. His research on the pre-glacial physical and chemical landscape of Canada has implications for the design and implementation of geochemical exploration programmes in glaciated terrains in Canada and elsewhere.

Together with M. Leybourne and W.D. Goodfellow, Dan played a key role in the development of exploration techniques using ground and surface water geochemistry in regions of thick glacial overburden. Their study area again was the Bathurst Mining Camp, New Brunswick, Canada. Serendipitously, while examining old oil drill hole cuttings from the basement rocks beneath the Carboniferous sedimentary rocks in New Brunswick, Dan noted the presence of Ti- and P-bearing ferrogabbro. This led to the discovery of a large (currently unexploited) titaniferous (+vanadium) mineral deposit in the Coverdale Complex, New Brunswick.

While working in the Bathurst Mining Camp, Dan made a key observation that the tin content of massive sulphide mineralization was directly related to the overall size of the massive sulphide deposit. He was unable to formally publish this observation, including his explanation for this relationship (that the tin was likely of magmatic origin, and therefore, those large deposits with concomitantly high tin reflected a greater contribution of metals from magmatic sources rather than leached host rocks), and the obvious exploration implications, before he died. However, these observations and ideas strongly influenced the conclusions of Goodfellow & McCutcheon (2003).

Environmental geochemistry

Dan's research in the field of hydrogeochemistry focused on the effects of ground and surface water quality on human health issues and the characterization of acid mine drainage events at Canadian mining operations. Dan was responsible for designing and carrying out the largest federal groundwater quality survey in Canada, covering most of the Maritime Carboniferous Basin. His research on the environmental geochemistry of fluorine led to the discovery of a number of areas in the Maritime provinces of Canada where fluoride is present at toxic levels, as well as areas where the element is so deficient in groundwaters that dental decay is endemic.

Dan worked closely with various health officials and Health and Welfare Canada's Drinking Water Criteria Division on the occurrence of fluoride in potable waters throughout Canada and its possible environmental consequences. This research has been instrumental in determining the factors (natural softening) causing high fluoride levels in groundwaters and the likely geological environments in which such levels would occur. Fluoride is a priority toxic element on Environment Canada's toxicology agenda. At the request of the Ghana Government and the Canadian International Development Agency (CIDA), Dan contributed to the study of toxic fluoride occurrences in the groundwaters of the rural populations of the Upper Regions of Ghana.

Together with GSC colleagues Bob Turner and Gwendy Hall, Dan extended his work on groundwater geochemistry to another element of focus – arsenic – in an island community near the city of Vancouver, Canada. Arsenic levels were found to be elevated, and the sources and health implications were assessed.

Another facet of Dan's research in the field of hydrogeochemistry focused on the characterization of acid mine drainage events at Canadian mining operations.

Dan applied his understanding of sulphide oxidation processes by characterizing the hydrogeochemistry and hydrology of groundwaters at the large Myra Falls base-metal mining complex in Strathcona Provincial Park, Vancouver Island, Canada. Dan was part of a multidisciplinary team that integrated hydrogeochemical, hydrological, geophysical, and lithogeochemical methods to better characterize the processes that led to acid mine drainage and metal mobilization before, during, and after mining. Their research results here have greatly aided acid mine prevention and reclamation policies. While working on the gold-rich gossan at Murray Brook in the Bathurst Mining Camp, he recognized and explained the process of mobilization of mercury from a gossan tailings pile.

Dan also contributed to the concepts of dose–response to environmental geochemical data to predict human health outcomes. He integrated environmental geochemistry and groundwater geochemistry with epidemiological studies of certain diseases such as osteoporosis, heart disease, certain cancers (e.g. bone) and thyroid diseases. Such information is invaluable in conducting health risk assessments and in land-use planning

One of his last research projects was a CIDA sponsored project in Guangzhou and Guizhou provinces, China, that focused on thallium dispersion from natural sources; this was causing many villagers to suffer serious health problems. This project had strong ties to universities in China, and he supervised two PhD and one MSc students.

A constant in Dan's research was his recognition of the potential health hazards of natural point sources of certain elements in the geological landscape, which he referred to as natural geochemical contaminants and deficiencies.

Groundwater geoscience and technology

In his drive to monitor and sample groundwaters, Dan found the tools and techniques he required to be lacking. Dan was a "tinkerer" and inventor at heart, and he worked on devising new, more efficient, more reliable, and more cost-effective tools and methodologies. He ultimately designed and engineered eleven new systems that span the fields of pollution monitoring, groundwater sampling, aquifer definition, limnological research, overburden drilling technology, and *in-situ* sampling and analysis. He was granted a patent in 1989 (System for Emplacement of Filter Packs and Annular Seals for Groundwater Monitoring. Canadian Patent No. 610,848-2; USA Patent No. 07/578,298; exclusive licence to Solinst Canada Ltd). Dan's innovation in the design and construction of this system was recognized within the Canadian federal government by Dan being awarded a Crown Innovation Award and a GSC Divisional Merit Award. He also held two licences (1990: GSC Multi-level Groundwater Sampling Piezometer System – a monitoring system which allows both geochemical sampling and hydraulic parameter analysis with a single piezometer, exclusive licence to Solinst Canada Ltd; GSC Pipe and Tube Tapping System with Cutting Removal,exclusive licence to Solinst Canada Ltd).

Together with workers at the Canada Centre for Mineral and Energy Technology (CANMET) and the Canadian drilling industry, Dan developed a method for using reverse circulation overburden drilling to install groundwater piezometers in thick glacial overburden where removal of drill rods and hole collapse would not allow use of conventional methods. This system permits installation of monitoring piezometers in highly unconsolidated overburden, for which no other methods previously existed.

Dan also developed a groundwater lake seepage meter that greatly expanded the monitoring and research capabilities of environmental limnology by allowing accurate water and nutrient balances in environmental basin studies. Further research on this topic led to the development of a gel profiling system for measuring seepage fluxes to lakes and characterizing sediment pore water chemistries. Both these systems and the expertise that goes with them have been requested by the Israeli Government to study and possibly solve problems of salinization through groundwater seepage into that country's major fresh water supply, Lake Kinneret (Sea of Galilee).

He also designed a portable borehole packer pneumatic-hydraulic system for discrete groundwater sampling and measurement of *in-situ* hydrological parameters; this tool was used with great success in the Bathurst Mining Camp to sample groundwaters (see above). Many of these technologies had no precedent, and all required considerable testing and the application of mechanical, electrical, and chemical engineering techniques. His groundwater monitoring technologies were adopted in 1992 by the US Department of Energy and Reynolds Engineering at the Nevada Nuclear Test Site.

LEADERSHIP

Dan was actively involved in Canadian national and international science organizations. He has been an advisor or member of 17 national and 9 international scientific bodies. Over the years, Dan played a key role in the activities of the CIM. In 1991 he organized a special session on environmental geophysics for the CIM annual meeting in Vancouver, and served as chair of that session. Again in 1992 he organized a special session on exploration geochemistry in Canada for the CIM annual meeting in Montreal. From 1992 to 1997 he represented the CIM on the Canadian Geoscience Council. Since 1990 Dan was the chairman of the environmental committee of the Geology Society of CIM. His multi-faceted background served him well as a member of the editorial boards of the "Canadian Institute of Mining, Metallurgy and Petroleum Bulletin" and the journal of their Geological Society *Exploration and Mining Geology*, from 1990 to 2000. He was to be the next incoming president of the Geological Society of the CIM, but he was unable to take up his duties because of his illness. In 2002 Dan posthumously received the CIM's Julian Boldy Memorial Award. This was the same year his father, Bob Boyle, received the CIM Distinguished Service Medal and marks the first time two members of the same family received awards in the same year.

On the international scene, his other favoured organization was the International Association on the Genesis of Ore Deposits (IAGOD), which his father helped to found in 1966. Over the years he served as vice chairman of their working group on tin and tungsten deposits (1990–1996), and was organizer and chair of a session on supergene mineral deposits at the 8th symposium held in Ottawa in 1990. Together with Dave Sinclair, he organized and led an IAGOD field trip on mineral deposits of New Brunswick and Nova Scotia, Canada, as part of this meeting, and served as editor of the fieldtrip guidebook. From 1992 to 1996 Dan served as vice president of IAGOD.

From 1990 to 1996 he also was a contributing member of International Geological Correlation Program 317 on palaeo-weathering records and palaeosurfaces. From 1993 to 1995 he was a member of the International Union of Geological Sciences (IUGS) working group on geo-indicators.

Dan was regularly consulted by industry, national and foreign government agencies, and the media to provide expertise, testimony at hearings, and training, to present talks, and to write popular articles on geochemical exploration technology, groundwater sampling and monitoring methodologies, and environmental geochemistry issues. He also gave freely of his time to supervise graduate and undergraduate students in geology and environmental sciences at the University of Ottawa, Carleton University, University of Quebec at Chicoutimi, and Ghuizhou University, China.

CONCLUDING REMARKS

A bibliography for Dan can be obtained by request from us. Dan's scientific contributions are an impressive and lasting legacy, but he is also most fondly remembered as a true friend and dedicated colleague. He is survived by his wife, Christy Vodden, son Matthew, sister Heather, and mother Marguerite, all of whom spent time working as his field assistants, for Dan continued the Boyle family tradition of blending work and family time whenever he could. As a dedicated and loving family man who made time in his busy schedule to coach his son's Little League baseball and hockey teams and to patiently teach his wife the finer points of golf, we surmise that Dan

would have said that his family life brought him greater pleasure than his scientific accomplishments.

The idea for a special issue of *Geochemistry: Exploration, Environment, Analysis* (*GEEA*) to celebrate the career and life of Dan Boyle goes back to December 2000, shortly after Dan's death. Due to our other commitments, it took until May 2002 for us to formalize our concept, present it to *GEEA* editor Gwendy Hall, and put out a call for papers from potential authors. Our request brought an immediate and strongly positive response for contributions. Several of the contributing authors (Namik Çağatay, Gwendy Hall, David Blowes, Tangfu Xiao, and Jayanta Guha) were friends and colleagues of Dan's. Others never knew Dan, but were impressed by his accomplishments or worked on similar issues, and wished to contribute toward the success of this special issue.

The paper by Xiao *et al.* stems from the research project Dan was part of in China. The paper by Bierlein on the stable isotope systematics of hydrothermal alteration haloes associated with orogenic gold deposits in Victoria, Australia, and that by Van Kranendonk & Pirajno on 3.45 Ga chert–barite deposits of the Pilbara, Australia, remind us of Dan's strong interest in mineralogy, lithogeochemistry, hydrothermal alteration and its mass balance effects, and hydrothermal mineral deposits in general. The paper by Çağatay *et al.* on the pore-water and sediment geochemistry of the Marmara Sea, Turkey, celebrates Dan's efforts to thoroughly understand geochemical processes and reactions in the geological environment. The paper by Nelson *et al.* on the rare earth element geochemistry of groundwater in the Palouse Basin, Idaho and Washington, addresses a direct research interest of Dan's, namely the factors influencing the chemical makeup of groundwaters. Cohen & Waite's experimental and theoretical paper on the interaction of aqueous gold species with goethite, smectite, and kaolinite draws attention to Dan's strong interest in understanding geochemical processes associated with gossan formation and sulphide oxidation.

We assembled more papers than could be published in a single issue of *GEEA*, and consequently some of the papers will appear in the issue immediately following this one: Karimzadeh Somarin's paper on the Mazraeh Fe–Cu skarn in Iran celebrates Dan's strong interest in international research, collaboration and travel, and contributions toward the understanding of the genesis of a wide variety of mineral deposit types. The paper by Gillis *et al.* focuses on the geochemistry of groundwaters associated with a base-metal deposit in the Abitibi belt of northern Ontario, Canada, and addresses a direct research interest of Dan's, namely the potential use of groundwater in mineral exploration. The contribution by Phipps *et al.* presents some of the results on groundwater geochemistry and its use in mineral exploration based on Dan's and his students' work at the Myra Falls volcanogenic massive sulphide deposit on Vancouver Island. Akçay & Moon's paper deals with the enviromental impact of mining in the Pontides of Turkey, based on geochemical results and GIS (Geographic Information System) analysis.

We hope that collectively, in our own small way, the editors and authors of this issue have succeeded in our efforts to celebrate the life and career of our friend and colleague . . . Dan, you are sorely missed.

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