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TRUTH AND BEAUTY IN METAMORPHISM: A TRIBUTE TO DUGALD M. CARMICHAEL

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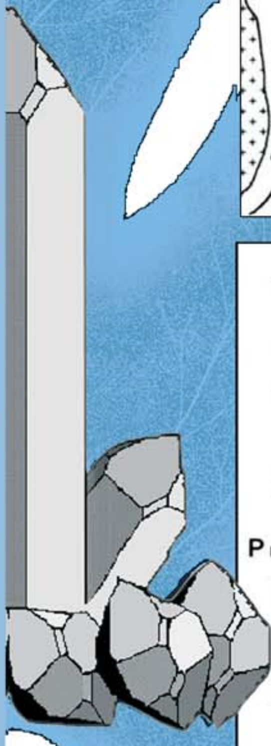
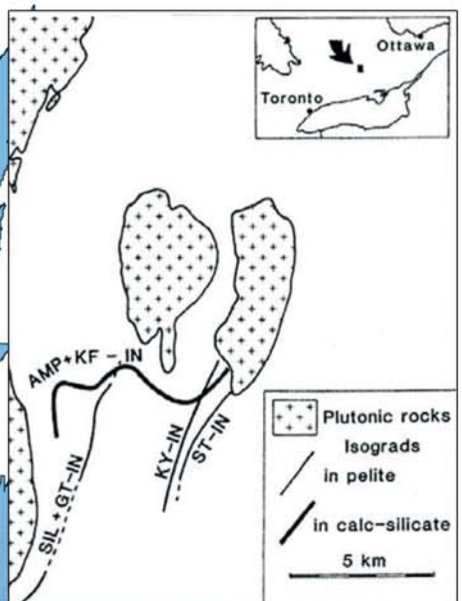
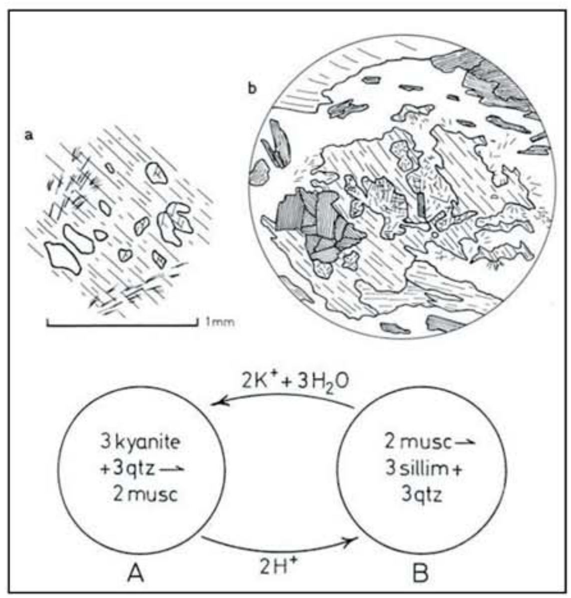
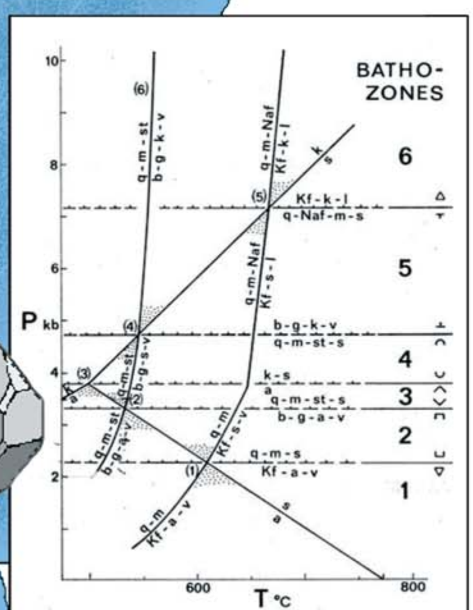




TRUTH AND BEAUTY IN METAMORPHISM:

A tribute to Dugald M. Carmichael





D.R.M. Pattison, M.R. St-Onge,
N.J. Bégin and R.F. Martin, editors

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(cont'd overleaf)

Petrology and Structure

Application of Metamorphic Petrology to Tectonics

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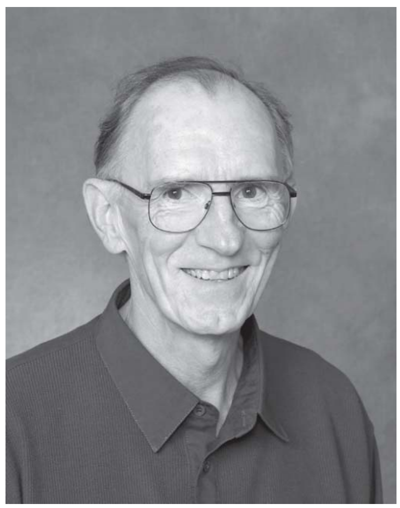

DUGALD MACAULAY CARMICHAEL (2003).

PREFACE

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Introduction

Every now and again, there comes along an individual of such originality and unique personality that an indelible mark is left on all concerned. In the field of metamorphic petrology, few could argue that Dugald Carmichael (Frontispiece) is such a figure. Dugald's scientific attributes of acute observation, intellectual rigor, insight, and clarity of expression have left a lasting mark in themselves. Add to these qualities an unassuming, gregarious rural Ontario personality, from which shines as much uninhibited delight in the aesthetic pleasures of metamorphic rocks as in paddling a canoe down a series of river rapids, and one begins to understand why Dugald has had such an impact on the metamorphic petrology community, particularly in Canada. Dugald is an individual for whom feelings of respect and affection are intertwined.

Dugald Macaulay Carmichael was born on November 30, 1939 and raised in the town of Deep River in the upper Ottawa Valley, a first-generation Canadian of Scottish descent. He attended Queen's University in Kingston, Ontario, where he produced a Bachelor's thesis on the structure and petrology of high-grade gneisses near Westport, Ontario (Carmichael 1962), a harbinger of future endeavors. Dugald then went to the University of California at Berkeley, intending to study structural geology with Professor Lionel Weiss. There, he was

TABLE 1. LOCATIONS, COLLEAGUES, STUDENTS AND RESEARCH THEMES OF DUGALD CARMICHAEL'S FIELD WORK IN CANADA

Location	Year	Colleagues	Students	Theme
		ARCHEAN: Superior Craton		
Nipigon and Longlac map areas	72			reaction isograds and bathozones
Timmins-Chapleau map area	79-80	H. Helmstaedt	J. Percival	petrological and structural mapping
Matachewan map area	89-91	C. J. Hodgson	W. Powell	reaction isograds and bathograds
Red Lake Greenstone Belt	95		C. Damer	metamorphosed alteration zones
		ARCHEAN: Nain Craton		
Hopedale map area	89	H. Helmstaedt, I. Ermanovics	M. van Kranendonk	petrological and structural mapping
		ARCHEAN: Hearne Craton		
Henik Lakes map area	63	K. Eade		sedimentology of Hurwitz and Montgomery Groups
		ARCHEAN: Rae Craton		
Woodburn Lake map area	80	H. Helmstaedt, M. Schau	K. Ashton	petrological and structural mapping
		ARCHEAN: Slave Craton		
Hackett River map area	75	H. Helmstaedt	V. Sterenberg	reaction isograds
Contwoyto Lake map area	88	H. Helmstaedt, J. King	C. Relf	isograds and bathozones
Yellowknife map area	96-97	K. Bethune, W. Bleeker		isograds in contact aureoles
		PROTEROZOIC: Penokean Orogen		
Agnew Lake and Killarney map areas	69	K. Card	J. Fox	regional and contact aureole pelitic assemblages
		PROTEROZOIC: Trans-Hudson Orogen		
Lynn Lake map area	84-85	E. Froese, T. Gordon	S. Jackson	petrological and structural mapping
Cape Smith Belt	86-87	M. St-Onge	N. Bégin	isograds in metabasites
Narsajuaq arc	91	M. St-Onge, S. Lucas	P. Monday	petrological and structural mapping
southern Baffin Island	95-96	M. St-Onge, D. Scott	I. Russell	petrological mapping in granulite-facies rocks
central Baffin Island	00-01	M. St-Onge, D. Scott	K. Dubach	isograds in metapelites

TABLE 1 (continued). LOCATIONS, COLLEAGUES, STUDENTS AND RESEARCH THEMES OF DUGALD CARMICHAEL'S FIELD WORK IN CANADA

Location	Year	Colleagues	Students	Theme
		PROTEROZOIC: Thelon Orogen		
Artillery Lake map area	84	J. Dixon J.B. Henderson	D. James	petrological and structural mapping
		PROTEROZOIC: Wopmay Orogen		
Hepburn Lake map area	77-79	P. Hoffman	M. St-Onge, D. Pattison	isograds in low-P metapelites, thermobarometry
Redrock Lake map area	81	H. Helmstaedt, M. St-Onge	J. King	petrological and structural mapping
		PROTEROZOIC: Grenville Orogen		
Gananoque map area	61	H. Wynne-Edwards		structural petrology
Whetstone Lake map area	64-66	J. Moore	S. Duffel	reaction isograds
La Malbaie - Baie St-Paul map areas	67	A. Philpotts		shock metamorphism
Whetstone Lake map area	68		W. Trzcienski	microprobe study of reaction isograds
Mont Laurier map area	70		J. Bourne	humite-bearing marbles
Dickey Lake map area	74		G. Walton	metasomatic zones around a wollastonite skarn
Chicoutimi map area	80		L. Corriveau	garnet-cordierite gneisses
Tyson Lake map area	87-88	H. Helmstaedt, A. Davidson	K. Bethune	petrological mapping
Cobden map area	98			prospective zone for magnesium ore
		PHANEROZOIC: Appalachian Orogen		
East half, Prince Edward Island	59	V. Prest, G. Crowl		surficial geology
Mount Royal	71		A. Williams-Jones	contact aureole
Sherbrooke map area	73			bathozones
Coaticook map area	78		P. Erdmer	isograds in metapelites and calcschist
mainland Nova Scotia	80			bathozones
Bathurst area	84	W. Trzcienski, H. Helmstaedt		blueschists
		PHANEROZOIC: Cordilleran Orogen		
Rocky Mountains north of Jasper Park	60	L. Slind		stratigraphic sections, structural mapping
Porcupine, Rat and Peel Rivers	62	T. Owen		engineering geology
Riondel map area	72		T. Hoy	reaction isograds in calcshist
Creston map area	75	R. Price	K. Glover	reaction isograds and bathozones
Sifton and Deserters Ranges	81	R. Price	C. Evenchick	petrological and structural mapping
Monashee Range	82	J. Dixon, R. Brown	M. Journeay	isograds and bathozones
Nelson map area	82	H. Helmstaedt, J. Reesor	A. Leclair	isograds and bathozones
Meadow Creek map area	91	R. Price	M. Warren	contact aureole
Revelstoke map area	91-93	R. Price	M. Colpron	petrological mapping, contact aureole
Esplanade Range	93			isograd geometry
Penfold Creek map area	95	R. Price	M. Cooley	isograds in metapelites

stimulated by Berkeley's legendary strength in petrology and geochemistry, especially Professors Chuck Meyer, Bill Fyfe, Frank Turner, and their topnotch graduate students. But mainly it was Proterozoic rocks in his chosen Ph.D. area near Whetstone Lake, southeastern Ontario (Table 1, Fig. 1) that focused his interest on metamorphism. These rocks had nothing revolutionary to say about structure, but they appeared to confirm a theoretical prediction by Greenwood (1962) that intersecting isograds should be mappable. Their textures elucidated the mechanism of prograde metamorphic reactions, showing that matrix minerals may act as catalysts to the growth and dissolution of porphyroblasts. The Whetstone Lake area, then and since, has been the inspiration and test-bed for many of Dugald's ideas, and has become one of the iconic names

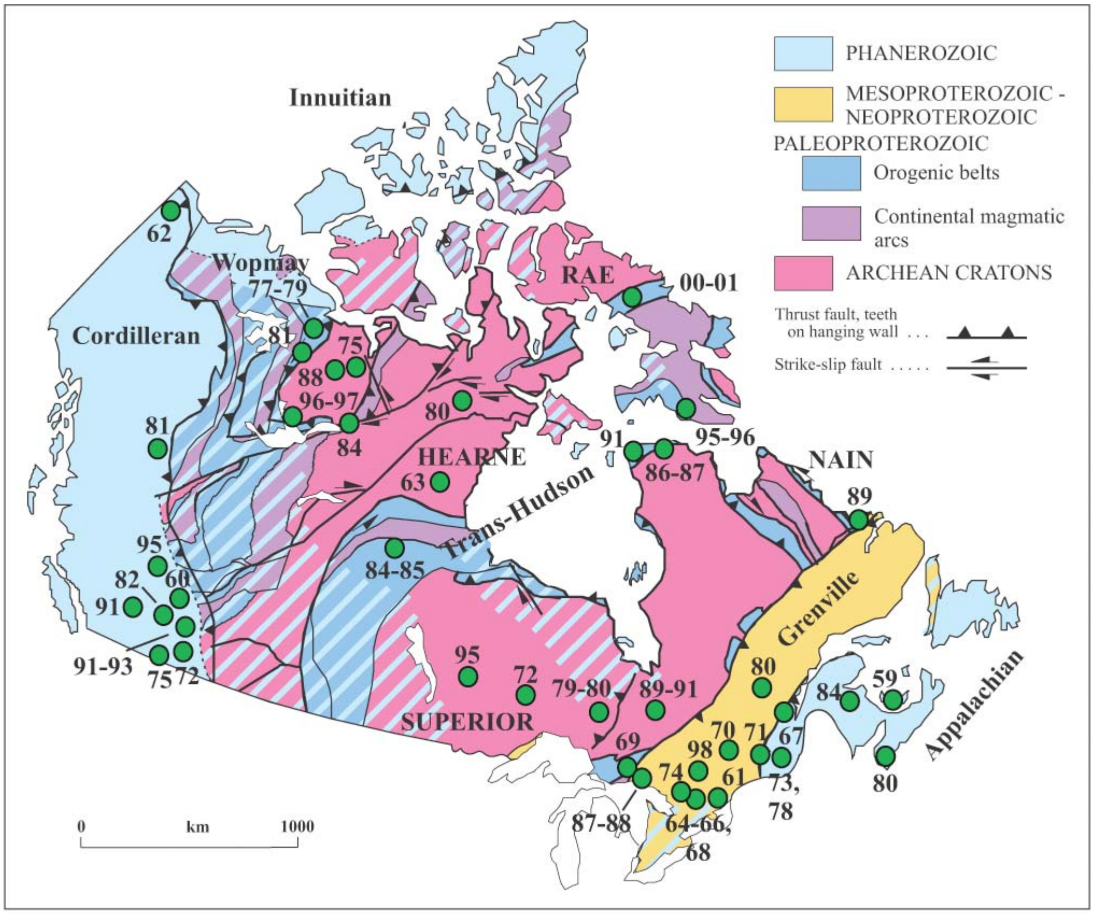

FIG. 1. Simplified geological map of Canada, modified after Hoffman (1988, 1989), Ross *et al.* (1995) and Wheeler *et al.* (1996). Blue diagonal stripes represent areas where the Precambrian basement is covered by the Phanerozoic platformal cover, which is not illustrated. Upper-case names are Archean cratons; lower-case names are Proterozoic and Phanerozoic orogens. Green dots and two-digit numbers indicate location and corresponding year(s) of field work by Dugald and are cross-referenced to Table 1.

in metamorphic petrology. Following completion of his Ph.D. (Carmichael 1967), he was hired by McGill University in 1968 and then moved to Queen's University in 1970, where he inspired many students and conducted research until his retirement in 2002.

Dugald has often spoken in admiration of individuals who change the way we think. It is altogether in keeping with his personality that it seems not to have dawned on him that he is one of these people. He suggested that his petrological legacy could be summed up in less than 15 seconds. Indeed, Dugald's published output reveals that he never practiced the art of the minimum publishable unit. His impact is measured instead by the publication of a few key papers of jewel-like quality and originality, combined with countless personal interactions with students and colleagues, on an outcrop, behind a microscope, in the kitchen tent, on a field trip, at the other end of a review, over a phase diagram, that rarely failed to elevate the mind and spirit of those involved, and make them feel more insightful and enthused about what they were working on. At the Special Session in Dugald's honor (see below), Tom Chacko introduced a new term to petrology, the "Dugaldism", meaning a difficult concept explained with simplicity, clarity and elegance. Mike Brown expressed what many have felt, that Dugald made the study of metamorphic petrology fun!

Dugald's scientific impact has been felt in several overlapping spheres that are outlined below. The papers of this special volume have been correspondingly grouped.

Reaction Mechanisms

The first paper Dugald published from his Ph.D. research was entitled *On the Mechanism of Prograde Metamorphic Reactions in Quartz-Bearing Pelitic Rocks* (Carmichael 1969). It is difficult to exaggerate the impact of this paper, as it is one the most highly cited papers in metamorphic petrology and is referred to in virtually every petrology textbook. It brought the field of metamorphic reaction processes out of the dark ages to become a vibrant research area in its own right.

It is illuminating to read the (slightly paraphrased) introduction to his paper because it illustrates many of the hallmarks of Dugald's outlook and approach: recognition of a universal problem based on careful observations, petrological insight, novel application of simple concepts, and clearly, elegantly written prose:

"It has long been a problem that the textures of a sequence of rock specimens collected across an isograd, as seen in thin section, generally do not accord with the reaction that may be deduced by comparing mineral assemblages on either side of the isograd…. Generally, the products do not grow directly in contact with the reactants. Instead, the products and reactants are in different domains in the same thin section, separated from each other by minerals that are stable on both sides of the isograd…… The aim of this paper is to show that [these] isogradic textures …can be reconciled with the metamorphic reactions inferred to have been in progress …by deducing from the textures of a single thin section a set of metasomatic cation-exchange reactions, which proceed in different microscopic domains in the rock, but which add up on the scale of the whole thin section to give the balanced metamorphic reaction" (after Carmichael 1969, p. 244-245).

The impact of the paper has less to do with the actual metasomatic cycles he inferred than the way he thought about the problem, and the conceptual window it opened for others working on similar problems. Dugald has remained engaged with reaction mechanisms for most of his career, examining their importance to a wide range of microstructural and petrological phenomena, including geothermobarometry based on solid-solution equilibria (Carmichael 1979, 1987), induced stress, secondary mass-transfer and the tendency toward a constant-volume constraint in diffusion metasomatism (Carmichael 1987), and replacement creep (Carmichael 2001).

Reaction Isograds and Mixed-Volatile Reactions

The second paper Dugald published, *Intersecting Isograds in the Whetstone Lake Area, Ontario* (Carmichael 1970), had almost as large an impact as his first, but in a rather different realm of petrology, namely isograds and mixed-volatile reactions. The first part of the paper is a beautiful exposition of the procedure and theoretical advantages of mapping isograds based on specific metamorphic reactions, as opposed to index minerals. Dugald applied this approach to four metapelite dehydration-reaction isograds and one metacarbonate mixed-volatile reaction isograd in the Whetstone Lake area, and to his delight, found that they crossed! Being familiar with Hugh Greenwood's (1962) work on mixed volatiles, he plotted the five reactions in a T – $X(CO_2)$ diagram and showed in a simple and elegant fashion that this hitherto unrecognized phenomenon could be explained by gradients in the proportion of H_2O and CO_2 in the metamorphic fluid phase, related to the proximity of nearby granitic plutons.

Dugald's interest in isograd reactions and mixed volatiles also ran as a theme through his career, as revealed by papers on matrix analysis of metamorphic reactions (Carmichael & Trzcienski 1970), metasomatic processes in gold deposition (Carmichael 1990a), a review of mixed-volatile reactions (Skippen & Carmichael 1977), univariant mixed-volatile reactions as reaction isograds (Carmichael 1991), and the metastability of the hydrosphere (Carmichael 1990b)!

Bathozones, Bathograds and the Metapelitic Petrogenetic Grid

Despite the fact that Dugald clearly found the study of metamorphism to be intellectually satisfying and engaging in itself, he often remarked that metamorphic petrology is of most use when it contributes to other areas of geology, in particular tectonics. This belief is revealed in the third of his seminal papers, *Metamorphic Bathozones and Bathograds: A Measure of the Depth of Post-Metamorphic Uplift and Erosion on the Regional Scale* (Carmichael 1978). Dugald's aim was to be able to portray *in map form* boundaries between regions that had experienced different amounts of post-metamorphic uplift and erosion. This information could then complement maps of lithology and structure, allowing comparison between different terranes and first-order inferences about tectonic processes.

The scheme was based on mineral assemblages in metapelitic rocks. It is at once simple and ingenious, involving the intersections of two key metapelite-dehydration equilibria (staurolite-out and muscovite-out) with the phase boundaries for the Al_2SiO_5 polymorphs (kyanite, andalusite and sillimanite). These intersections gave rise to a new type of purely pressure-sensitive isograd which Dugald termed a *bathograd*, which could be viewed as "slicing" P–T space into pressure intervals he termed *bathozones*. Dugald applied his scheme to the classic metamorphic terranes of the world, including the Scottish Highlands, New England, and the Alps, mapping out bathograds and bathozones that delineated graphically the differences in post-metamorphic exhumation across these areas in a way that had never been done before. The beauty of the scheme is that it is based on natural mineral assemblages and does not require mineral analyses, making it a useful tool for a wide range of field geologists, not just metamorphic aficionados. At the same time, it encouraged the careful observation of mineral assemblages in the field, which may explain why Dugald is often to be found sprawled out on an outcrop searching for metamorphic minerals (Fig. 2).

The paper was not without its critics. Reading from the paraphrased introduction to the paper:

"This paper is aimed at a bimodal audience. On one hand I hope to reach a large group of field geologists who will be able to help with the mapping of map bathograds, quite independently of what their significance may be…. On the other hand I hope to convince a small group of metamorphic specialists that so simple a geo-barometric scheme is not hopelessly naïve. An anonymous member of the latter group "… is rather taken aback at the rather cavalier fashion in which the author approaches the problem." Nevertheless, [the diagrams that follow] appear to me to justify a somewhat less cautious use of a petrogenetic grid…than has been the general practice up to now…." (Carmichael 1978, p. 771).

Given the current resurgence of interest in estimating the P–T conditions of metamorphic rocks by analyzing the stability of mineral assemblages in quantitative petrogenetic grids and associated pseudosections, the justification seems to have been abundantly fulfilled 25 years later.

The paper in addition marks Dugald's career-long involvement with petrogenetic grids, especially the one for metapelites. The evolution of Dugald's metapelitic petrogenetic grid is one of the great underground tales of Canadian petrology, because virtually an entire generation of Canadian geologists and students have used his grids even though they have never been published outside class notes and field guides (for example, Davidson *et al.* 1990)! The grid shown in his 1978 paper is a much-simplified extract of his full grid. Dugald's metapelitic grids nevertheless appear frequently in publications, usually with references like Carmichael (19xx, personal communication) or (19xx, unpublished). Dugald also devised grids and associated bathograd–bathozone schemes for other bulk compositions, including metabasites (Bégin & Carmichael 1987, 1992, Powell *et al.* 1995), calcium- and alkali-deficient bulk compositions (Percival *et al.* 1982) and high-grade boron-bearing metapelitic compositions (Carmichael 1994).

Tectonics and Field Studies

Canada is blessed with an exceptionally rich geological endowment spanning a broad spectrum of Earth history, from the oldest rocks in the world (the Acasta gneisses, Slave Craton) to rocks being actively formed and eroded today. Dugald has taken full advantage of this prime natural laboratory by combining his petrological interests with field work in virtually every craton and orogen in Canada (Table 1, Fig. 1). In the process, either through direct field contributions or his interaction with colleagues and students, he has significantly added to the current understanding of the geology of Canada.

Dugald's field career in Canada is summarized in Table 1, with the location of field areas shown on Figure 1. The 42 map-areas in which he has worked are ordered in Table 1 from the older Archean cratons to the younger Phanerozoic orogens. Principal field-work themes, thesis students, and immediate colleagues involved are listed; on some of the larger projects, Dugald interacted with as many as 20 colleagues and university students. In addition to the Canadian projects portrayed in Figure 1 and Table 1, Dugald also conducted field-based petrological research in the European Alps, Scottish Caledonides, New Zealand Alps, Lachlan Fold Belt of Australia, and the American Cordillera. Not included in Table 1 and Figure 1 are the memorable field trips that Dugald has led with colleagues in the Grenville and Penokean orogens (including the famous "boat-and-beaver-dam" field trip to Whetstone Lake following the 1978 Geological Society of America meeting in Toronto; Carmichael *et al.* 1978) and the numerous field schools he taught both in Canada and the U.S.A. (Fig. 3).

Examination of Table 1 allows a number of primary field-research themes to be identified, many of which quite naturally became the foundation for Dugald's petrological research. His long-term interest in mineral growth and deformation-fabric relationships began with a field season in the Westport map area (Grenville Orogen) in 1961, and it remained a central theme for his work in Timmins – Chapleau (Superior Craton), Hopedale (Nain Craton), Lynn Lake and Narsajuaq (Trans-Hudson Orogen), Artillery Lake (Thelon Orogen), Redrock Lake (Wopmay Orogen; Fig. 4), and the Sifton and Deserters Ranges (Cordilleran Orogen). Reaction isograds, of critical importance in understanding the Whetstone Lake area (Grenville Orogen) in 1964–1966, were the focus of Dugald's field work in Nipigon, Longlac, and Matachewan (Superior Craton), Hackett River, Contwoyto Lake and Yellowknife (Slave Craton), Cape Smith Belt and central Baffin Island (Trans-Hudson Orogen), Hepburn Lake (Wopmay Orogen), Coaticook (Appalachian Orogen), and the Riondel, Creston, Monashee, Nelson, and Penfold Creek areas (Cordilleran Orogen). Bathozones and bathograds, quintessentially Dugaldian concepts that bridged the disciplines of petrology and field-based tectonics, were mapped in Nipigon, Longlac and Matachewan (Superior Craton), Contwoyto Lake (Slave Craton), Hepburn Lake (Wopmay Orogen), Sherbrooke and mainland Nova Scotia (Appalachian Orogen), and the Monashee and Nelson areas (Cordilleran Orogen). In addition to these primary petrological themes, Dugald's field work encompassed metamorphosed alteration zones, stratigraphy and structure of low-grade sedimentary sequences, products of shock metamorphism, prospective areas for magnesium ore, Pleistocene sedimentary units, and dam sites for engineering geology studies.

The following anecdote, one of many in a long and distinguished mapping career, provides an example of the breadth and eclectic nature of Dugald's interests and the all-encompassing nature of his field observations. During the 2000 field season on central Baffin Island, it was Dugald's sharp field observations and powers of deduction, which included deducing the amount of post-glacial uplift and consequent shoreline retreat for the east side of Foxe Basin, that enabled the first-ever identification of a Thule-type archeological site in that part of the Canadian Arctic (N. Hallendy, 2002, pers. commun.). All of this was accomplished during the course of a regular traverse in folded Paleoproterozoic biotite-bearing metaturbidites!

Graduate Student Education

During the course of his career at McGill University and Queen's University, Dugald supervised 34 graduate students who completed 36 theses, 13 at the M.Sc. level and 23 at the Ph.D. level, not to mention a large number of B.Sc. theses. The first two graduate theses were done at McGill University (1970–1971), whereas the other 34 were undertaken at Queen's University (1973–2003). Of the 36 theses, 35 were field-based projects in Canada. Many of the students worked in conjunction with regional mapping projects of the Geological Survey of Canada and various provincial surveys, and were co-supervised by Dugald's colleagues at Queen's University, including Hugh Wynne-Edwards, Ray Price, John Dixon, Jay Hodgson and, perhaps above all, Herb Helmstaedt, Dugald's long-time friend and collaborator.

Dugald's influence on his students was multi-faceted and generated rich and congenial interactions and tremendous loyalty. Although known to miss the occasional meeting (!), these lapses were counterbalanced by the quality of his interactions with his students. He advocated a strong component of field work in which to put petrological research in context. Of course, mineral assemblages, the rules of Schreinemakers and P – T – $X(CO_2)$ diagrams could not be bypassed! He taught students to always try and ask the right question and to never ignore the seemingly impossible, in the process fostering creativity and enthusiasm. He encouraged students to make solid mineralogical and textural observations before pursuing quantitative petrological analysis, and never to isolate thermal processes from tectonic and deformation processes. Dugald was always supportive financially as a supervisor and encouraged his students to attend geological field trips and conferences to expand their horizons. On top of it all, he was always ready to hit the river in his canoe or entertain field camps or busloads of students on a field trip with his guitar and a song or two from Willie Nelson or Stompin' Tom Connors. If the music in the bar was good, he would never pass up a dancing opportunity!

Truth and Beauty in Metamorphism: A Tribute to Dugald Carmichael

Catalyzed by Dugald's retirement in 2002, it was for all of the above reasons that a Special Session and accompanying celebratory dinner were organized in his honor at the joint Geological Association of Canada – Mineralogical Association of Canada – Society of Economic Geologists (GAC – MAC – SEG) annual meeting in Vancouver, British Columbia, on May 26–27, 2003. The special volume in your hands is an outgrowth of that meeting.

The name of the session and of this volume, *Truth and beauty in metamorphism*, was inspired by a seminar Dugald gave in 1979 at Queen's University entitled *Metamorphic textures: A study in time, space, truth and beauty*. Though the details of the seminar have since faded, the title and its special resonance with Dugald's attitude and outlook on the study of metamorphism have remained vivid. The Special Session was the largest session of the meeting and included 43 talks and posters from colleagues and students from all corners of the globe.

The celebratory dinner afterward was held on a warm, breezy evening at Brock House, an elegant Vancouver ocean-side restaurant, with Dugald's wife Hilda, son Ian and daughter Wendy present. The camaraderie and good humor that were shared that evening are perhaps the enduring memory of the event. At the end of the evening, in a brief address, Dugald paid special tribute to Hilda, Ian and Wendy for the support and patience they showed in allowing him to engage so richly in his work and with his students. He said he felt privileged to have been active in an honorable profession like science, where people from different parts of the world can come together to discuss common problems and interests in which the incentive is not money or influence, but simply the pursuit of knowledge and understanding. Some might argue that this view is "hopelessly naive", to use Dugald's own phrase, but this outlook is one of the reasons that Dugald has left such a positive impact on all of us. He is truly an original.

Acknowledgements

We acknowledge Herb Helmstaedt of Queen's University for the field photographs and Greg Dipple of the University of British Columbia for the substantial help he provided in organizing the Special Session and celebratory dinner at the Vancouver 2003 GAC – MAC – SEG meeting. Terry Gordon, Herb Helmstaedt, Al Levinson, Robert F. Martin, John Percival and Dave

FIG. 2. Dugald searching for minerals and ignoring mosquitoes on an outcrop of kyanite – K-feldspar pelitic gneiss (bathozone 6!) in the Hepburn metamorphic–plutonic zone of Wopmay Orogen, Northwest Territories, summer of 1981.

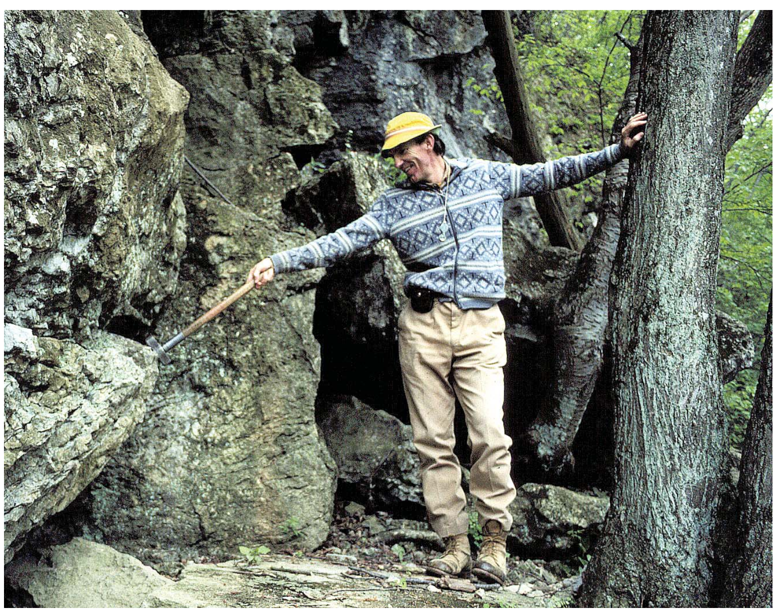

FIG. 3. Dugald highlighting a transverse down-dip lineation to senior field-school students from Queen's University in the Appalachian Mountains of Maryland, U.S.A., spring of 1980.

FIG. 4. Dugald standing on a major crustal structure separating continental rift-margin volcanic units on the right from deep-water pelagic sedimentary rocks (part of a 2.0-billion-year-old ophiolite) on the left, Cape Smith Belt, northern Quebec, summer of 1986.

Scott are thanked for their comments on this Preface. This is Geological Survey of Canada contribution number 2003123.

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