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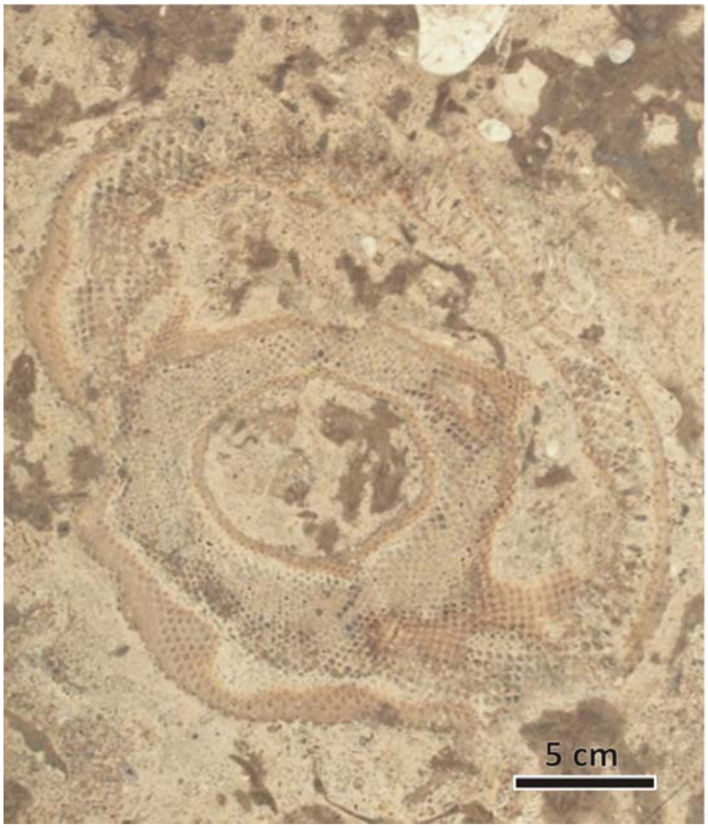

President Pontificates on Perplexing Puzzles

Extending Ideas for Infrastructure Deconstruction

Tiny Creatures from the Deep – A Lacustrine Lagerstätte

Geochemists Provide Advice on Multiple Pearcings

The Ventures of a GSC Pioneer – For Whom Did Bell Toil?

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Cover Photo: Geologists like nothing more than a puzzle. Fisherites Reticulatus (left, seen here in the famous Tyndall Stone) has been all over the taxonomic map, but its true affinities remain a mystery. The bizarre "Molar Tooth Structure" (right, seen here in Precambrian dolomite) has long puzzled observers, and has recently been interpreted as a product of fluidization caused by the shaking of ancient earthquakes. See Brian Pratt's presidential address for more discussion!

Photo credits: Brian R. Pratt

Presidential Address

Geology: In All Modesty

Brian R. Pratt

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When GAC president Steve Rowins telephoned me on a bright winter's morning in 2013 to invite me to join GAC Council as vice-president, which meant becoming president and then past-president, the initial glow of feeling flattered and flushed with a sense of purpose gave way to trepidation: I would have to deliver a presidential address. What could I possibly say that had not already been covered by Steve himself, or by my other immediate predecessors Stephen Johnston, Peter Bobrowsky and Dick Wardle? All of these presidents, in their own eloquent ways, gave such perceptive epistles on where geology is going in Canada. I knew I could not say anything new in this regard, even though the landscape has changed with the declining job market and worsening research funding. So I thought I might instead talk about… geology, and about how I think as a geologist, and why I find it so fulfilling. For me, geology is the most captivating of the sciences, and I did give the other ones a good try, I really did. Later I learned that geology had been the preeminent and most prestigious science in the 19th century, but over time it has been shouldered aside by other disciplines which have come to prominence. Now, it seems to be portrayed to the general public as a rather modest subject and not terribly relevant to modern society, and even bearing a whiff of guilt in an increasingly environmentally conscious world. When we think about it, however, we realize that geology is a most majestic subject because it incorporates so many things: all the other sciences plus the dimension of Deep Time. But these days, for various reasons I am anxious about the future of geology as we know it, that is, the study of rocks.

I am from Hamilton, Ontario, grew up in the embrace of the Niagara Escarpment, and did my undergraduate degree at McMaster University in the 1970s. Here is a photograph of the Highway 6 roadcut through the Silurian just north of Highway 403 (Fig. 1a). The lower half consists of sandstone and shale, passing upward into dolomite. When we as students measured sections in these roadcuts I remember that we couldn't find any fossils and condemned them as the most boring rocks ever. And yet they must have left a deep impression. I didn't realize then that hardly anyone had studied these units for years. That has changed, but even now every time I go back to the same localities, which I do often, I find new and amazing things. There really is a lot to see when you look.

It was flying by helicopter into the remote canyonlands north of the South Nahanni River after my second year that truly crystallized my passion for geology. The combination of science with outdoor adventure could not be beaten — not to mention the profusion of fossils in the Devonian limestone bedrock there. Yet the Niagara Escarpment of southern Ontario is just as exciting scientifically. Here is the cliff at Mount Nemo (Fig. 1b) between Burlington and Milton, south of Highway 401. It is just 13 km from that Highway 6 roadcut, but those boring thin-bedded dolomites pass into an entirely different facies: a huge shallow-water carbonate sand shoal deposit made of crinoid ossicles, cross-bedded and cut by spectacular scour surfaces. Digital elevation maps suggest that the shoal system was a complex of carbonate sand bars which are seen in cross-section in the cliffs and quarries. Over the past nearly 30 years I have prepared miles of photomosaics to document the internal architecture, ran ground-penetrating radar, collected fossils, studied the porosity under the SEM, and so on. This unit is unique in the Michigan Basin: how could the extremely high energy levels indicated by the sedimentary structures have arisen in a supposedly tranquil epeiric sea? These rocks – under our noses for so long – pose fundamental questions about Silurian oceanography and climatology.

As a budding éminence grise – without the eminence admittedly – I am at the stage in life when I wonder about my own thought processes, asking what geology is in the grand scheme of things scientific, how philosophers of science see us, and how to transmit these notions to students and people in other disciplines. Karl Popper told us that science moves along in a rather ordered way not by proving theories but by trying to falsify them. Does this fit with geology? Not exactly, because ours is an historical science: Mother Nature has already conducted the experiment, and we can't really test our hypotheses – interpretations – in the same way as in the 'hard' sciences like physics and chemistry. Paul Feyerabend felt that science proceeds more chaotically, and I think that is closer to how we practise geology. Thomas Kuhn considered that the slow advance of science was punctuated by sporadic intellectual or technological breakthroughs or revolutions, and in geology we can appreciate that, with plate tectonics as an obvi-

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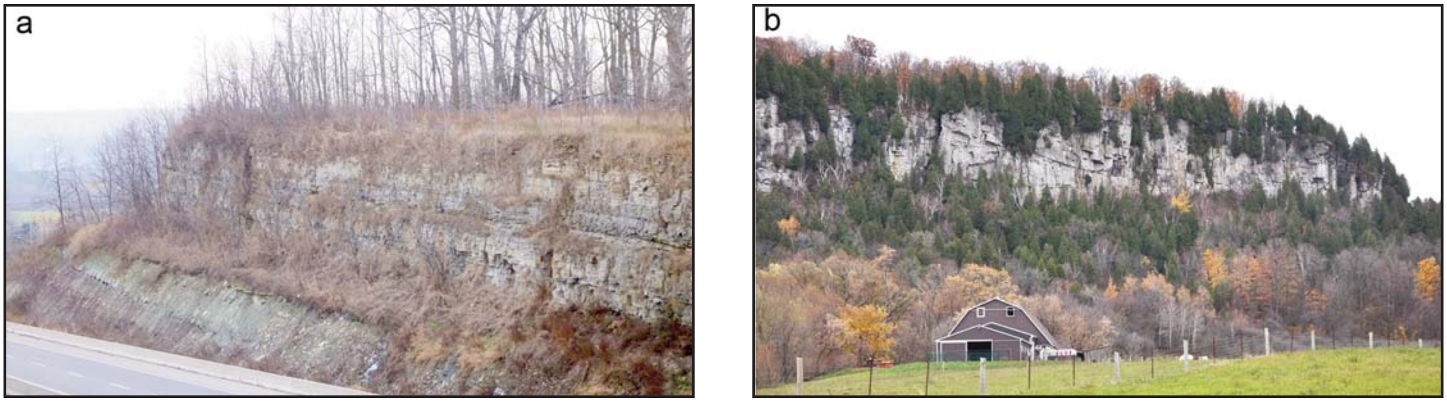


Figure 1. Lower Silurian strata of the Niagara Escarpment in the Hamilton–Burlington area, southern Ontario. (a) Highway 6 roadcut (Clappison's Cut) with Hamilton off to the left. The lower part consists of silty shale and sandstone belonging to the Grimsby and Thorold formations which are overlain by several dolomite formations separated by unconformities. The topmost unit is the Ancaster Member of the (traditional) Lockport Formation, which consists of cherty wackestone. A few hundred metres to the northeast it passes into thin- to medium- and lenticular-bedded crinoidal grainstone traditionally assigned to the Amabel Formation. (b) North-facing cliff face of Mount Nemo, 13 km north of Clappison's Cut. The Amabel Formation has thickened dramatically and consists of thick- and massively cross-bedded crinoidal grainstone with enormous scour surfaces.

ous example. I regard zircon dating and its use for sediment provenance as another one.

When geologists try to philosophize they don't seem to get too far. The 1963 book *The Fabric of Geology*, edited by Claude Albritton, is a collection of still-interesting papers but it does not set out overarching ideas or principles. The Geological Society of America celebrated its 125th anniversary in 2013 by publishing *Rethinking the Fabric of Geology* and two companion books that follow a similar approach. Maybe how we think in geology just can't be distilled into a single simple philosophy. On the other hand, the famous evolutionary biologist Ernst Mayr may have come close with his books in which he articulated a philosophy of biology. These include *Toward a New Philosophy of Biology* (1988), *This is Biology* (1997) and *What Makes Biology Unique* (2004). As a centenarian he witnessed astonishing advances and had plenty of time to ponder how they came about.

However, when most scientists, and journalists, think or talk about science, geology typically recedes from view. The downright pessimistic book *The End of Science,* published by John Horgan in 1996, didn't interview any geologists or even mention geology. It seems that the author forgot, or never knew, that in the 1800s geology was front and centre amongst the sciences. In those days, however, there was no way to measure the age of the Earth. Charles Darwin and Charles Lyell guessed it was in the hundreds of millions of years, based more on intuition and notions about rates of geological and evolutionary processes. Then physics stepped in, and Lord Kelvin famously, or infamously, calculated with great certitude an age of one hundred million years, which he later revised downward. But physics eventually did lead to the breakthrough that was necessary: the discovery of radioactivity and then radiometric dating.

Science is portrayed to the general public as being rooted in measurement and experiment, and heavy on technological wizardry and mathematics. Geology does all that too, but as Dolf Seilacher, the Sherlock Holmes of paleontology, once reminded me, the eye and the imagination are still valid scientific instruments. The roles of discovery and serendipity are by no means unique to geology but they are especially crucial, and experience and intuition help us make sense of it all. We must not surrender our rightful place because otherwise our special perspectives and contributions are easily overlooked. Unfortunately, research funding organizations seem to struggle with this legitimacy.

In what other ways are geologists different? We have a few basic stratigraphic principles but don't have scientific laws; if we did, they would be made to be broken. We continually return to the field, to make new or more observations of geological attributes and relationships. If we don't get these right, then all that follows is spurious. Every new student, then, needs to acquire basic field skills, and understand the strengths and limitations of field-based data — our version of 'experiential learning.' This can only be done by one-on-one mentoring, which is somewhat at odds with the pressure in universities to strive for ever higher student enrolment. Several years ago Chevron was running an advertisement in venues like *GSA Today* that showed geology students at an outcrop somewhere like in Utah or Arizona. It was aimed to attract new employees, but it should have been in magazines for the general public too: a perfect opportunity for putting a human, and geological, face on petroleum exploration. Instead, Chevron unleashed their 'We Agree' advertising campaign to showcase its concern for the environment, local communities and so forth — what is referred to, with some elasticity these days, as 'social licence.' It was immediately parodied by activists, and in advertising circles it is considered to have been an expensive flop. I would be curious to know if the companion advertising campaigns by several other oil companies managed to quell at least some anti-petroleum and anti-mining fervour.

Geologists engage in lifelong learning. We never stop, be it peering at a granite countertop or watching ripples form at the beach. Geologists are also renowned for getting the interpretation either completely wrong or partially wrong, and that is accepted quite happily as part of how geological problems are solved, as Bob Dott pointed out in his 1998 *GSA Today* essay. By the time Imperial Oil drilled the famous discovery well Leduc #1 in 1947, it had 133 consecutive dry holes to its credit — but we wouldn't really say the exploration geologists were wrong all along, would we? When I worked in Calgary in the early 1980s, a senior geologist once joked to me that, given the vast number of dry holes that riddle the province – now running into the many hundreds of thousands – oil and gas wells could have been drilled on a random basis and exploration would have been just as successful. Yes, it is true that millions of dollars are spent in search of a field, but there is an accumulation of knowledge that ultimately does lead to discovery, which is followed by a dramatic advance in understanding as the field is developed, such as this one in the Cretaceous Glauconite Formation in Alberta (Fig. 2). The intellectual background is therefore integral to a geological advance and that is why the archival literature remains important, perhaps more so than in other disciplines. So, geologists seem to be especially forgiving of making mistakes. Not for us Max Planck's famous (paraphrased) aphorism that "science advances one funeral at a time." At the same time, geologists are not too impressed by dogmatic interpretations about Earth's history or exaggerated predictions of Earth's future.

Geologists also have a unique ability, which they acquire in short order, to move seamlessly and effortlessly across spatial scales from nanometres to thousands of kilometres, and temporal scales from seconds to billions of years. We can all think of geological objects and phenomena to populate a graph of distance or size versus time (Fig. 3a). A meteorite impact crater tens of kilometres across took just seconds to form. A fossil animal like a Cambrian trilobite or archaeocyathan sponge a few centimetres in size (Fig. 3b) may have lived up to a decade or two or three. That would imply that the associated constituents (Fig. 3c) formed in a broadly similar time span, and a rough idea of sedimentation rate, in this case how long it took to build a patch reef, can be estimated. If we find the same species of fossil on another continent, that tells us something about ocean currents, larval biology and so forth, and allows us to correlate the two distant areas. Of course, if we do not find it elsewhere that tells us something too — in geology the absence of something can be as important as its presence.

Another aspect of geology that I find so fascinating is how we approach geological problems using what I like to call the 'interrogative trinity,' asking the questions 'what,' 'how' and 'why.' Different geological tasks or activities involve these questions in different ways and proportions, and they can be plotted on a ternary diagram (Fig. 4). When we make a geological map we are determining factual information: the *what*. An

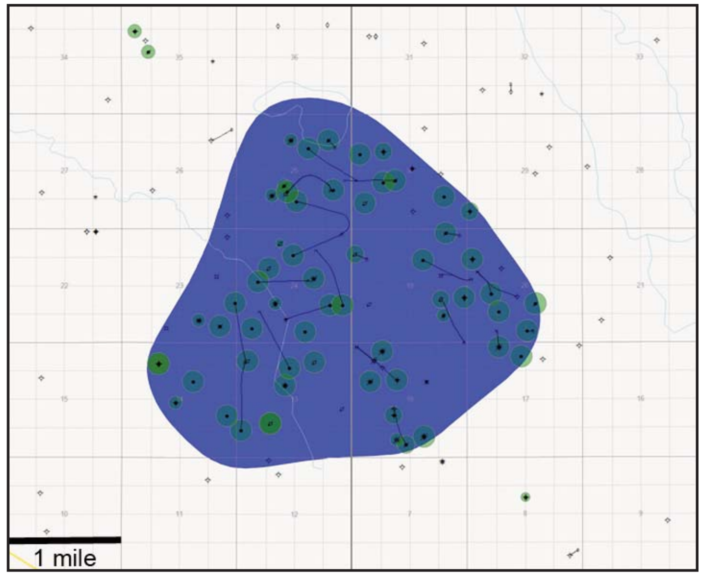


Figure 2. Map of a portion of eastern Alberta showing an oil field in the Lower Cretaceous Glauconite Formation (blue area) and location of oil wells (green circles) and dry holes (most of the uncoloured dots in and around the field). As drilling proceeded, it was revealed that the field is developed in fluvial channel sandstone and development became more precise. Map courtesy of J. Weissenberger, Husky Energy.

experiment might tell us *how* something formed. If we do a facies analysis we describe *what* the rocks consist of, but then we want to know what they mean: the *how* and the *why*. Geology can be quite numerical, and occasionally it lends itself to mathematical modelling. A model is a simplification of a complex system and cannot be taken as fact or proof, but it may help support interpretation of *how* and *why* based on observation and experiment.

After a few years working in the Calgary oil patch I decided to embark on PhD studies on paleontology in order to round out my grasp of geology, which had hitherto been mainly sedimentological. I discovered that fossils capture well the essence of geological thinking, and far from being a stale exercise in stamp collecting, there is a wealth of questions to ask. After all, life is the only creative force in the Universe, and fossils represent 3.5 billion years of that creativity, and thus they are the

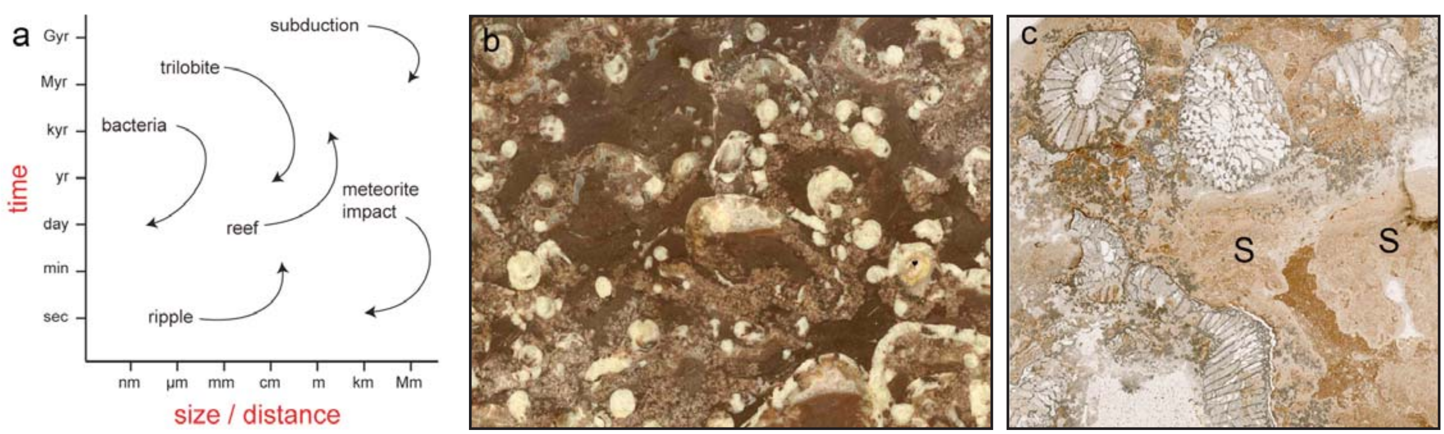


Figure 3. (a) Graph of temporal (y-axis) versus spatial (x-axis) scales as a framework for geological phenomena, such as meteorite impacts, formation of ripples, growth of bacteria and fossils, reef accretion, and the development of a subduction zone. (b) Polished slab of lower Cambrian reef rock (Forteau Formation, southern Labrador). Archaeocyathan sponges are the white domes and sticks; the calcimicrobe *Renalcis* forms pinkish masses that bind the archaeocyaths together. The matrix is red lime mudstone. Field of view is 15 cm wide. (c) Thin section photomicrograph of the same reef rock. The archaeocyaths are intricate skeletons, whereas *Renalcis* appears as dark-grey clusters. The matrix turns out to be mostly microbial here, i.e. weakly laminated stromatolites (S). Field of view is 2.5 cm wide. We can imagine these framebuilding elements formed in a matter of a decade or so and the overall reef might have taken tens of thousands of years to accrete — perhaps faster than usually thought.

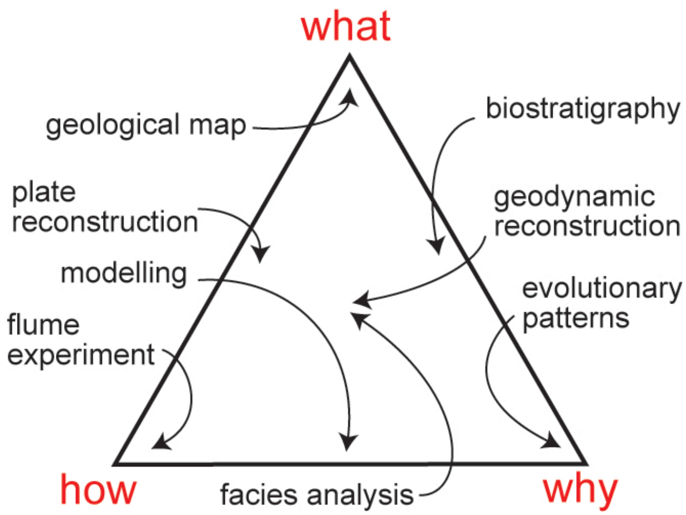


Figure 4. Geological subject matter in the context of an 'interrogative trinity' expressed as a ternary diagram. The geologist inherently knows the domains occupied by the various activities. For example, a geological map aims to be a purely factual rendition, whereas creating sedimentary structures in a flume is determining how they formed. Reconstructing the positions of ancient continental plates is an attempt to identify what they are and then account for how they got to there. Modelling is more a combination of trying to understand certain phenomena and why they took place. Study of fossils might be combinations of asking what and why, depending on what one wants out of the fossils. Efforts like facies analysis and understanding an orogenic belt occupy the central domain because they incorporate all three questions.

evidence for biological evolution. You have to understand the rocks that contain them and their stratigraphic relationships. Fossils tell you the time. You learn something about depositional processes because they were sedimentary particles. As they were once living things you can deduce their paleobiology. Traces in the sediment give clues to locomotion and feeding behaviour, and if you find coprolites you know something about nutrition and digestion. Fossils were part of communities and there is a paleoecological story to tell. You try to figure out which fossils were predators and which were prey, which were herbivores and which grubbed around the sediment or benignly filtered food from the water. Depending on the circumstances, there is much room for bold ideas. Two decades ago we realized that we had phosphatized embryos in acid-resistant residues from a Cambrian limestone: a taphonomic miracle if there ever was one, and now we know something about early development. (Initially we speculated they were trilobite embryos, but now we know they belonged to a kind of worm.) There is more: using synchrotron X-ray fluorescence we found geochemical evidence in a Burgess Shale arthropod for Cu-bearing blood called hemocyanin — the circulatory system! While this may seem the epitome of curiosity-driven research – and of course we may be wrong – shale geochemistry has important practical applications.

Doing geology is like having fun solving a puzzle. Virtually every rock sample presents more questions than answers. One of the things I like to tell students or visitors is that they may be holding something in their hand that despite years of study we simply can't explain. My favourite is the striking fossil *Receptaculites*, which is common in Tyndall Stone, Canada's most famous dimension stone (Fig. 5a). This fossil has been all over the taxonomic map, from sponges to algae to pine cones. It's still a mystery. Another puzzle is the bizarre crumpled calcite vein arrays called 'molar-tooth structure,' first observed in Precambrian limestone along the border between Alberta and Montana and so named in 1885 because of its resemblance on bedding planes to the surface of elephant molars. Then it lay dormant for a century, ignored by geologists and absent from textbooks. I first laid eyes on molar-tooth structure while hiking there in 1976. What on earth is this? Nobody knew. The Eureka! moment for me came one evening 15 years later: these veins formed by lime mud fluidization and injection during earthquake-induced shaking of the sea floor. Hundreds of

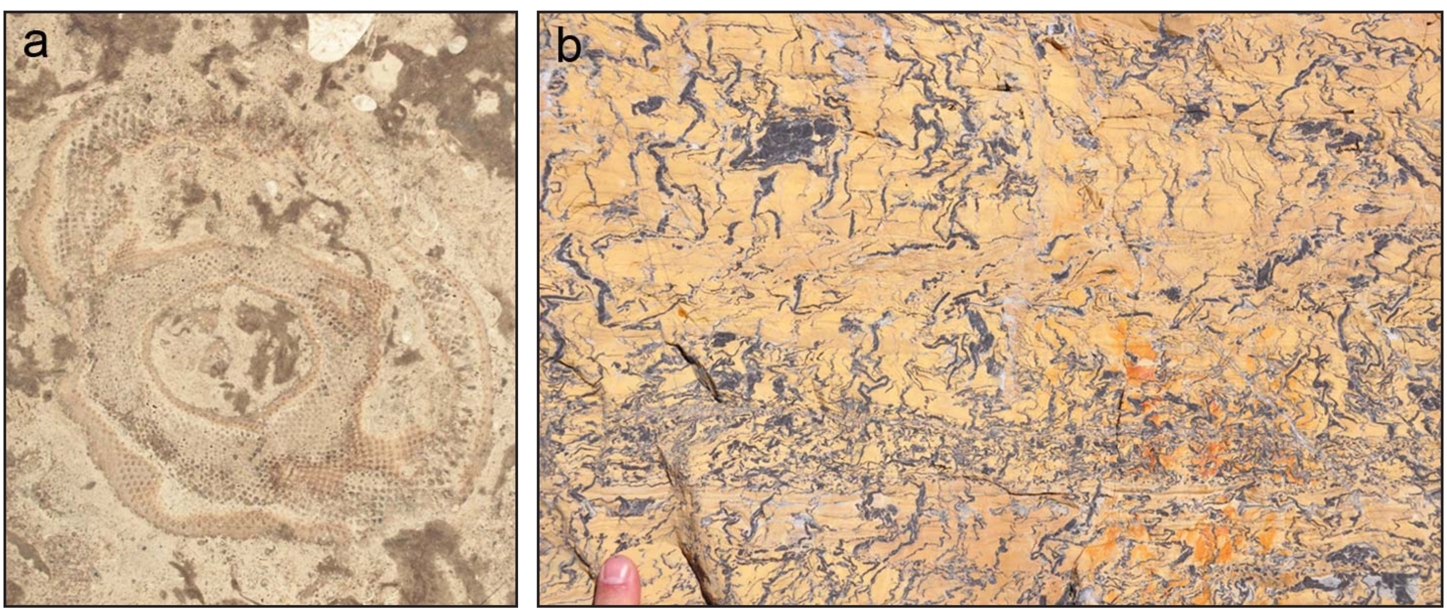


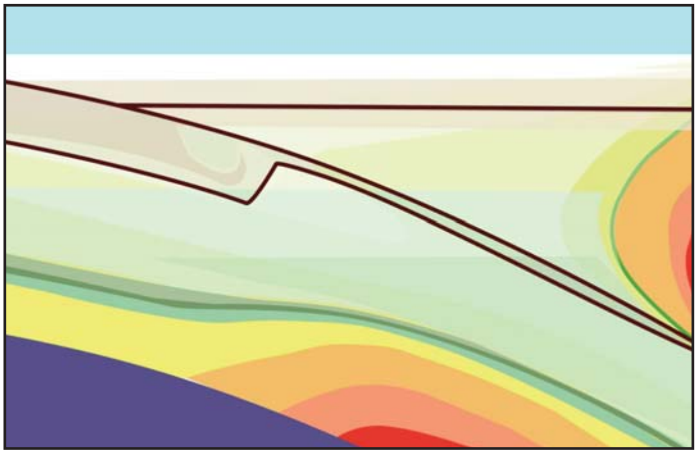
Figure 5. Doing geology can be like solving a puzzle. (a) Polished Tyndall Stone cut parallel to bedding, showing *Receptaculites* fossil [more correctly *Fisherites reticulatus* (Owen 1844)]. This is part of the memorial wall in the Geology Building, University of Saskatchewan. The stone belongs to the Selkirk Member of the Red River Formation (Upper Ordovician), southern Manitoba. Field of view is 27 cm wide. (b) View perpendicular to bedding of the Mesoproterozoic Siyeh Formation (= Helena Formation in Montana) showing dolomitic lime mudstone cut by folded calcite-filled veins. These veins are 'seismites.' This is part of an ornamental block at a viewpoint on Highway 6 just north of the entrance to Waterton Lakes National Park, Alberta. Finger is 18 mm wide.

samples and thin sections later: QED. Molar-tooth structure turns out to be a stratigraphic seismograph! Like so much in geology, a seemingly small thing can have big implications in the narrative.

Doing geology is storytelling. Everyone loves a good story. So let's celebrate geology and brag about it — while we follow our passion and keep on having fun! Figure 6 points the way.

Figure 6. Important advice in Yosemite National Park, California.

ANDREW HYNES SERIES: TECTONIC PROCESSES



Deconstructing the Infrastructure: A Complex History of Diachronous Metamorphism and Progressive Deformation during the Late Cretaceous to Eocene in the Thor-Odin–Pinnacles Area of Southeastern British Columbia

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SUMMARY
The Thor-Odin dome is a basement-cored tectonothermal culmination in southern British Columbia containing high-grade metamorphic rocks that were polydeformed in the Late Cretaceous to Eocene. The rocks south of the Thor-Odin dome that extend ca. 20 km to the Pinnacles culmination and Whatshan batholith comprise a heterogeneous tract of polydeformed medium- to high-grade metamorphic rocks and host the South Fosthall pluton near the base of the structural section. They lie in the footwall of the Columbia River fault (CRF) zone, a moderately east-dipping, ductile-brittle, normal fault that was active after ca. 55 Ma and reactivated periodically up to 30 Ma. This tract of rocks has been interpreted as a mid-crustal zone that was exhumed and cooled during Eocene extension or, alternatively, a mid-crustal channel that was bounded at the top by the CRF and was active during the Late Cretaceous to Eocene. However, the timing of metamorphism, deformation, anatexis in basement rocks, and intrusion of leucogranite plutons reveals that there are four tectonothermal domains within the tract that each experienced metamorphism, deformation and cooling at different times. These rocks record Cretaceous metamorphism and cooling in the upper structural levels and three stages of progressive metamorphism and penetrative deformation that migrated into deeper crustal levels in the Paleocene and Eocene producing a complex structural section that was exhumed in part due to motion on the Columbia River fault zone, and in part due to NE-directed transport over a basement ramp.

RÉSUMÉ
Le dôme de Thor-Odin correspond à une culmination tectonothermique d'un noyau de socle dans le sud de la Colombie-Britannique renfermant des roches métamorphiques de haute intensité polydéformées entre le Crétacé supérieur et l'Éocène. Les roches au sud du dôme de Thor-Odin qui s'étendent sur environ 20 km jusqu'à la culmination des Pinnacles et du batholite de Whatshan sont constituées d'une bande hétérogène de roches polydéformées à faciès métamorphique d'intensité moyenne à élevée qui constitue l'encaissant du pluton de South Fosthall près de la base de la colonne structurale. Elles se trouvent dans l'éponte inférieure de la zone de faille de la rivière Columbia (CRF), une faille normale à pendage modéré vers l'est, ductile-fragile, qui a été active après 55 Ma environ et a été réactivée périodiquement jusqu'à 30 Ma. Cette bande de roches a été interprétée comme une zone de mi-croûte qui a été exhumée et a refroidi durant l'extension éocène ou alors comme un canal mi-crustal qui a été limité au sommet par la CRF, et qui a été actif de la fin du Crétacé jusqu'à l'Éocène. Toutefois, la chronologie du métamorphisme, de la déformation, de l'anatexie dans les roches du socle, et de l'intrusion de plutons de leucogranite, montre qu'il existe quatre domaines tectonothermiques pour chaque bande qui ont subit du métamorphisme, de la déformation et du refroidissement à différents moments. Ces roches exhibent un métamorphisme et un refroidissement crétacé dans les niveaux structuraux supérieurs et trois stades de métamorphisme pro-

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gressif et de déformation pénétrative qui ont migré dans les niveaux crustaux profonds au Paléocène et à l'Eocène constituant ainsi une colonne structurale complexe qui a été exhumée en partie en raison du mouvement de la zone de faille de Columbia River, et en partie en raison du transport vers le N.-E. sur une rampe de socle.

Traduit par le Traducteur

INTRODUCTION: SUPRASTRUCTURE–INFRASTRUCTURE FRAMEWORK AND THE SOUTHEASTERN CANADIAN CORDILLERA

The rocks of the southeastern Canadian Cordillera have a protracted history of deformation and metamorphism. At the present latitude of the southern Canadian Cordillera, the orogeny developed into a doubly vergent, medium-sized, warm orogenic belt (Evenchick et al. 2007; Simony and Carr 2011) in a transpressional setting during the Cretaceous to Eocene (Monger and Price 2000). Crustal shortening on the western edge of the Laurentian craton occurred in the Jurassic and continued until the Late Cretaceous to Paleocene and juxtaposed pericratonic and oceanic terranes with the Laurentian margin successions (Monger et al. 1982; Colpron et al. 1996). By the Middle Jurassic some of the accreted terranes, e.g. the Slide Mountain ocean basin which closed before the Late Permian (Klepacki 1985) and rocks of the Quesnel terrane which include Laurentian-derived clastic sediments and pericratonic juvenile oceanic arc-derived rocks (Unterschutz et al. 2002), had been obducted over the pericratonic Kootenay terrane (Brown et al. 1986; Ross et al. 2005; Evenchick et al. 2007). The main periods of crustal thickening and shortening of supracrustal rocks in the eastern retrowedge side of the orogen occurred between ca. 100 Ma and 52 Ma (Simony and Carr 2011 and references therein). The collision of the Alexander terrane and Wrangellia with the Cordilleran margin occurred during the mid-Cretaceous to Tertiary (Monger et al. 1982; Monger and Journeay 1994).

Late Cretaceous to Eocene tectonothermal events overprint older structures formed during Paleozoic basin inversion, Late Triassic to Jurassic accretion of inboard terranes (Monger et al. 1982; Colpron et al. 1996), and/or structures developed during Jurassic to Cretaceous shortening and deformation, all formed in a transpressional setting (Evenchick et al. 2007; Simony and Carr 2011 and references therein). At ca. 52 Ma, the plate tectonic setting changed from a fully transpressional setting to one that included a component of local extension due to more oblique convergence of the Kula and Laurentian plates (Lonsdale 1988; Andronicos et al. 2003). This led to a structural regime dominated by strike-slip faults in the western and northern Cordillera and, in rocks of present day southeastern British Columbia, regional extension. This extension was characterized by magmatism, north-south striking, shallow to moderately dipping ductile–brittle extensional detachments with fault traces between 100 and 200 km long (Fig. 1); steep brittle north-south striking fault systems; and tectonic exhumation of rocks that were in the mid-crustal infrastructure in the Eocene (Parrish et al. 1988; Carr 1991a; Johnson and Brown 1996; Adams et al. 2005; Johnson 2006; Kruse and Williams 2007). At the latitude of the Thor-Odin dome (Fig. 1), the east-dipping Columbia River fault zone and the west-dipping Okanagan Valley–Eagle River fault zones are important Eocene, ductile–brittle extensional fault systems (Parrish et al. 1988; Johnson and Brown 1996; Teyssier et al. 2005; Johnson 2006 and references therein; Thompson et al. 2006; Brown et al. 2012).

The Thor-Odin–Pinnacles area (Fig. 2a) is located in the Western Internal zone of the southeastern Canadian Cordillera (Fig. 1) which contains predominantly metamorphic and igneous rocks, and includes several tectonothermal culminations which expose high grade metamorphic and plutonic rocks. Some of these culminations contain exposures of Laurentian basement rocks, for example the Priest River complex (Doughty et al. 1998), the Malton gneiss complex (Murphy 1987), the Frenchman Cap dome (Armstrong et al. 1991; Parkinson 1991) and the Thor-Odin dome (Reesor and Moore 1971). In others, for example, the Kettle dome/Grand Forks complex, the Okanogan dome (Parrish et al. 1988; Kruckenberg et al. 2008), and the Valhalla complex (Carr et al. 1987; Hallett and Spear 2011), the basement rocks are not exposed. All these domes have been described as metamorphic core complexes, or part of metamorphic core complexes (Ewing 1980; Armstrong 1982; Coney and Harms 1984), characterized by domal culminations of deeply exhumed, high-grade metamorphic rocks bounded by shallowly outward-dipping normal faults with low-grade metamorphic rocks in the hanging walls (Whitney et al. 2013); in detail, they may have different tectonometamorphic histories (Gervais and Brown 2011; Simony and Carr 2011).

Mechanisms that have been investigated to explain the evolution and geometry of tectonothermal culminations in the Cordillera can be discussed in terms of three main categories. These are i) channel flow models (Glombick 2005; Teyssier et al. 2005; Brown and Gibson 2006; Lemieux 2006; Kuiper et al. 2006; Williams et al. 2006; Gervais and Brown 2011; Rey et al. 2011); ii) thrust sheet models (Brown et al. 1986; Price 1994; McNicoll and Brown 1995), some with a component of inter-deformation within sheets (Carr and Simony 2006; Hallett and Spear 2011); and iii) diapirism (Vanderhaeghe et al. 1999, 2003; Norlander et al. 2002; Teyssier et al. 2005; Gordon et al. 2008; Rey et al. 2009, 2011). The relative importance of exhumation along Eocene extensional fault systems (Parrish et al. 1988; Thompson et al. 2004, 2006; Brown 2010) is also under debate. Each culmination must be evaluated individually and this study aims to clarify the Paleocene–Eocene evolution of the Thor-Odin dome with reference to some of the main mechanisms that have been proposed for dome evolution.

In this study, we discuss the Thor-Odin–Pinnacles area in terms of an orogenic infrastructure–suprastructure framework. The terminology is that of Murphy (1987), Carr and Simony (2006), Culshaw et al. (2006) and Williams et al. (2006), which describes the infrastructure at lower structural levels as composed of high-grade, penetratively deformed metamorphic rocks with transposed structures and isoclinal regional folds. The upper structural levels, or suprastructure, contain rocks of lower metamorphic grades with variably oriented upright open folds, and thrust faults. From north to south, the Monashee complex consisting of the Frenchman Cap and Thor-Odin domes (Fig. 1), and the Thor-Odin to Pinnacles area represents a structural section including Laurentian basement rocks deep in the Frenchman Cap dome (and possibly the Thor-Odin dome) beneath the Cordilleran orogenic base

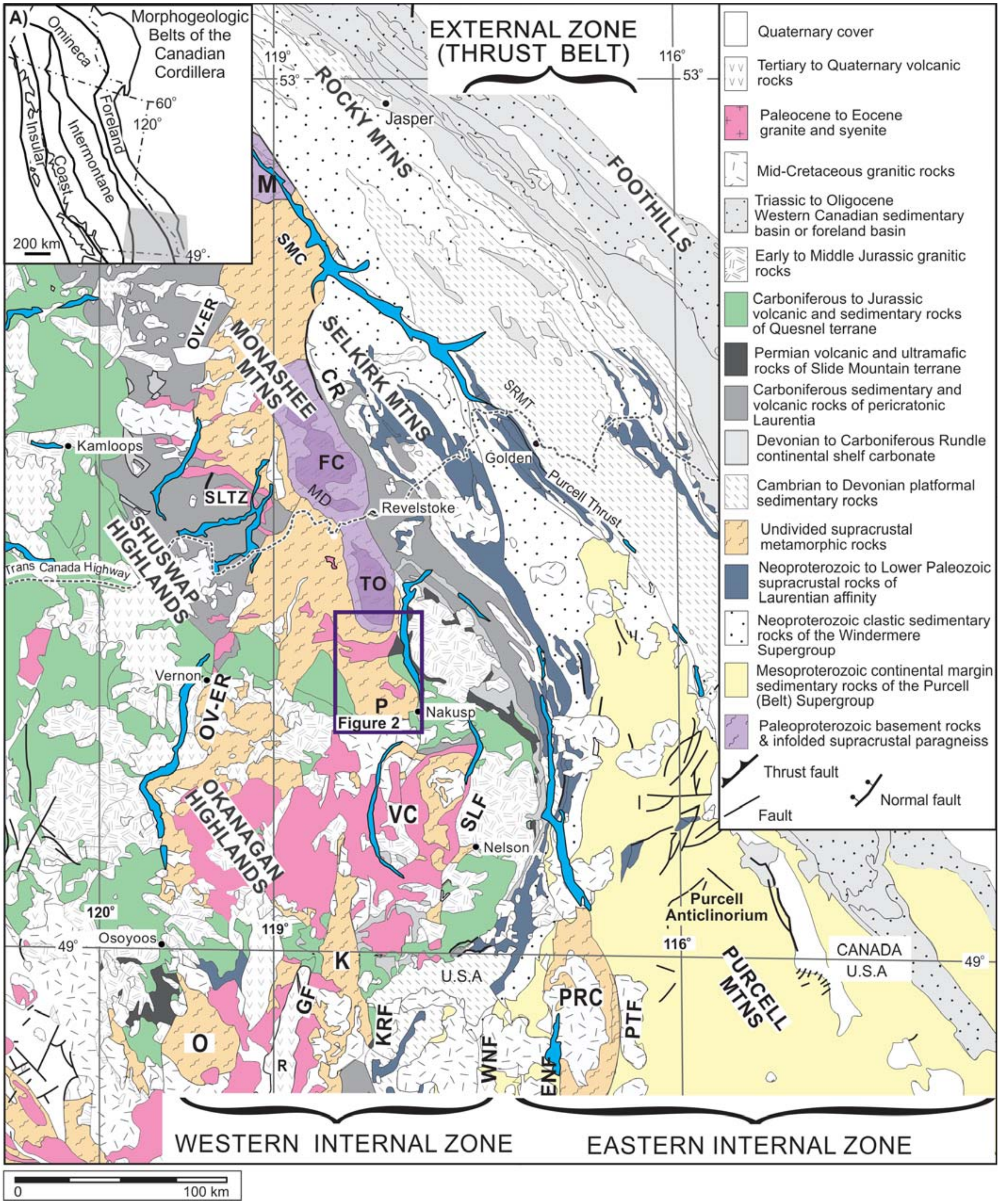

Figure 1. Geological map of the southeastern Canadian Cordillera showing the External, Western Internal, and Eastern Internal zones, (modified after Wheeler and McFeely 1991; Carr 1991b; Johnson and Brown 1996; Simony and Carr 2011). The shaded area of the inset locates the map within the morphogeological belts of the Canadian Cordillera. In the Eastern Internal zone: PRC = Priest River complex, the bounding Western (WNF) and Eastern Newport faults (ENF), and the PTF = Purcell Trench fault. In the Western Internal zone: K – Kettle dome–Grand Forks complex, O – Okanogan dome, R – Republic Graben, VC – Valhalla complex; and complexes with basement rocks include the Frenchman Cap (FC) dome; Malton complex (M); and Thor-Odin dome (TO). Eocene normal fault systems that bound high-grade rocks in the Western Internal zone include the Okanagan Valley–Eagle River fault system (OV–ER); Columbia River fault (CR), SLTZ – Shuswap Lake Transfer Zone and Slocan Lake-Champion Lake fault systems (SLF), the Granby fault (GF) and the Kettle River fault (KRF). SMC – Selkirk-Monashee-Cariboo metamorphic complex; SRMT – southern Rocky Mountain Trench.

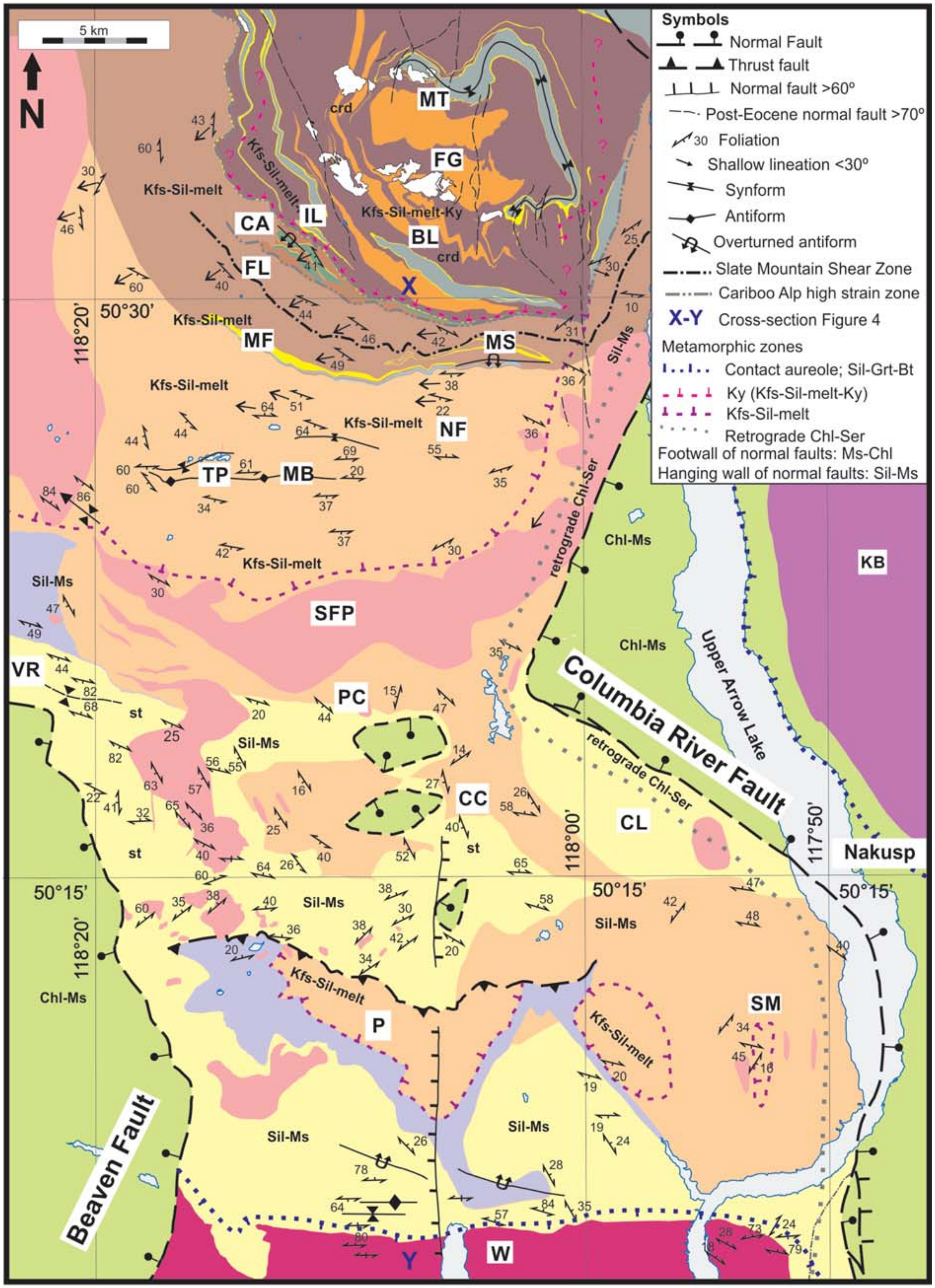

Figure 2a. Simplified geological map of the Thor-Odin–Pinnacles study area. This map shows metamorphic zones, major study locations and lithology. Structural information focuses solely on the youngest generations of foliation in each area, major folds, and fault zones; bedding and overprinted foliations are omitted for clarity. It is important to note that the structures and metamorphic data shown here do not represent coeval events, for further discussion see text and Figure 3 for details. The legend for this map outlining the lithology of major tectonostratigraphic units is included in Figure 2b, along with illustrations of the dominant fold styles in different areas. X and Y indicates the position of the cross-section in Figure 4. (Modified after Reesor and Moore 1971; Coleman 1990; Carr 1990, 1991b; Kruse et al. 2004; Thompson et al. 2004; Hinchey 2005.) Mineral abbreviations after Kretz (1983).

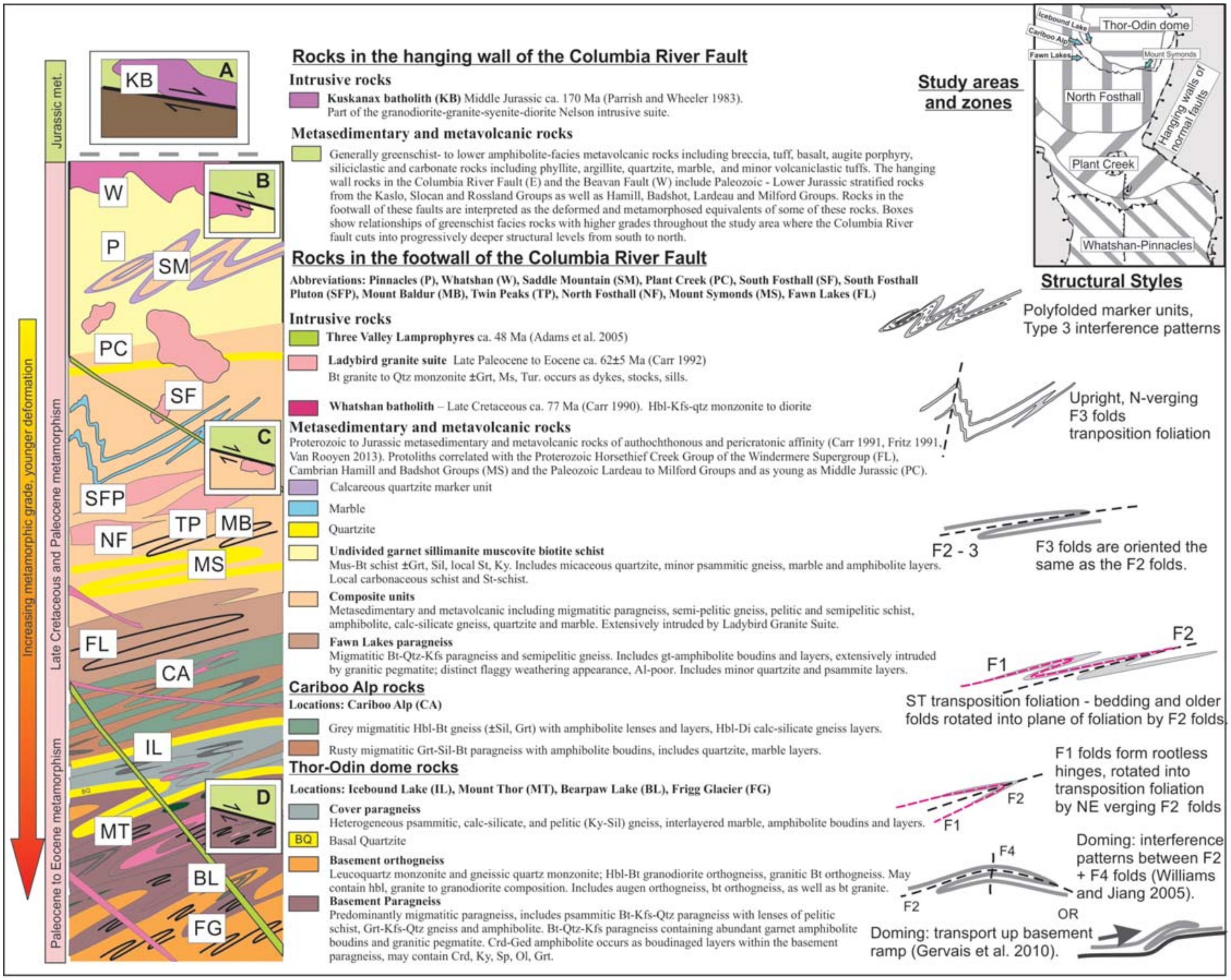

Figure 2b. Simplified lithostratigraphic column summarizing the tectonic elements, structural styles and major lithologic units, and projected locations of study areas. The figure inset contains a sketch map of the study area, where the extent and locations of the different zones discussed in the text are given for easy geographical references. It also serves as the legend for Figures 2a, 3, and 4. Specific areas discussed in the text are Bearpaw Lake (BL), Cariboo Alp (CA), Fawn Lakes (FL), and Frigg Glacier (FG), Icebound Lake (IL), Mount Baldur (MB), Mount Symonds (MS), Mount Thor MT), North Fosthall (NF), Plant Creek (PC), Pinnacles (P), Saddle Mountain (SM), South Fosthall (SF), South Fosthall pluton (SFP), Twin Peaks (TP), and Whatshan batholith (W). Data from Read and Wheeler 1976; Archibald et al. 1983; Parrish and Wheeler 1983; Parrish and Armstrong 1987; Parrish et al. 1988; Coleman 1990; Carr 1990, 1991a, b, 1992, 1995; Smith and Gehrels 1992; Colpron and Price 1995; Vanderhaeghe et al. 1999; Johnston et al. 2000; Norlander et al. 2002; Kuiper 2003; Gibson et al. 2004, 2005; Adams et al. 2005; Glombick 2005; Lemieux 2006; Hinchey et al. 2006, 2007; this study.

(Crowley 1999; Crowley et al. 2008; Gervais et al. 2010). The Laurentian basement rocks are tectonically overlain by a heterogeneous package of mid-crustal rocks in which the age of deformation youngs downward towards the basement (Parrish 1995; Glombick 2005; Williams and Jiang 2005; Carr and Simony 2006; Hinchey et al. 2006; Gibson et al. 2008; Gordon et al. 2008; Gervais et al. 2010). Internal infrastructural transitions of different ages have been documented within this mid-crustal package of rocks (Murphy 1987; Glombick 2005; Hinchey et al. 2006; Carr and Simony 2006). The hanging walls of the Eocene extensional faults contain Paleozoic to Early Jurassic stratigraphic units, and these rocks preserve the Middle Jurassic to Early Cretaceous deformational and metamorphic histories acquired when they were in the suprastructure of the orogen (Evenchick et al. 2007 and references therein; Simony and Carr 2011 and references therein).

This study integrates published and new geochronological, metamorphic and thermochronological datasets to describe and construct a history of the region from the southern flank of the Thor-Odin dome to Pinnacles. The data show that there are tectonothermal belts that preserve different Cretaceous to Eocene deformation and metamorphic histories. An important contribution of this study is to extend the definition and description of infrastructure-suprastructure associations and penetrative deformation active in the infrastructure in the study area to include a temporal dimension, recognizing that these divisions are dynamic and the boundary between them migrates with time.

REGIONAL SETTING OF THE THOR-ODIN–PINNACLES AREA OF SOUTHEASTERN BRITISH COLUMBIA

Located southwest of Revelstoke and west of the Columbia valley, the study area is approximately 50 x 20 km in size and includes the southern part of the Thor-Odin dome and rocks that lie to the south of it in the Thor-Odin–Pinnacles area (Fig. 2). The rocks are generally southwest to south dipping in a panel that has a roughly 12–15 km structural thickness, including the top 2–3 km of basement in the Thor-Odin dome. The deepest structural levels are exposed in the northern part of the study area, in the core of the high-grade metamorphic, migmatitic, Paleoproterozoic basement-cored Thor-Odin dome (Armstrong et al. 1991; Parkinson 1991). They are structurally overlain by Laurentian-derived metasedimentary rocks which are in turn overlain by metamorphosed rocks of the pericratonic Kootenay and Quesnel terranes (Monger and Price 2000). A number of volumetrically significant igneous units of Mesozoic to Eocene age occur in the study area. Some of the important igneous rocks include the Jurassic Nelson suite (Parrish and Armstrong 1987), the Cretaceous Whatshan batholith (Carr 1992), the Paleocene to Eocene Ladybird granite (Carr 1992; Hinchey et al. 2006) and the Eocene Three Valley lamprophyre suite (Adams et al. 2005). The Jurassic to Eocene intrusive rocks mark major periods of igneous activity in the Canadian Cordillera (Parrish et al. 1988; Gabrielse et al. 1991; Parrish 1995) and, taken with field relationships, they are important as strain markers and in providing geochronological constraints on timing of deformation.

One very important tectonic element in the study area is the Ladybird granite, a peraluminous anatectic granite suite derived from melting of basement rocks with Laurentian affinities (Carr 1990; Carr 1991a; Hinchey and Carr 2006). It makes up the largest igneous body in the study area, the South Fosthall pluton (Fig. 2) and is present throughout the study area (Carr 1991a, b). The Ladybird granite is a useful strain marker because it consists of pre-, syn-, and post-tectonic intrusions with well-constrained U–Pb zircon crystallization ages ranging between ca. 64 and 52 Ma (Parrish et al. 1988; Carr 1991a, 1992), discussed in more detail in subsequent sections.

The ca. 200 km long, generally north-south striking Columbia River fault zone (CRFZ) (Fig. 1) is a shallow to moderately east-dipping ductile–brittle extensional fault system bounding the eastern margin of the Frenchman Cap, Thor-Odin and Pinnacles culminations and intervening metamorphic rocks (Parrish et al. 1988; Carr 1990: Lemieux et al. 2003, 2004). We restrict our discussion to the southern part of the fault zone adjacent to the area between the southern flank of the Thor-Odin dome and northern margin of Whatshan batholith, termed the Thor-Odin–Pinnacles area (Fig. 2). The CRFZ shows significant displacements of 10–30 km and is interpreted as a crustal scale detachment (Parrish et al. 1988). This interpretation is supported by data from seismic reflection profiles (Cook et al. 1992; Varsek and Cook 1994; Cook 1995;), geological mapping (Read and Brown 1981; Brown and Read 1983; Johnson and Brown 1996; Johnson 2006) and thermochronology studies (Archibald et al. 1983; Vanderhaeghe et al. 2003; Van Rooyen 2013; Van Rooyen and Carr in press)

The Columbia River fault zone was active between ca. 58 and 55 Ma on the basis of strain recorded within mylonitic Paleocene to Eocene Ladybird granite and pegmatites in the lower plate of the fault zone where deformed Ladybird granite represents syntectonic intrusions (Parrish et al. 1988; Carr 1991a, 1992). After ca. 55 Ma the Columbia River fault zone experienced a major episode of motion, resulting in widespread cooling in the footwall rocks (Van Rooyen 2013; Van Rooyen and Carr in press). On the basis of field and thermochronological data, the fault zone is interpreted to have been reactivated in the brittle field and overprinted by steep brittle faults periodically until ca. 30 Ma (Lorencak et al. 2001). There is a sharp contrast in metamorphic ages and cooling histories between hanging wall rocks which generally preserve greenschist- to amphibolite-facies Jurassic metamorphism (discussed in the following paragraph) and the footwall rocks in the study area which show Cretaceous to Eocene amphibolite- to granulite-facies metamorphism (discussed under individual study areas below).

Jurassic to Early Cretaceous metamorphism is recorded in the Selkirk Mountains, Kootenay Arc, Purcell anticlinorium and in the Cariboo and Monashee mountains (Gibson et al. 2004, 2005). Specifically, the hanging wall of the CRF to the east of the Thor-Odin–Pinnacles area contains greenschist- to lower amphibolite-facies metasedimentary and metavolcanic rocks that experienced peak metamorphic pressures and temperatures of 5–8 kbar and 500–600°C in the Jurassic at 187–160 Ma (Read and Wheeler 1976; Archibald et al. 1983; Parrish and Wheeler 1983; Parrish and Armstrong 1987; Smith and Gehrels 1992; Colpron et al. 1996). These rocks are Paleozoic–Lower Jurassic stratified rocks from the Kaslo, Slocan and Rossland Groups as well as Hamill, Badshot, Lardeau and Milford groups (Read and Wheeler 1976; Thompson et al. 2006). These rocks were deformed and metamorphosed and were intruded by the extensive Middle Jurassic Nelson granodiorite suite (depths of 3–4 kbar), where sillimanite is present in the contact aureoles of plutons in the Thor-Odin–Pinnacles map area (Parrish and Armstrong 1987; Carr 1991b). The intrusions are syn- to post-tectonic, and crosscut Middle Jurassic (and older) folds and foliations (Parrish and Armstrong 1987; Carr 1991b, 1992). These rocks were exhumed and cooled in the Late Jurassic – Early Cretaceous (cf. Evenchick et al. 2007 and references therein) and during the Late Cretaceous–Eocene, this upper crustal domain formed the suprastructure relative to structurally deeper rocks of the Late Cretaceous–Eocene infrastructure. Additional juxtapositions of Jurassic-age greenschist-facies rocks with Late Cretaceous amphibolite-facies rocks occur as klippen of the CRF in the central part of the study area (Brown and Read 1983; Parrish et al. 1988; Carr 1991b, 1992; Lemieux et al. 2003, 2004; Van Rooyen 2013) and in the southwestern part of the area across the Beaven fault, a moderately (average 45 degrees) west-dipping, predominantly brittle (at the present exposure level), normal fault which is part of the Eocene, west-dipping Okanagan Valley–Eagle River fault system (Tempelman-Kluit and Parkinson 1986; Parrish et al. 1988; Carr 1990; Johnson and Brown 1996; Johnson 2006 and references therein; Thompson et al. 2006; Brown 2010).

MAP SCALE GEOLOGY OF THE STUDY AREA FROM THE SOUTHERN THOR-ODIN DOME AND THE WHATSHAN BATHOLITH

The study area exposes an approximately 12–15 km thick, tilted structural section in the footwall of the CRF with the deepest exposed rocks to the north. The map in Figure 2a includes metamorphic mineral zones but it is important to note that these zones do not represent metamorphic events that are the same age. For example, the Sil-Kfs-melt zones (likely representing the reaction Ms + Qtz = Sil + Kfs + melt) include Sil-Kfs-melt metamorphism that is Early Cretaceous in the Whatshan–Pinnacles area (Carr 1992; Glombick 2005; Lemieux 2006), as well as Late Cretaceous to Paleocene in the South Fosthall and Twin Peaks areas (Carr 1991b, 1992; Glombick 2005; Lemieux 2006). Likewise, structures like the map-scale folds, for example, at Pinnacles and Mount Symonds, represent Early Cretaceous and Paleocene structures, respectively (Carr 1991b, 1992; Glombick 2005). The study areas are discussed in order of increasing structural depth, starting at the top of the tectonostratigraphic column (Fig. 2b) as follows: i) Whatshan–Pinnacles, ii) Plant Creek–South Fosthall, iii) North Fosthall–Mount Symonds, iv) Fawn Lakes–Cariboo Alp, and v) the Thor-Odin dome. For each area we present the important structures, lithologies, metamorphic data and geochronology data. Figure 2b illustrates the main structural styles of the rocks in the study area in a stylized tectonostratigraphic column, Figure 3 summarizes the geochronological and metamorphic data discussed in subsequent sections, and Figure 4 is a N–S cross-section from the southern flank of the Thor-Odin dome to the Whatshan batholith that includes interpretations of structures and the location of zones that were being penetratively deformed at different times.

Whatshan–Pinnacles

The Whatshan–Pinnacles area, in the southern part of the study area, makes up a roughly 3–4 km thick package of generally medium-grade Grt-Bt-Ms-bearing and Ms-Sil-bearing schist and paragneiss with minor local migmatitic Grt-Sil-Bt-Kfs-bearing rocks (Carr 1990; Thompson et al. 2004; Glombick 2005). These rocks are not generally characterized by transposition foliation because original stratigraphy is preserved and can be recognized, unlike at deeper levels where all lithologic and structural elements are transposed into a composite foliation (cf. Tobisch and Paterson 1988). The rocks of the Saddle Mountain area extend across Upper Arrow Lake in the southeast corner of the map on the basis of correlative marker units (e.g. calcareous quartzite), and are interpreted here to be at the same structural level as Pinnacles (Fig. 2). Upright, doubly vergent structures defining the main map pattern in this area with Type 3 interference patterns (Figs. 2b, 4) are older than Late Cretaceous, as well as refolded, flat-lying, nappe-style folds (Carr 1991a). The area around Pinnacles (Fig. 2a) has a mapped north-verging thrust fault which places higher grade Kfs-Sil-melt-bearing rocks over the dominant lower grade Sil-Ms-bearing rocks and is interpreted as a ductile, Late Cretaceous or Paleocene structure (Fig. 4). The Whatshan batholith has a U–Pb titanite crystallization age of 75.5 ± 1.5 Ma from a sample locale south of the Pinnacles area (Carr 1991a). This constrains the age of deformation in the host rocks to be older than ca. 75 Ma. This structural level is considered to be equivalent to the Joss Mountain area on the western flank of the Thor-Odin dome (N of the study area, outside of Fig. 2a), where deformed granitic pegmatites have been dated at ca. 73 Ma and undeformed pegmatites at ca. 70 Ma, indicating that the end of deformation is bracketed within that time period (Johnston et al. 2000).

The age of regional metamorphism in the Whatshan–Pinnacles area is constrained by U–Pb dating of monazite (Glombick 2005; Lemieux 2006) and spans the Early to Late Cretaceous, between ca. 130 and 90 Ma (the younger ages generally in structurally deeper areas), with some evidence for earlier metamorphism as old as ca. 200 Ma (Fig. 3). The foliation and pre- to syn-deformational metamorphic minerals aligned within it are cut by the Late Cretaceous Whatshan batholith, suggesting a pre-Campanian metamorphic history. In contrast, andalusite, garnet, and biotite are present in the contact aureole of the Whatshan batholith, overprinting the previously discussed regional metamorphic rocks (Glombick 2005). Kyanite and staurolite are present in the footwall rocks of the Beaven fault, but these cross-cut foliations and overprint older metamorphic assemblages (Reesor and Moore 1971; Carr 1991b). These minerals are restricted to minor aluminous lithologies in the footwall of the Beaven fault and are interpreted as mineral growth at conditions below peak metamorphism, possibly related to conditions during exhumation (Carr 1991b). Metamorphic titanite in the contact aureole of the Whatshan batholith dated at ca. 64 Ma is interpreted as a cooling age after the intrusion of the batholith (Carr 1992). The Whatshan–Pinnacles area represents rocks that are in the suprastructure of the orogen by ca. 75 Ma because the regional penetrative foliation and associated metamorphic mineral assemblages predated the low-pressure andalusite, garnet and biotite in the contact aureole of the Whatshan batholith (Carr 1992), and there is no evidence of overprinting of Paleocene or Eocene events on the regional metamorphism and deformation (Glombick 2005).

Plant Creek–South Fosthall

The central part of the study area, the Plant Creek–South Fosthall area, south of the South Fosthall pluton, comprises a structural thickness of approximately 2–3 km. The metamorphic grades of the rocks in the Plant Creek area (similar to the lower grade rocks between Whatshan and Pinnacles discussed above) are the lowest in the study area, and are mainly medium-grade Bt-Grt-Sil-Ms±St-bearing schist with mixed metasedimentary and metavolcanic protoliths (Plate 1a, 1b). The protolith ages of these rocks range from Cambrian to Devonian, with some as young as Jurassic (Van Rooyen 2013).

In general, the map pattern is controlled by tight asymmetric F3 folds with moderately to steeply dipping axial planes that fold the dominant transposition foliation, and refold coaxial F2 folds and rootless isoclinal folds (Carr 1991a). The axial planes of F3 folds north of Plant Creek dip to the south (Fig. 2b, Plate 1c), and axial planes of F3 folds in the southern part of the Plant Creek area dip to the north, exposing the lowest grade metamorphic rocks in the study area, in the structural depression (Fig. 4). This structural interpretation is supported by the geometry of crustal reflectors imaged by the Lithoprobe Project (Cook et al. 1992; Cook 1995). The cross section in Figure 4 illustrates the structural context of this area as part of a regional syncline with the lowest grade rocks in the core. Within this part of the study area are klippen of the hanging wall of the Columbia River fault, where Jurassic rocks metamorphosed at greenschist-facies conditions are in fault contact with the high-grade footwall rocks with Cretaceous to Eocene thermal and deformation histories being discussed here (Van Rooyen 2013; Van Rooyen and Carr in press).

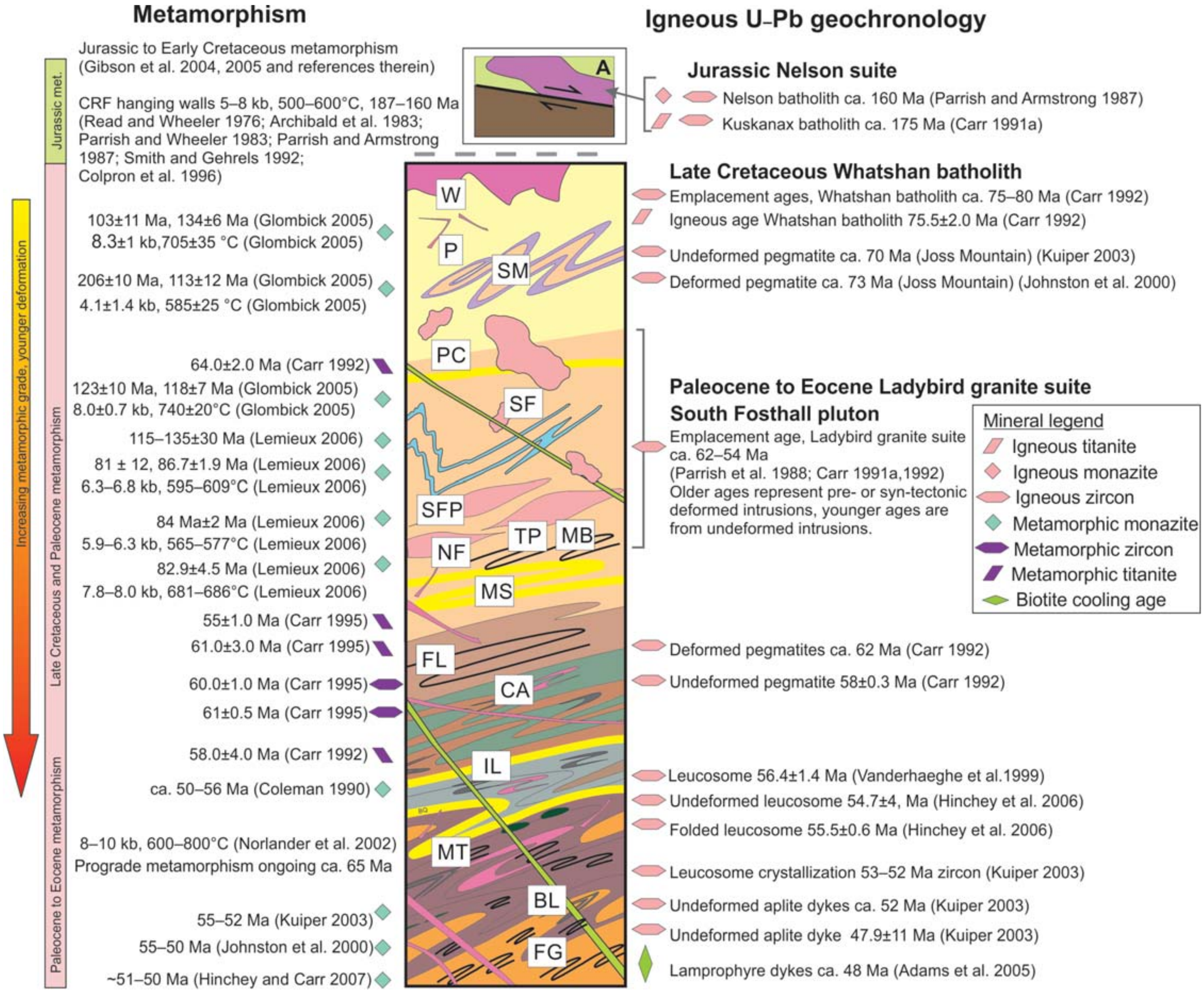

Figure 3. Tectonostratigraphic column of the study area summarizing the timing of metamorphism, pressure and temperature conditions, and U–Pb zircon ages of deformed and undeformed igneous rocks. The *P–T* determinations and dates are projected into the structural section as presented in column form, and represent the structural level at which they are listed. The *P–T* and geochronology data do not necessarily represent data from exactly the same rocks, but they are representative of the same general areas. Data from Read and Wheeler 1976; Archibald et al. 1983; Parrish and Wheeler 1983; Parrish and Armstrong 1987; Parrish et al. 1988; Coleman 1990; Carr 1990, 1991a, 1992, 1995; Smith and Gehrels 1992; Colpron et al. 1996; Vanderhaeghe et al. 1999; Johnston et al. 2000; Norlander et al. 2002; Kuiper 2003; Gibson et al. 2004; Adams et al. 2005; Glombick 2005; Lemieux 2006; Hinchey et al. 2006, 2007; this study.

Metamorphic minerals occur aligned with S2 foliations that developed together with F2 folds, which are generally refolded by F3 folds (Carr 1991b). In some cases F3 folds contain axial planar foliations. The timing of the onset of prograde metamorphism is not well constrained, but it is likely that prograde metamorphism in the Plant Creek area was ongoing during the Late Cretaceous (Fig. 3), spanning the time between ca. 100 and 80 Ma based on U–Pb monazite dating (Lemieux 2006). Folded rocks are cut by the syn- to post-deformational ca. 62–54 Ma Ladybird suite (Carr 1992). Hornblende $^{40}Ar/^{39}Ar$ cooling ages in the Plant Creek–South Fosthall area vary between ca. 62 and 58 Ma and biotite cooling ages vary between ca. 52.5 and 50.5 Ma, while muscovite and biotite cooling ages from Ladybird granite pegmatites are between 51 and 50.5 Ma (Van Rooyen 2013; Van Rooyen and Carr in press). At ca. 73–64 Ma the rocks of the Plant Creek-South Fosthall area, structurally above the South Fosthall pluton, were being penetratively deformed in the infrastructure (Fig. 4).

North Fosthall to Fawn Lakes

The North Fosthall area, from the South Fosthall pluton to the southern margin of the Thor-Odin dome, includes study areas at Twin Peaks, Mount Symonds, and Fawn Lakes (Figs. 2, 3). It makes up a structural thickness of roughly 4–5 km, 2–3 km of which is within the boundaries of the South Fosthall pluton. The age of the South Fosthall pluton is bracketed by U–Pb zircon ages between ca. 62 and 54 Ma (Carr 1992). The rocks between the South Fosthall pluton and the southern margin of the Thor-Odin dome comprise a south-southwest-dipping panel of heterogeneous, polydeformed, medium- to high-

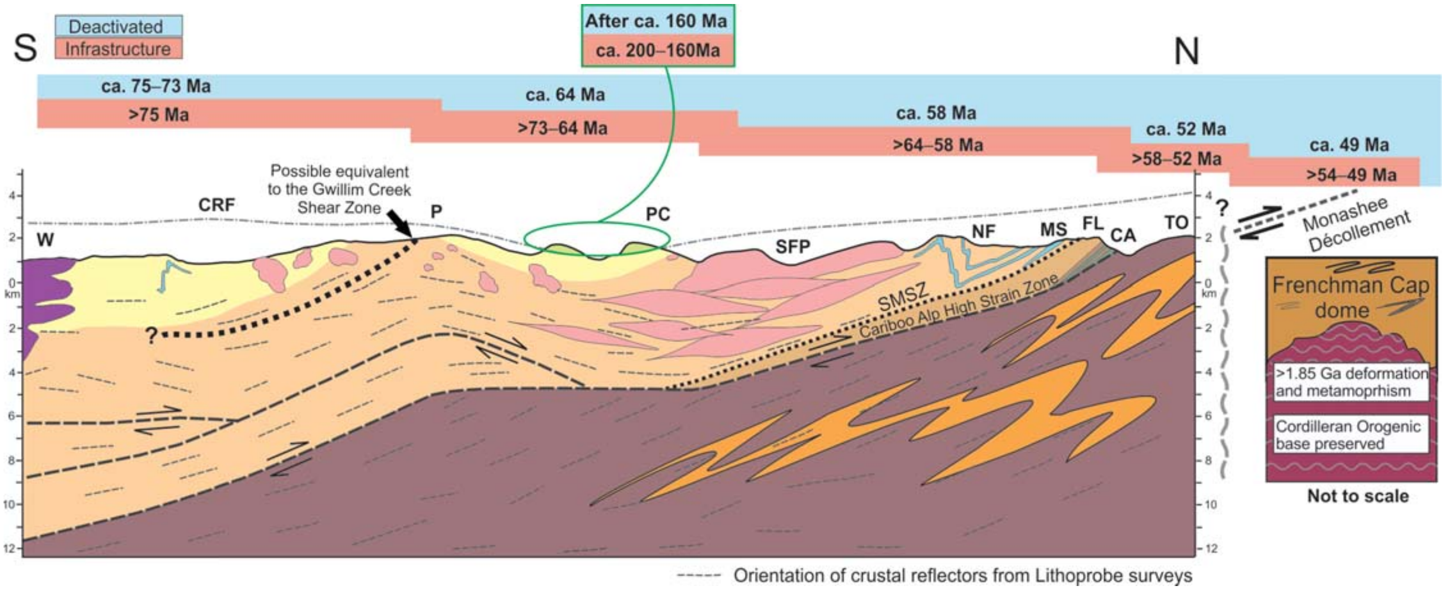

Figure 4. N–S cross-section of the study area on line X–Y in Figure 2a. This cross-section illustrates the general structural styles and orientations of units in the study area. Note that minor lithological units are omitted for clarity, and marker units (e.g. the blue calcareous units) have been given an exaggerated thickness to illustrate fold styles. The structural interpretation is supported by data from Lithoprobe seismic reflection studies (Carr 1995; Cook 1995). The shapes of the South Fosthall pluton and Whatshan batholith in the subsurface are speculative, but illustrate the interpretation discussed in the text that the intrusions are mostly sheet-like bodies within the country rocks. The proposed analogue for the Gwillim Creek shear zone in the Pinnacles area (as mapped on Figure 2) follows crustal seismic reflectors parallel to the deeper thrust slice interpreted to be located under Pinnacles. (SMSZ – Slate Mountain shear zone; CRF – Columbia River fault zone).

This cross-section also illustrates the interpretations we make based on U–Pb zircon, monazite and titanite geochronological data presented in Figure 3, in combination with $^{40}Ar/^{39}Ar$ cooling data. We suggest that there are at least four tracts of rocks with different structural, metamorphic and (in part) cooling histories in the Thor-Odin–Pinnacles area and that they represent progressively younger phases of metamorphism and deformation migrating downwards into the structural section. Also illustrated is the projected relationship with the Frenchman Cap dome which represents an even younger phase of deformation, and contains the base of Cordilleran deformation, below which only Paleoproterozoic deformation and metamorphism is evident (Gervais et al. 2010).

grade metasedimentary and metavolcanic rocks (Carr 1991a). The map pattern is created by northeast-verging km-scale tight asymmetric F2–F3 folds with moderately to steeply dipping axial planes (Reesor and Moore 1971; Carr 1991b), which fold a pervasive older transposition foliation present in all the rocks in this area. The southeastern dip of the panel is controlled by the long limbs of the F2–F3 folds (Figs. 2b, 4). Pegmatites occur as pre-, syn-, and post-deformational intrusions. Plate 1d shows an example of a syn-deformational pegmatite boudinaged along the foliation plane in the North Fosthall area.

The Twin Peaks area is located northwest of the South Fosthall pluton and consists mostly of migmatitic Sil-Grt-Bt-Kfs-bearing paragneiss with a well-developed composite transposition foliation, primarily moderately south- to southwest-dipping (Fig. 4). Ladybird granite intrusive rocks are abundant and are concordant with layering in the host rocks in some cases, and crosscut the layering in others. The regional transposition foliations in this area generally dip steeply (40–60°) towards the south and southwest, with some on the northern side of the valley dipping towards the north and northeast (Fig. 2a). The area is located on a regional scale northeast-verging F2 fold, similar in orientation and style to folds in other study areas (e.g. Mt. Symonds), but contains a fold closure with fold axis plunging to the west-southwest and axial plane dipping steeply to the south. Plate 1e shows parasitic Z folds in migmatitic Sil-Grt-Bt-Kfs-bearing paragneiss that reflect the regional fold style. These cm-scale folds have axial planes that dip steeply to the south and fold hinges that plunge shallowly to the west. Plate 1f shows migmatitic Hbl-Bt-bearing amphibolite gneiss with a well-developed transposition foliation in which the foliation is crosscut by coarse-grained granitic leucosome, suggesting that these rocks underwent progressive episodes of deformation and anatexis with syn-deformational leucosome intrusion. The timing of deformation in this area is constrained by geochronology in an adjacent area at the same structural level at Mount Baldur (Fig. 3). Mount Baldur is situated east of the Twin Peaks area, within the South Fosthall pluton (Carr 1990; Hinchey 2005) and is dominated by Ladybird granite with up to 30% screens of paragneiss, psammite, quartzite and amphibolite country rock within the granite (Hinchey and Carr 2006). Around the South Fosthall pluton the age of the transposition foliation is Late Cretaceous to Paleocene, bracketed by U–Pb zircon ages from deformed and undeformed Ladybird granite indicating that deformation was ongoing at ca. 62 Ma, and largely over by ca. 55 Ma (Carr 1992). The amphibolite-facies metamorphic assemblages are folded by the transposition foliation and the granite cuts the foliation, indicating that the peak metamorphism is pre- or syn-deformational (Carr 1991a; this study).

The Mount Symonds area (Fig. 2) comprises a mixed assemblage of migmatitic Sil-Kfs-Grt-Bt-bearing paragneiss, quartzite, amphibolite, marble and psammite, with a well-developed, moderately south-southwest-dipping composite transposition foliation. Several marker units have Proterozoic (i.e. Fawn Lakes Assemblage) to Cambrian protolith ages (i.e. Empress Marble south of Mount Symonds) which can be traced along strike for up to 30 km. The area is located on the long limb of a km-scale isoclinal fold, interpreted as F2, which formed during northeast-directed transport and compression. The axial plane of this fold dips steeply to the south, similar to

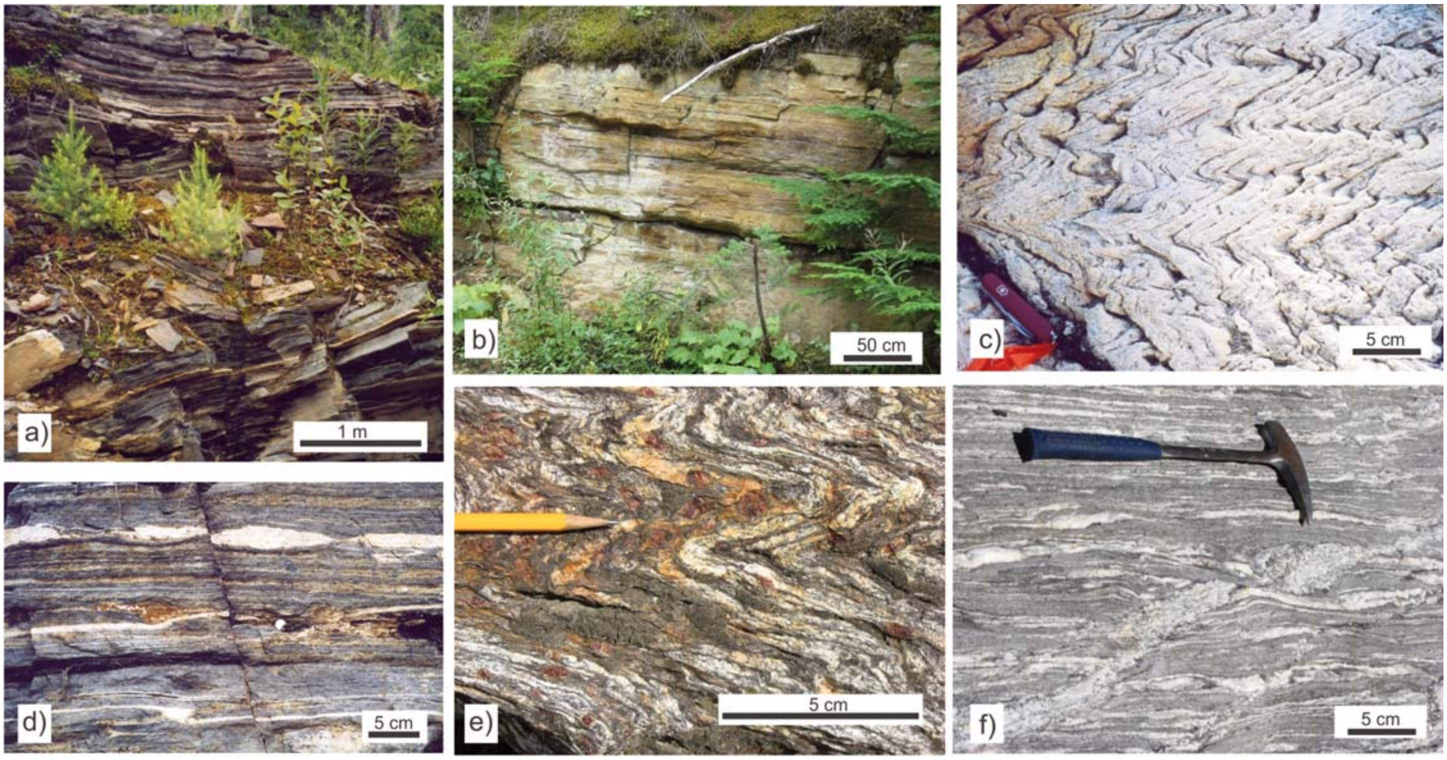

Plate 1. Illustrations of major structural styles and important geological units or lithologies throughout the structural section shown in Figures 2, 3, and 4. **(a)** Shallow south-dipping metasedimentary and calc-silicate rocks in the Plant Creek–South Fosthall area. These metamorphic rocks are typical of the mixed assemblage of upper amphibolite-facies metasedimentary and metavolcanic rocks found in the center of the study area. **(b)** Moderately south-dipping metasedimentary rocks south of the Plant Creek area showing stratigraphy parallel to foliation. **(c)** Parasitic folds in a mixed calc-silicate–marble unit in the Plant Creek area illustrating the dominant fold style in the central part of the map area. This sample is not in situ, but the outcrop folds in the same unit have axial planes dipping moderately to the south. **(d)** Boudinaged pegmatite layer in highly strained calc-silicate amphibolite in the North Fosthall area. The orientation of the boudinaged leucosome within the south-dipping foliation plane suggests elongation in an east-west direction. **(e)** Small scale folds in migmatitic Sil-Grt-Bt-bearing paragneiss at Twin Peaks illustrative of the regional fold style. These cm-scale folds have axial planes that dip steeply to the south and fold hinges that plunge shallowly to the west, similar to the regional fold closure mapped at Twin Peaks. **(f)** Migmatitic amphibolite orthogneiss at Twin Peaks with a well-developed transposition foliation. Below the hammer is a crosscutting vein of coarse-grained granitic leucosome. The leucosomes in the foliation are crosscut by this coarse-grained pegmatite vein which in turn has been deformed, illustrating the progressive nature of leucosome generation, pegmatite intrusion and deformation.

the regional km-scale folds (Fig. 2b) at Fawn Lakes and Mount Symonds. Pegmatites crosscut the transposition foliation in some instances, and are concordant with it in others indicating a combination of syn- and post-deformational intrusion of pegmatites.

The apparent age of at least some stages of tight F2 and F3 folding (Fig. 2b) and metamorphism is older than ca. 58 Ma and formed, in part, at ca. 62 Ma based on the age of metamorphic titanite (Carr 1992). The Ladybird granite west of Mount Symonds is concordant with folds in the host paragneiss and has a U–Pb zircon crystallization age for magmatic zircon of ca. 60 Ma (Vanderhaeghe et al. 1999), indicating that folding was still ongoing after that date. Metamorphism was ongoing in the Mount Symonds and North Fosthall rocks at ca. 61–60 Ma (Fig. 3) based on metamorphic ages in titanite and zircon (Carr 1995) (Fig. 3). In the Twin Peaks–Fosthall pluton area and at Mount Symonds hornblende cooling ages vary between ca. 57 and 53 Ma, and biotite cooling ages are in the 52.5–50.5 Ma range, while biotite cooling ages from Ladybird granite pegmatites are between 51 and 50.5 Ma (Van Rooyen 2013; Van Rooyen and Carr in press).

The Fawn Lakes area contains primarily migmatitic Grt-Bt-Kfs±Sil-bearing paragneiss with subordinate quartzite, amphibolite and psammite collectively mapped as the Fawn Lakes Assemblage (Carr 1991a). It is situated on the long limb of a regional scale northeast-verging F2 fold (Fig. 2b) and has a well-developed south-southwest-dipping composite transposition foliation in all units. The geometry of the panel of rocks is controlled by the enveloping surface of two phases of coaxial northeast-verging coaxial folds (Fig. 2b, Plate 1g). Metamorphism was ongoing in the Fawn Lakes rocks at ca. 61–60 Ma (Fig. 3) based on metamorphic ages in titanite and zircon (Carr 1995). At Fawn Lakes the hornblende cooling ages are similar to Plant Creek at ca. 62–58 Ma and biotite cooling ages are between 52.5 and 51 Ma (Van Rooyen 2013; Van Rooyen and Carr in press).

Cariboo Alp

The southwestern margin of the Thor-Odin dome at Cariboo Alp area is an approximately 1 km-thick structural package of highly strained rocks with a pervasive southwest-dipping transposition foliation (Plate 1h) and northeast-verging isoclinal folds (Reesor and Moore 1971; McNicoll and Brown 1995). This southwest-dipping panel of rocks is characterized by 1 x 5 km lozenges of transposed migmatitic Kfs-Sil-Grt-Bt-bearing gneiss folded and refolded by F2–F3 northeast-verging tight rootless antiforms and synforms (Fig. 2b, Plate 1i). The lozenges thin and pinch out into a high strain zone (Fig. 4) on the western, southern and southeastern flanks of the dome (McNicoll and Brown 1995). The rocks are predominantly

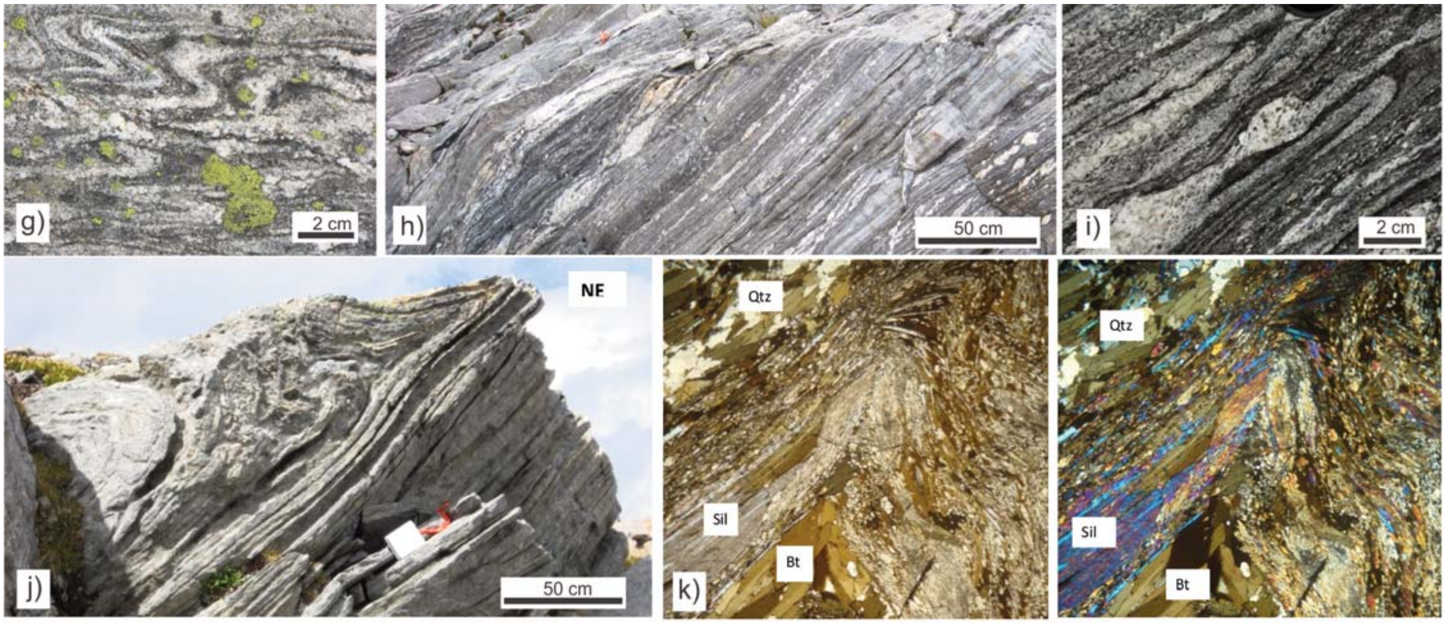

Plate 1. ***Cont'd*** **(g)** Grt-Kfs-Bt-bearing paragneiss at Fawn Lakes. The cm-scale folds show sheared out fold limbs and some coarse-grained leucosomes that are late in the transposition history. The axial plane of this fold dips steeply to the south, similar to the regional km-scale folds at Fawn Lakes and Mount Symonds. **(h)** Migmatitic Hbl-Bt-bearing orthogneiss at Cariboo Alp. Coarse-grained granitic leucosomes and boudinaged pegmatites, elongate in a northeast-southwest direction along the southwest dipping foliation planes, crosscut the transposition foliation. **(i)** Details of the grey Di-Hbl-Bt-bearing orthogneiss at Cariboo Alp. These photos show the composite transposition foliation, rootless isoclinal fold hinges, and cm-scale gneissic layering defined by biotite, diopside and hornblende alternating with quartz and plagioclase. **(j)** Fold in grey Sil-Bt-bearing quartzofeldspathic paragneiss at Cariboo Alp with axial plane parallel to the main SW-dipping transposition foliation. The fold vergence indicates a top-to-the-northeast directed sense of movement at Cariboo Alp. **(k)** Photomicrographs of Grt-Sil-Kfs-Bt-bearing paragneiss (DC184) at Cariboo Alp in plane-polarized light (left) and under crossed polars (right). The fold in this section shows a northeast-verging sense of motion, similar to the direction of motion determined from outcrop-scale folds. The section is oriented perpendicular to the northeast-southwest 'motion plane.' The folded sillimanite needles are interpreted as evidence for pre- or syn-deformational growth of the high temperature metamorphic assemblage.

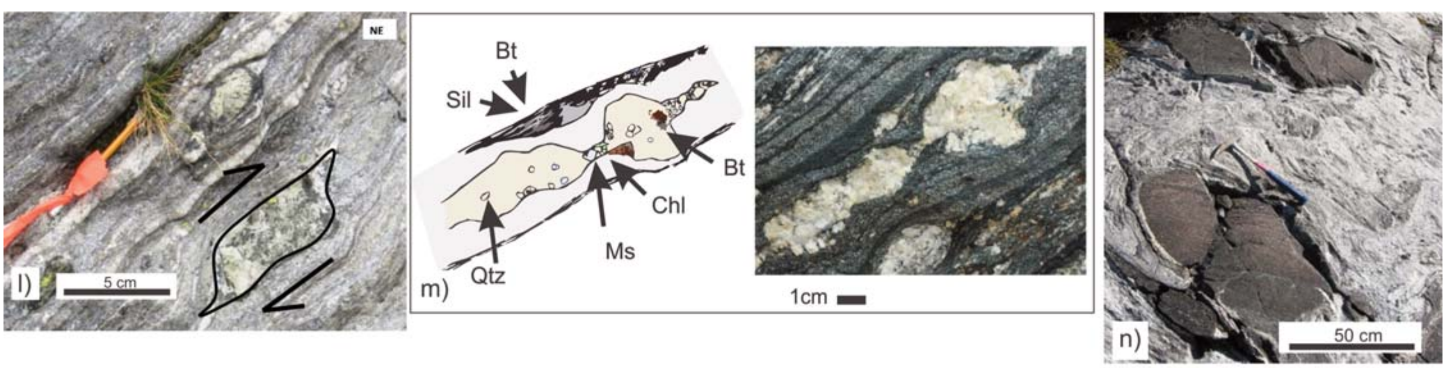

Plate 1. ***Cont'd*** **(l)** Asymmetric pressure shadows on a large diopside crystal aggregate in grey migmatitic Di-Hbl-Bt-bearing calc-silicate gneiss at Cariboo Alp. The shear sense is top-to-the-northeast, consistent with the northeast-verging folds observed at Cariboo Alp. **(m)** Muscovite crystals in leucosomes at Cariboo Alp. These muscovite (1 cm) crystals occur in pressure shadows of peritectic K-feldspar or plagioclase crystals in leucosome pods within the host migmatitic Hbl-Bt-bearing gneiss at Cariboo Alp. The muscovite is intergrown with chlorite, and interpreted as evidence for retrograde metamorphism. Both minerals are present as euhedral crystals 0.1 mm to 10 mm in diameter with sharp grain boundaries. As an alternative interpretation it is possible that the muscovite crystallized from the leucosome melt and that the chlorite overgrew it during retrograde metamorphism. This does not change the interpretation that the cooling age of the muscovite is regionally significant. **(n)** Garnet amphibolite rafts and lenses in migmatitic Grt-Bt-bearing quartzofeldspathic paragneiss at Icebound Lake.

alternating lenses and layers of grey migmatitic Sil-Grt-Kfs-Bt-bearing paragneiss and rusty migmatitic Kfs-Grt-Sil-Bt-bearing paragneiss with southwest-plunging sillimanite and hornblende mineral lineations and stretching lineations. The structural interpretation of the margin of the dome is controversial and has been interpreted as a ductile thrust-sense shear zone termed the Monashee décollement (Brown et al. 1992; McNicoll and Brown 1995), the border of a diapir (Vanderhaeghe et al. 1999, 2003; Norlander et al. 2002; Fayon et al. 2004), or as a high strain zone that formed as a result of ductile extension during normal faulting (Kruse and Williams 2007). It has also been proposed that there is no structural break at the Monashee décollement and that the highly strained rocks are part of a zone of crustal channel flow that includes both the dome and overlying rocks (Johnston et al. 2000; Williams and Jiang 2005; Kuiper et al. 2006; Williams et al. 2006).

The sense of shear interpreted from kinematic indicators and fold vergence (Fig. 2b) indicates top-to-the-northeast (Plate 1i–l) as the dominant transport direction, generally interpreted as forming in a compressional setting (McNicoll and Brown 1995). Plate 1h and 1i show details of the composite transposition foliation, such as rootless isoclinal fold hinges and cm-scale gneissic layering (Plate 1i) in the grey migmatitic Hbl-Bt-bearing orthogneiss. Primary layering, as seen in the different lithologies contained in the main paragneiss units, is concordant with the foliation. The most prominent folds at Cariboo Alp are tight to isoclinal northeast-verging F2 folds (Plate 1j and 1k). The axial planes and limbs of the F2 folds are approximately concordant with the predominant gneissic transposition foliation (Fig. 2b). The calc-silicate unit of the grey gneiss contains pressure shadows containing leucosome and hornblende around diopside (Plate 1l), indicating a top-to-the-northeast sense of movement. Shear bands are found between boudinaged pegmatite lenses and also indicate top-to-the-northeast sense of movement.

High strain deformation and the formation of the transposition fabric were coeval with metamorphism (Fig. 3) between ca. 62 and 58 Ma based on U–Pb dates in metamorphic titanite (58 ± 4 Ma) from paragneiss at Cariboo Alp (Carr 1992) and metamorphic zircon U–Pb dates (61 ± 0.5 Ma) in the Fawn Lakes Assemblage (Carr 1992). Deformation ongoing at Cariboo Alp stopped by ca. 58 Ma (Carr 1992), based on the U–Pb zircon crystallization age of an undeformed pegmatite (Fig. 3) cross-cutting the dominant transposition foliation (Carr 1992). U–Pb monazite ages from a quartzite at Cariboo Alp yielded prograde metamorphic ages of ca. 56–54 Ma with errors ranging between 1 and 4 Ma and were interpreted to represent post-deformational growth of monazite (Coleman 1990). Hornblende cooling ages at Cariboo Alp are between 55 and 53 Ma, biotite cooling ages are in the 52.5 to 50.5 Ma range, and muscovite cooling ages from leucosome within the host gneiss (illustrated on Plate 1m) and from Ladybird granite pegmatites are between 51 and 50.5 Ma (Van Rooyen 2013; Van Rooyen and Carr in press). The Cariboo Alp area represents infrastructure to the structurally higher and deactivated South Fosthall–Plant Creek zone by ca. 64 Ma. The Cariboo Alp area transitioned to being deactivated, relative to the deeper rocks within the Thor-Odin dome by ca. 58 Ma.

The Thor-Odin Dome

The Thor-Odin dome (Fig. 2) comprises a roughly 4–5 km structural thick block of polydeformed, migmatitic rocks that includes rocks with Laurentian basement affinity and supracrustal cover rocks complexly infolded with the basement rocks (Reesor and Moore 1971; Parkinson 1991, 1992; Hinchey et al. 2006 and references therein). The southern part of the Thor-Odin dome consists of migmatitic ortho- and paragneiss with a pervasive transposition foliation (Reesor and Moore 1971; Parkinson 1992; Spark 2001; Hinchey et al. 2006). The oldest structures are isoclinal folds, with limb lengths of 60–80 km involving Proterozoic Laurentian basement rocks and a cover sequence of metamorphic supracrustal rocks of uncertain age (Reesor and Moore 1971; Parkinson 1991). The large-scale domal structure is dominated by interference patterns between these early folds and three subsequent generations of folds (Fig. 2b), designated F2, F3, and F4 by Kruse et al. (2004) and Williams and Jiang (2005). The main prograde metamorphic assemblages in the migmatitic paragneiss are Grt-Sil-Kfs±Ky, with Crd±Sp forming during decompression from 8–10 kbar to 4–5 kbar after ca. 65 Ma (Norlander et al. 2002; Hinchey et al. 2006).

The following descriptions include results from Icebound Lake (this study), and Bearpaw Lake, Mount Thor, and Frigg Glacier as mapped and described by Hinchey (2005, her maps 3, 4, and 5). Icebound Lake, 1 km north of Cariboo Alp, is located on the southwestern flank of the Thor-Odin dome and represents the structurally highest rocks in the dome. The dominant diatexite migmatitic Grt-Kfs-Bt-bearing paragneiss (Plate 1n) is unconformably overlain by a southwest-dipping metasedimentary package dominated by Kfs-Sil-Grt-Bt-bearing paragneiss (Figs. 2b, 4), with a distinct layer of quartzite near the base of the package. There are well developed moderately southwest-dipping composite transposition foliations in metasedimentary rocks. These rocks are interpreted to be part of a southwest-dipping panel of transposed rocks on the lower limb of a regional southwest-dipping overturned synform, following the interpretation of Reesor and Moore (1971) and subsequently Williams and Jiang (2005) (Fig. 2b).

At Bearpaw Lake the dominant lithologies are migmatitic Hbl-Bt-bearing orthogneiss and migmatitic Grt-Sil-Bt-Kfs-bearing paragneiss containing abundant leucosome (Hinchey and Carr 2007). At Mount Thor, the dominant rock type is migmatitic Hbl-Bt-bearing orthogneiss, which is interpreted to be unconformably overlain by a heterogeneous package of moderately northeast-dipping metasedimentary rocks with a quartzite layer at its base (Reesor and Moore 1971; Duncan 1984; Spark 2001; Hinchey 2005). The Mount Thor area is located on the lower limb of a regional scale F2 northwest-verging fold (Fig. 2a) (Reesor and Moore 1971; Spark 2001; Hinchey 2005) (Fig. 2a). At Frigg Glacier, of the structurally deepest rocks exposed in Thor-Odin, the dominant lithologies are migmatitic Hbl-Bt-bearing orthogneiss and migmatitic Kfs-Hbl-Bt-bearing granodiorite; both containing abundant leucosome, with minor amphibolite boudins present throughout the area and the dominant structures are transposed foliations (Hinchey 2005).

Northeast-verging isoclinal F1 folds and tight, asymmetric, coaxial F2 and F3 folds generally dip to the southwest on the southwestern flank of the dome. All areas of the Thor-Odin dome and overlying rocks were affected by F4 folds (Fig. 2b); broad, upright folds which arch older structures. In the rocks overlying the Thor-Odin dome this folding did not significantly alter the map pattern created by F3 folds, but in the Thor-Odin dome itself, F4 folding was in part responsible for the outward-dipping domal geometry of the culmination (Williams and Jiang 2005) (Fig. 2b). In other words, the shape of the Thor-Odin dome is interpreted as a result of the interference pattern (Fig. 2b) between the late F4 and the dominant Eocene age F2–F3 structures within the dome (Hinchey 2005; Williams and Jiang 2005).

While there is no firm date for the onset of prograde metamorphism, it is likely that metamorphism was ongoing by the Paleocene to Eocene (Fig. 3), between ca. 65 and 56 Ma (Norlander et al. 2002; Hinchey et al. 2006). Monazite growth over a period of 62.3 ± 3 Ma to 50.1 ± 2 Ma (Coleman 1990; Hinchey and Carr 2007) has been interpreted as evidence for a protracted period of metamorphism. Monazite growth and recrystallization can occur over a wide range of temperatures in different lithologies and these ages do not necessarily represent peak metamorphic conditions (Parrish 1990; Spear 1993; Crowley and Parrish 1999; Gibson et al. 2004; Cubley et al. 2013). Monazite is predicted to be unstable above the Ms + Qtz = Sil + Kfs + melt reaction boundary (Cubley et al. 2013) and monazite growth in the migmatitic assemblages of the

Thor-Odin dome is therefore likely to represent post-peak metamorphism.

Deformation in the Thor-Odin dome interior was ongoing ca. 56–54 Ma as determined by U–Pb igneous zircon crystallization ages in deformed leucosomes (Hinchey et al. 2006). The age of at least some stages of isoclinal folding (Fig. 2b) and prograde metamorphism is as young as ca. 56–54 Ma (Norlander et al. 2002; Hinchey et al. 2006). Deformation ended between ca. 54 and 52.5 Ma (Hinchey et al. 2006), based on zircon U–Pb crystallization ages in undeformed leucosomes. Biotite cooling ages from the Icebound Lake area on the flank of the dome are between 52 and 51 Ma, and from the interior of the dome between 53 and 52 Ma, while muscovite cooling ages from Ladybird granite pegmatites at Icebound Lake are between 51 to 50.5 Ma (Van Rooyen 2013; Van Rooyen and Carr in press). The rocks of the Thor-Odin dome are estimated to have been exhumed from a depth of 26–33 km based on estimates of peak metamorphic pressures between 8 and 10 kbar (Norlander et al. 2002). When the rocks in the overlying Cariboo Alp area were structurally deactivated ca. 58 Ma, the rocks of the dome were still being penetratively deformed in the infrastructure. The Thor-Odin rocks were structurally deactivated during the ca. 54–52.5 Ma period when penetrative deformation ended. It is interesting to note that penetrative deformation in the Frenchman Cap dome north of Thor-Odin continued after ca. 52 Ma until ca. 49 Ma (Crowley 1999). Therefore, it is permissible to suggest that the Thor-Odin dome represents a higher structural level of infrastructure that was deactivated relative to the deeper rocks in the Frenchman Cap dome after ca. 52.5 Ma (Figs. 4, 5).

LATE CRETACEOUS TO EOCENE INTRUSIVE ROCKS – THE LADYBIRD GRANITE SUITE AS A STRAIN MARKER AND CONSTRAINT ON AGE OF DEFORMATION

The peraluminous, anatectic Ladybird granite suite is the dominant igneous suite in the Thor-Odin–Pinnacles area (Carr 1990, 1991a; Hinchey and Carr 2006). The largest intrusion of Ladybird granite in the area is the South Fosthall pluton, a roughly 4–5 km thick composite laccolithic complex where sheets of granite or pegmatite are concordant with the metasedimentary layers comprising the country rock (Carr 1990). The U–Pb zircon crystallization ages for the Ladybird granite range between ca. 64 and 52 Ma and are generally older towards the south in the Valhalla complex (Parrish et al. 1988) and the Grand Forks complex (Parrish 1992; Cubley et al. 2012, 2013). The youngest pegmatites related to the Ladybird granite are tourmaline-bearing and may locally be as young as ca. 50 Ma on the western margin of the Thor-Odin dome (Johnston et al. 2000).

Carr (1990) and Vanderhaeghe (1999) presented evidence of strain variations and strain partitioning within the South Fosthall pluton and surrounding Ladybird granite, indicating that the Ladybird granite was intruded, in part, while penetrative deformation was ongoing. This is consistent with observations in this study that some of the pegmatites in the Icebound Lake, Cariboo Alp, Fawn Lakes, and North Fosthall areas, including Twin Peaks and Mount Symonds, were deformed concordantly with the host rock, indicating that they experienced at least the last increment of deformation together. Other pegmatites of the area crosscut the fabrics in the host

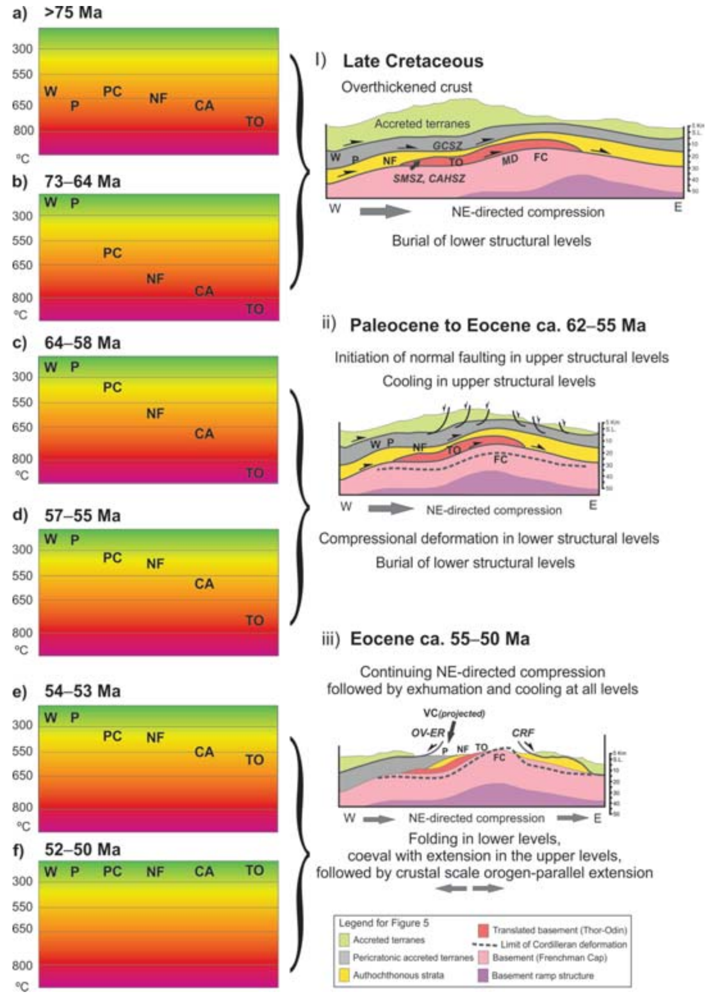

Figure 5. Illustration of the thermal evolution of the Thor-Odin–Pinnacles area as discussed in the text. The thermal cartoons on the left show the times at which different structural levels (as represented by specific study areas) passed through particular temperature ranges of 900°C for zircon crystallization, 650°C for wet granite solidus (Spear 1993), 550–570°C for argon closure temperature in hornblende, and 320–330°C for argon closure temperature in biotite (details about closure temperatures in Van Rooyen and Carr in press). They illustrate the simultaneous exhumation of some areas and burial of structurally deeper ones, based on metamorphic temperatures determined for various areas, and on $^{40}Ar/^{39}Ar$ cooling ages summarized in the text. They also illustrate the increased cooling rates in the lower structural levels, interpreted as resulting at least in part from the transport of these rocks over a basement ramp during NE-directed compression. The sketch cross-sections on the right show the general physical configuration of the area during different times and note important events and changes in deformation styles. (SMSZ – Slate Mountain Shear Zone; CAHSZ – Cariboo Alp High Strain Zone; CRF – Columbia River fault zone; OV–ER – Okanagan Valley–Eagle River fault zone; GCSZ – Gwillim Creek shear zone).

rocks and appear undeformed. The pegmatites in the Plant Creek area, in the upper part of the structural section, crosscut all the fabrics in the host rocks, indicating that the host rocks were not actively deforming during pegmatite intrusion. As mentioned in the preceding sections, muscovite and biotite cooling ages from Ladybird pegmatites are consistently between 51 and 50.5 Ma indicating rapid cooling in pegmatites throughout the area (Van Rooyen 2013; Van Rooyen and Carr in press).

The South Fosthall pluton is located between the shallowly east-dipping Columbia River fault and the moderately west-dipping Beaven fault. The structures in the South Fosthall pluton occur primarily as shallowly east-dipping mylonitic fabrics on the eastern side of the pluton, linked to the east-dipping Columbia River fault and, on the western side of the pluton, west-dipping directed mylonitic fabrics and shear zones are linked to the west-dipping Beaven fault (Parrish et al. 1988; Carr 1991b; Vanderhaeghe et al. 2003). Field relations and U–Pb zircon crystallization ages (by TIMS) in the east-dipping mylonitic fabric overprinting NE-directed compressional structures indicate that the Columbia River fault was actively deforming the Ladybird granite at 55.1 ± 1.5 Ma (Parrish et al. 1988), interpreted at the time as the earliest evidence of extensional activity on the Columbia River fault.

The South Fosthall pluton is one of several examples of laccolithic composite bodies of intrusive granite in the Eastern Internal zone of the Canadian Cordillera. The Pukeashun granite, an anatectic leucogranite suite of Eocene age, ca. 56 Ma, located to the northwest of the Thor-Odin dome in the Shuswap Lake transfer zone (SLTZ, Fig. 1) between the North Thompson–Adams and Okanagan Valley–Eagle River fault systems, occupies a similar structural setting as the Ladybird granite (Johnson 2006). The Ladybird granite is also present as a laccolithic complex of sheet-like bodies in the Valhalla complex south of Thor-Odin–Pinnacles, intruded between ca. 59 and 56 Ma (Carr et al. 1987), where the upper margin of the granite bodies coincide, in part, with the Valkyr Shear Zone, a zone of ductile deformation that is cut by the younger east-dipping Columbia River and the Slocan Lake normal faults (Carr 1995). Johnson (2006) suggested that the South Fosthall pluton, the Pukeashun granite and the Ladybird granite in the Valhalla complex, all occupy step-over zones between sets of extensional normal faults (Fig. 1), and that the distribution of these granite bodies may be linked to the presence of releasing zones in basement ramps. The emplacement of granite was localized in low-angle extensional shear zones, providing a weak rheology in which deformation was concentrated during extension (Johnson 2006).

DIACHRONOUS METAMORPHISM AND DEFORMATION IN THE THOR-ODIN–PINNACLES AREA; INFRASTRUCTURAL ZONES MIGRATING THROUGH TIME

The rocks of the Thor-Odin–Pinnacles area discussed in this study experienced protracted (but not necessarily continuous) deformation and metamorphism throughout the Cretaceous to Paleocene and into the Eocene, possibly overprinting Early Cretaceous or older events. We identify the time at which belts of rocks were penetratively deforming in the infrastructure, and when the formation of transposition foliation ended, and when the rocks cooled (Van Rooyen 2013; Van Rooyen and Carr in press). In the area between the Thor-Odin dome and the Whatshan batholith, the timing of tectonothermal events is younger structurally downwards, reflecting the downward migration of the active infrastructure boundary through time, in combination with upwards migration of rocks and NE-directed transport towards the foreland. Metamorphic grade generally increases downwards throughout the structural section into the dome. Based on data compilation which includes timing of metamorphism, deformation, anatexis in basement rocks, and intrusion of leucogranite, at least four belts of rocks, or tectonothermal domains, are recognized that experienced regional metamorphism and deformation at different times, with cooling rates that increase downward into the section (summarized below and on Figures 3 and 4).

Metamorphism in each structural level was broadly coeval with the penetrative ductile deformation, with thermal peak metamorphism predating the end of deformation. However, the timing of the onset of prograde metamorphism is uncertain. Periods of prograde metamorphism are recorded from ca. 130–90 Ma in rocks of the Whatshan area (Glombick 2005) continuing to sometime before ca. 75 Ma (Carr 1992); ca. 100–80 Ma in the Plant Creek–South Fosthall area (Lemieux 2006) and continuing to ca. 64 Ma (Carr 1992); ca. 73–62 Ma in the North Fosthall–Mount Symonds area (Carr 1991b, 1992); ca. 65–58 Ma at Cariboo Alp (Coleman 1990; Carr 1991b, 1992); and ca. 65–56 Ma in the Thor-Odin dome (Norlander et al. 2002; Hinchey et al. 2006, 2007).

Penetrative deformation progressively young down-section; from >75 Ma at the top in rocks of the Whatshan area (Carr 1991b, 1992), to ca. 56–54 Ma within the Thor-Odin dome (Hinchey et al. 2006) at the bottom, and represents progressive heating and deformation migrating downwards due to burial, radiogenic heating, incubation and structural weakening of structurally lower rocks. The rocks of the Whatshan–Pinnacles area were polyfolded in the Late Cretaceous (pre-ca. 75 Ma) and represent the infrastructure before ca. 75 Ma. They preserve Cretaceous metamorphism and deformation and were not remobilized during Late Paleocene to Eocene north-east-directed transport. At ca. 75–64 Ma, the Whatshan–Pinnacles area rocks were deactivated and acted as suprastructure to the underlying Plant Creek–South Fosthall area rocks, from the central part of the tract structurally above the South Fosthall pluton. This central part of the section was being penetratively deformed within the infrastructure at this time. After ca. 64 Ma, the Plant Creek–South Fosthall area rocks were deactivated, as demonstrated by the timing of the end of penetrative deformation. Rocks in the lowest part of the tract, below the South Fosthall pluton (i.e. Mount Symonds–Cariboo Alp area) continued to be deformed after ca. 64 Ma. After ca. 58 Ma the lowest part of the tract, the Mount Symonds–Cariboo Alp area, was no longer active relative to the infrastructure now comprised of the deforming rocks in the Thor-Odin dome. The Thor-Odin dome rocks remained in the infrastructure until ca. 52 Ma.

Hornblende cooling ages (for a closure temperature of ca. 550–570°C for the grain sizes and cooling rates in the study area – see Van Rooyen and Carr in press) span about 12 m.y.; ca. 62–58 Ma in the Plant Creek–South Fosthall area; ca. 57–55 Ma in the North Fosthall area; and 55–53 Ma on the upper margin of the dome at Cariboo Alp. Biotite cooling ages (for a closure temperature of 320–330°C) are all between 52.5 and 50.5 Ma throughout the entire structural section including the Thor-Odin dome, regardless of lithology, (including Ladybird pegmatites), indicating that the entire panel of rocks cooled through the closure temperature for biotite as a unit (ca. 320–330°C; see calculations in Van Rooyen and Carr in press). Muscovite cooling ages from Ladybird pegmatites are between 51.5 and 50.5 Ma from all parts of the structural section (for a closure temperature of 450–465°C – see calculations in Van Rooyen and Carr in press), indicating that the pegmatites all cooled at the same time regardless of structural position, and all cooled slightly later than their host rocks. This cooling history shows differential cooling rates throughout the study area, with rates increasing towards the deeper part of the section into the Thor-Odin dome. Cooling in the upper structural levels (as is the case with deformation and metamorphism already discussed) was coeval with deformation and anatexis in the lower structural levels, and the early cooling front (represented by hornblende cooling ages) migrated progressively down into the section. However, since the entire section has the same biotite and muscovite cooling ages, the area can be characterized as having experienced a major period of cooling and exhumation after 56–55 Ma, after which the tilted crustal section represented by this study area passed through the closure temperature for argon in biotite and muscovite close together in the period around 52–50 Ma. This interpretation is illustrated in Figure 5 as a thermal time series which shows the different times at which different study areas passed through particular temperatures. Figure 4 summarizes the times at which the different structural levels in the study area were actively deforming in the infrastructure and when they were deactivated.

HYBRID MODEL FOR THE EVOLUTION OF THE FRENCHMAN CAP – THOR-ODIN–PINNACLES TECTONOTHERMAL CULMINATIONS

As summarized in the introduction to this study, the formation of tectonothermal culminations in the southern Canadian Cordillera is primarily discussed in terms of diapirism, horizontal channel flow, or thrust-related deformation (cf. Carr and Simony 2006). In this section, we discuss the possible contributions of these mechanisms to the tectonic evolution of the Thor-Odin–Pinnacles area in the Late Cretaceous to Eocene.

It has been proposed that the driving force for the exhumation of Thor-Odin dome was gravitational instability created by the presence of anatectic melt and the subsequent ascent of partially molten crust in the core of the dome as a diapir (Vanderhaeghe et al. 1999, 2003; Norlander et al. 2002; Fayon et al. 2004; Teyssier et al. 2005). Evidence for decompression melting in the Thor-Odin dome (specifically the Bearpaw Lake area, Fig. 2) was reported by Norlander et al. (2002). Rocks underwent decompression from 8–10 kbar in the kyanite zone to 4–5 kbar, which equates to exhumation from ca. 25–33 km to ca. 15 km depth. These authors have suggested that this occurred as isothermal or near-isothermal decompression with coeval anatexis, based on reaction textures, mineral assemblages, and the extensive presence of anatectic melt in the rocks.

Models for the Thor-Odin dome invoking diapirism, delineated Cariboo Alp (Vanderhaeghe et al. 1999; Teyssier et al. 2005) as a possible boundary along which the dome is exhumed. In thermochronological studies of core complexes, as well as in numerical modelling, cooling ages always young towards the extensional shear zone (Tirel et al. 2006, 2008; Sullivan and Law 2007), which is the case here only for hornblende, not biotite or muscovite. Based on the hornblende and biotite cooling ages (Van Rooyen 2013; Van Rooyen and Carr in press), in combination with the timing of metamorphism and deformation, the geometry of the southwest-dipping package of rocks with their southwest-dipping transposition foliation in Cariboo Alp was likely formed before the Eocene cooling and exhumation of the dome. Movement along the Cariboo Alp area must have taken place at temperatures higher than 550–570°C (upper estimate of hornblende Tc), and before ca. 58 Ma (end of formation of transposition foliation), after which rocks on both sides equilibrated and cooled together to ca. 320–330°C by ca. 52 Ma. The Cariboo Alp area therefore did not accommodate km-scale extension or significant reactivation related to exhumation during the Eocene. Not only is the Cariboo Alp area not a major post-metamorphic extensional fault, it was also not involved in the exhumation of the dome, as discussed above.

Rey et al. (2009) proposed that one of the driving forces behind the formation of migmatite-cored tectonothermal culminations is the interplay between extension rates and the amount of melt present in the crust during extension. In two-dimensional thermal-mechanical modelling Rey et al. (2009) demonstrated that the fraction of melt present in the deeper structural levels of the crust during extension coupled with differences in extension rates produces domal structures with different characteristics. Their models showed that when extension rates are fast ($2*10^{-16}$/s, equivalent to 25.5 mm/y) domes are produced with weakly deformed migmatitic cores where migmatite crystallizes at low pressures (e.g. the Thor-Odin dome), and in settings where extension is slower ($2*10^{-15}$/s, equivalent to 0.85 mm/y), the cores of domes preserve pre-exhumation structures and crystallization of migmatite at depth (e.g. the Ruby Mountain–East Humboldt Range in Nevada). Increasing the melt fraction present produces faster exhumation rates and more extensive isothermal decompression (Rey et al. 2009).

As discussed earlier, the core of the Thor-Odin dome is not composed purely of diatexite migmatite and actually preserves significant NE-verging structures that developed during NE-directed transport toward the foreland. Some aspects of the Thor-Odin dome certainly reflect rapid melt ascent and crystallization at low pressure with fast extension rates as described in the model by Rey et al. (2009), such as a period of near-isothermal decompression between ca. 56 and 52 Ma (Norlander et al. 2002; Hinchey et al. 2006). In addition, the fast cooling rates predicted for domes like this (ca. 35–65°C/km) are actually lower than the rates suggested for the Thor-Odin dome (>100°C/km; Van Rooyen 2013; Van Rooyen and Carr in press). However, the cooling rates for the areas that structurally overlie the core of the dome also match or exceed the proposed rates but the pre-exhumation history and NE-verging structures are preserved in coherent stratigraphic successions. We propose that the Thor-Odin dome, therefore, preserves at least in part a history of pre-exhumation structural development that is not completely overprinted by Eocene anatexis and exhumation, as would be expected in a dome formed by diapiric ascent as the dominant process. In particular, the documented polyphase folding of leucosomes in the Thor-Odin dome (Hinchey et al. 2006) precludes this interpretation and the complexity of the infrastructure transitions and the cooling history of the rocks in the footwall of the Columbia River fault zone in the Thor-Odin–Pinnacles area are not consistent with the interpretation of the Thor-Odin dome as a diapir. The dome is best interpreted as a fold interference structure (Williams and Jiang 2005; Hinchey et al. 2006), perhaps amplified by some buoyancy effect, but the preservation of NE-directed compressional structures is not consistent with that of a diapir.

A variant of gravity-driven models to explain domal geometries presented by Rey et al. (2011) relates to so-called 'double domes,' where the main domal culmination contains two sub-domes, separated by a steeply dipping high strain zone, illustrated specifically in the Naxos dome in Greece, and the Montagne Noire in France. In two-dimensional thermal-mechanical modelling these double domes, of which the Thor-Odin dome could be an example, develop during initial convergence where crustal flow is primarily horizontal followed by the rotation of this flow in an upward direction during extension (Rey et al. 2011). Based on currently available data and the interpretations presented in this study, the Thor-Odin dome does not seem to be a good candidate for developing through the double dome model of Rey et al. (2011) because there is currently no good estimate for where the steep dividing shear zone would be. The dominant steep features in the Thor-Odin area are N–S striking, steep to near-vertical brittle faults (some dextral strike-slip, some normal) that post-date and dismember metamorphic sequences (Kruse and Williams 2007; Kuiper et al. 2015) and largely reflect extension after peak metamorphism and subsequent exhumation.

Another category of tectonic mechanisms proposed in the Cordillera to form tectonothermal culminations involves ductile extrusion and channel flow (Johnston et al. 2000; Williams and Jiang 2005; Brown and Gibson 2006; Glombick et al. 2006; Kuiper et al. 2006; Gervais and Brown 2011), in which mid-crustal rocks flow in a channel and are bounded by two opposite-verging shear zones at the top and base, active at the same time. The Frenchman Cap dome, immediately to the north of the Thor-Odin dome (Fig. 1) has been extensively studied with respect to exhumation mechanisms and deformation history. Crowley et al. (2008) and Gervais et al. (2010) documented the preservation of ca. 1.85 Ga Proterozoic deformation, metamorphism, and magmatism in the deepest exposed basement rocks of the Frenchman Cap dome, approximately 1.5 km structurally below the basal quartzite of the cover rocks. The uppermost 1.5 km of these Proterozoic rocks preserve a Cordilleran thermal overprint documented by monazite growth, but no documented Cordilleran deformation. Below the thermal overprint all recorded events are Proterozoic in age, and include ca. 1.9 Ga metamorphism and deformation, and 1.85 Ga igneous intrusions by the Bourne Granite suite. The preservation of Proterozoic deformation in the core of the Frenchman Cap dome indicates that it could not have formed as a result of vertical diapiric rise of partially molten crust (Crowley et al. 2008; Gervais et al. 2010), as proposed for the Thor-Odin dome (Vanderhaeghe et al. 1999, 2003; Norlander et al. 2002; Fayon et al. 2004; Teyssier et al. 2005) and the Okanogan dome (Kruckenberg et al. 2008). As is the case in the Frenchman Cap dome, the preservation of extensive folded and refolded migmatites and the presence of generally NE-directed deformation fabrics in the Thor-Odin dome are inconsistent with diapirism as the sole mechanism of exhumation.

Gervais and Brown (2011) proposed a model of formation for the Frenchman Cap dome that is based in the sequential extrusion of mid-crustal material up a basement ramp, in which the Monashee décollement represents the lower boundary of a mid-crustal channel and the Okanagan Valley–Eagle River Fault represents the upper boundary, or lid, of the channel. In this model, the rocks of the Lower Selkirk Allochthon (taken to be equivalent to the rocks between Thor-Odin and Pinnacles) were exhumed while the underlying Monashee complex rocks were being buried. Movement on the east-verging Monashee décollement in the Frenchman Cap dome was coeval with amphibolite-facies metamorphism (forming kyanite and K-feldspar) and penetrative ductile deformation between ca. 60 and 55 Ma (Parrish 1995; Crowley and Parrish 1999; Crowley et al. 2001; Gibson et al. 2004). The main period of formation for north-northeast-directed folds and transposition foliations in a top-to-the-east shear zone in the Frenchman Cap dome was between ca. 53 and 49 Ma (Crowley et al. 2001; Gervais et al. 2010) (Fig. 4).

Despite documented differences in the pressures, temperatures, and deformation histories of the Frenchman Cap dome and the Thor-Odin dome discussed elsewhere (Hinchey 2005; Gervais 2009) some aspects of the evolution of the Thor-Odin dome are broadly similar in the Frenchman Cap dome. Specifically, the thermochronology data showing that the upper structural levels (e.g. Plant Creek area) were being cooled through 550°C while the lower levels were being penetratively deformed, followed by crustal scale extension over the whole area, is kinematically consistent with the channel flow model for Frenchman Cap discussed by Gervais and Brown (2011). Carr and Simony (2006) argued against a full model of channel flow in the southeastern Canadian Cordillera and have suggested instead that channel flow was active for a short duration and was arrested before extrusion occurred; however, the duration of channel flow or the extent to which the channel extruded in either dome does not affect the major conclusions of this work. In subsequent work, Simony and Carr (2011) presented a model in which sequential ductile thrusts in the hinterland of the Cordillera can be linked to major thrust faults in the foreland fold and thrust belt that suggested that channel flow is not a necessary mechanism in the SE Cordillera and that the deformation histories can be explained by internal deformation in crystalline thrust sheets.

We propose in this study that the Thor-Odin dome–Pinnacles area is best viewed as a coherent crystalline thrust sheet that was transported and shortened during NE-directed compression (Fig. 5). During this process it was transported up a basement ramp (analogous to the Frenchman Cap dome), during which the ages of metamorphism and penetrative deformation young downwards into the section as progressively lower levels get heated and deformed (Fig. 5). This type of transport of ductile rocks over basement ramps has also been documented for the Valhalla dome south of Pinnacles, where the Gwillim Creek shear zone represents a major ductile shear zone and represents the top of a series of Late Cretaceous to Eocene belts of younging-downward infrastructure (Carr and Simony 2006; Hallett and Spear 2011; Simony and Carr 2011), consistent with the transitions documented in this study. The Gwillim Creek shear zone is known to have transported rocks over a basement ramp (Hallett and Spear 2011) and it was suggested by Simony and Carr (2011) that this type of transport is a mechanism that can be extended to the Thor-Odin dome. The Gwillim Creek shear zone was active between ca. 90 Ma and 60 Ma and is interpreted to have transported a coherent crystalline thrust sheet during NE-directed compression in the Cretaceous, with displacements of 80–100 km (Carr and Simony 2006). It was active during a period of thickening of the orogen in the Late Cretaceous, which allowed for metamorphism and deformation in the rocks above the nascent shear zone, which were then transported up a basement ramp during Paleocene northeast-directed compression and cooled against a cold basement footwall (Hallet and Spear 2011). The hanging wall of the Gwillim Creek shear zone records a downward-increasing strain gradient through an approximately 30 km-thick thrust sheet, which contains (among others) Jurassic to Cretaceous intrusive rocks (Simony and Carr 2006). The downward-increasing strain gradient reflects the progression of deformation through the structural section; penetrative deformation youngs downward throughout the section, preserving the youngest deformation in the lowermost structural levels. This is similar to the general progression of deformation and metamorphism in the Thor-Odin–Pinnacles area described in this study. The Gwillim Creek shear zone is cut by the 59–55 Ma, extensional Valkyr-Slocan Lake fault system (Carr and Simony 2006), which is analogous to the Columbia River fault zone in the Thor-Odin–Pinnacles area. We suggest that the Thor-Odin–Pinnacles area may host an analogue for the Gwillim Creek shear zone in the Pinnacles culmination, where a thrust-sense ductile fault marks the approximate transition between deformation in the period between 75 and 64 Ma in the Whatshan–Pinnacles area, and after ca. 64 Ma in the Plant Creek area. In this area, the Slate Mountain Shear Zone and Cariboo Alp High Strain Zone (Figs. 2, 4, and 5) may be additional shear zones accommodating NE-directed compression on which overlying thrust sheets were carried over and incubated at structurally deeper levels. Extending this model to the Frenchman Cap dome, we suggest that the Monashee décollement carries rocks over the Frenchman Cap dome in the same manner, consistent with Gervais et al. (2010) and Gervais and Brown's (2011) model of sequential extrusion of mid-crustal rocks above a basement ramp.

CONCLUSIONS

In our view, it is not appropriate to look only at the core of the Thor-Odin dome to evaluate possible mechanisms for its formation; the structurally overlying panel (here illustrated as the area between the dome and the Whatshan batholith) has to be taken into account as well. When this area is viewed as a whole, the preferred model for the evolution of the Thor-Odin–Pinnacles area suggested by this study is, therefore, a hybrid model in which the primary tectonic process driving deformation and metamorphism was crustal thickening in a convergent setting (Fig. 5). Diapirism and gravity-driven buoyant exhumation of deep crustal rocks were definitely important factors in the exhumation of some of the rocks of this area (Norlander et al. 2002); however, the structural styles in the rocks dictate that they were limited in duration and spatial extent to areas in the core of the Thor-Odin dome. The rocks of the Thor-Odin–Pinnacles area were progressively heated and deformed as a result of crustal thickening as they were transported to the east to northeast over a basement ramp in the Late Cretaceous to Paleocene (cf. Gervais et al. 2010; Hallett and Spear 2011).

The top of the section (Whatshan to Pinnacles to South Fosthall) was the first to be penetratively deformed, and also the first to be deactivated. The structural style in the Whatshan–Pinnacles area is sufficiently different from that in the Plant Creek to Mount Symonds areas that the Whatshan–Pinnacles area is interpreted here as analogous to the upper plate of the Gwillim Creek shear zone as exposed in the Valhalla complex to the south, here represented by the South Fosthall to Mount Symonds areas. The structurally lowest part of the section in the core of the Thor-Odin dome hosts the youngest penetrative deformation, and was the last to be deactivated. This downward-younging progression continues into the Frenchman Cap dome, where the last increments of NE-directed deformation and transposition were coeval with cooling and deactivation in Thor-Odin. Compression-driven deformation in Frenchman Cap dome continued to ca. 49 Ma, after which it was also deactivated. The initial cooling to below ca. 550–570°C between 62 and 58 Ma in the upper part of the section (Pinnacles to South Fosthall) occurred as a result of syn-convergent exhumation of the suprastructure. The switch to cooling across the whole area, linked to crustal-scale extension, occurred only when the Columbia River fault cut across the entire crustal section, when all the rocks in the Thor-Odin–Pinnacles area cooled through ca. 320–330°C as a unit between ca. 52.5 and 51 Ma. This crustal scale extension marked the beginning of a period of intrusion by mantle-derived igneous rocks throughout the southeastern Canadian Cordillera (Adams et al. 2005) in an extensional tectonic regime.

In conclusion, the rocks between the Whatshan–Pinnacles area and the interior of the Thor-Odin dome record Cretaceous metamorphism and cooling in the upper structural levels, and three stages of infrastructural flow at progressively deeper crustal levels in the Late Cretaceous, Paleocene and Eocene. The generally downward-younging progression of metamorphism and deformation, as well as the structural style and transposition foliation in the lower part of the section, is consistent with a model in which rocks were progressively heated and deformed during compressional transport, possibly up a basement ramp, which facilitated doming and exhumation. This is the first study to discuss this area in terms of infrastructure transitions and to explain contrasting histories in different parts of the Thor-Odin–Pinnacles area. This framework makes it possible to explain seemingly conflicting geological histories in adjacent areas while linking the different histories into an internally consistent geological model, and can potentially be applied to complex orogenic belts in multiple tectonic settings.

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SERIES

Great Canadian *Lagerstätten* 5. Crawford Lake – A Canadian Holocene Lacustrine *Konservat-Lagerstätte* with Two-Century-Old Viable Dinoflagellate Cysts

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SUMMARY
In addition to commonly preserved microfossils like pollen and diatoms, the varved sediments of Crawford Lake, Ontario, contain the fossilized remains of otherwise rare microfossils. Bottom water anoxia resulted from the physiography of this small, deep lake and enhanced biochemical oxygen demand (BOD) during two distinct phases of human settlement: prehistoric Iroquoians (approximately 1268–1486 CE) and historic Euro-Canadians (since 1822 CE). The exceptional preservation of delicate organic-walled microfossils like rotifer loricae and cellulosic dinoflagellate thecae provides unparalleled insights into a Holocene freshwater lake ecosystem and allows the biological and taphonomic components of the fossil assemblage to be isolated. Bottom water anoxia may also have increased the longevity of cell contents: resting cysts of *Parvodinium [Peridinium] inconspicuum* (Lemmermann) Carty and *Peridinium volzii* Lemmermann. These were germinated from varves deposited nearly two centuries ago, extending the known span of viability of dinoflagellates.

RÉSUMÉ
En plus des microfossiles couramment conservés comme le pollen et les diatomées, les sédiments varvés du lac Crawford en Ontario, contiennent les restes fossilisés de microfossiles très rares. Le caractère anoxique des eaux de fond s'explique par la physiographie de ce petit lac profond et par une augmentation de la demande biochimique en oxygène (DBO) durant deux phases distinctes de peuplement humain : phase préhistorique iroquoienne (environ 1268 à 1486 CE) et une phase historique euro-canadienne (depuis 1822 CE). La préservation exceptionnelle de délicats microfossiles à membranes organiques comme rotifère lorica et les thèques cellulosiques de dinoflagellés, ouvre une fenêtre inédite sur l'écosystème d'un lac d'eau douce Holocène et permet aux composants biologiques et taphonomiques de l'assemblage de fossiles d'être préservés isolément. L'anoxie des eaux de fond peut également avoir augmenté la longévité du contenu des cellules: kystes dormants de *Parvodinium [Peridinium] inconspicuum* (Lemmermann) Carty et de *Peridinium volzii* Lemmermann. Ces derniers ont été activés à partir de varves déposés il y a près de deux siècles, ce qui allonge la durée connue de la viabilité des dinoflagellés.

Traduit par le Traducteur

INTRODUCTION
The concept of *Konservat–Lagerstätten* is virtually absent from the Holocene literature (Allison and Briggs 1993), despite the fact that exceptionally preserved deposits would serve as an important quantifiable bridge between biological and paleontological records. Several examples of exceptionally preserved large mammals, like mammoths and bison, have been reported from permafrost, prehistoric human remains have been found in glaciers (e.g. Ötzi from the Eastern Alps and Kwäday Dän Ts'ìnch from the British Columbia Rockies) and peat bogs (*Moorleiche* like Tollund Man and Lindow Man; Painter 1991and Oeggl et al. 2007), and concentrations of desiccated remains of plants and animals (*Konzentrat–Lagerstätten*) are known from cave deposits of various ages, including the Holocene. Examples of *Lagerstätten* representing a large fraction of the biocoenosis in modern lakes are rare, however, despite their relative abundance and the critical importance of freshwater resources.

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Lakes tend to be characterized by continuous and relatively rapid sedimentation conducive to excellent paleontologic resolution (Schindel 1980) and lacustrine *Lagerstätten* such as the Eocene Green River Shale (Bradley 1931; Grande 1980; Buchheim and Surdham 1981), the Oligocene Enspel 'oilshale' (Köhler and Clausing 2000; Poschmann et al. 2010), and the Miocene Clarkia Beds (Smiley and Rember 1981, 1985; Batten et al. 1999) provide exceptional insights into ancient continental environments. Long-term (pre-instrumental) environmental trends can be assessed through paleolimnology, but it is difficult to apply the abundant phycological and zoological literature to micropaleontological samples without understanding the impact of taphonomy on modern lake sediment. The optimal use of paleolimnological data to inform ecological management (e.g. Cabecinha et al. 2009; Smol 2010) depends on an accurate assessment of the biological community (biocoenosis), relative to the fossil assemblages (thanatocoenosis), requiring a thorough understanding of the impact of transport into and out of the lake, differential preservation of the various components of the ecosystem, and time-averaging of the record (Kidwell and Flessa 1996).

Meromictic lakes (lakes with layers of water that do not intermix, resulting in bottom water anoxia) have long been known to promote excellent preservation, allowing the biological component of variance between samples to be isolated from the taphonomic component (Bell et al. 1987). Additionally, the virtual absence of bioturbation allows for very high resolution in commonly annually laminated sediment (varves), although these are typically not very long records, since lakes tend to fill in (Schindel 1980). Annual chronological resolution in the late Holocene varved record of Crawford Lake, Ontario, allowed comparison with archaeological and historical records that document two distinct phases of human settlement and associated cultural eutrophication (Boyko 1973; Byrne and McAndrews 1975; McAndrews and Boyko-Diakonow 1989; Ekdahl et al. 2004, 2007; McAndrews and Turton 2010). As a result, in addition to commonly-preserved microfossils like pollen (Boyko 1973; Byrne and McAndrews 1975; McAndrews and Boyko-Diakonow 1989) and diatoms (Ekdahl et al. 2004, 2007) the varves deposited below the chemocline in the deep basin of Crawford Lake since the 13th century CE contain the fossilized remains of otherwise rare microfossils. These provide exceptional insights into the lake ecosystem, compared with the vast majority of lacustrine records that have been more taphonomically altered.

GEOLOGIC SETTING

Crawford Lake occupies a small, deep dolostone basin adjacent to the edge of the Niagara Escarpment World Biosphere Reserve near Toronto (Fig. 1). The Crawford Lake Conservation Area has been designated as an Area of Natural and Scientific Interest (ANSI) by the Government of Ontario (Niagara Escarpment Plan 2005) due to its geological, ecological, and archaeological attractions – the latter including the 'Iroquoian Village' reconstructed in 1972 by the Halton Region Conservation Authority (Conservation Halton) following an archaeological survey (Finlayson 1998). This survey was initiated by the discovery of the remains of cultivars such as corn (*Zea*), and sunflower (*Helianthus*) pollen spores in varved sediment from around the middle of the last millennium (Fig. 2) (Boyko 1973; Finlayson et al. 1973; Byrne and McAndrews 1975; McAndrews and Boyko-Diakonow 1989). This site, approximately 150 m from the lake, was intermittently occupied by between 200 and 300 people in the 13th to 16th centuries (Finlayson 1998; Byrne and Finlayson 1998) and was subsequently unoccupied until the Crawford homestead was established in ca. 1822 CE (McAndrews and Boyko-Diakonow 1989). The peak abundance of ragweed (*Ambrosia*) and other non-arboreal pollen in the late 19th century (Fig. 2) marks the most intensive Euro-Canadian impact in the watershed, when a sawmill operated on the southern shore of the small lake (Crawford Lake Conservation Area 2011).

The Crawford Lake basin is thought to have been excavated in relatively soft and soluble dolomite of the underlying Silurian Lockport Formation during the late Wisconsinan, when glacial meltwater flowed southward between two ablating ice lobes (McAndrews and Boyko-Diakonow 1989). Underground caves in this karstic region could have further facilitated this process. The lake does not fully overturn due to its relatively small surface area (about 250 x 150 m) and great depth (up to 22.5 m of water overlies approximately 4.5 m of postglacial sediment in the deepest part of the basin). Crawford Lake has a high affinity for meromixis (i.e. Zr >2 using the equation of Hutchinson (1957),

$$Zr = \frac{(50 \times Zm \times \sqrt{\pi})}{(\sqrt{A})}$$

with Zr = 10.25 (where Zr = relative depth, Zm = maximum depth, A = surface area). Seepage from a catchment of about 80 km^2 is the main inflow into this small (about 2.4 ha) lake, minimizing disturbance of the water column, and the mature eastern white cedar *(Thuja occidentalis)* forest on the slopes surrounding the lake acts as a wind-break, further reducing mixing of the water column (Yu et al. 1997). Water below the thermocline at around 15 m thus has a constant temperature of 5–6°C (McAndrews and Turton 2010) and over the last millennium bioturbation has been largely suppressed by bottom water anoxia. Since the 13th century CE, when the Iroquoian village was established and BOD (biochemical oxygen demand) increased due to cultural eutrophication (Ekdahl et al. 2004, 2007; Turton and McAndrews 2006), annual sediment couplets – varves – consisting of a white calcite-rich layer and a dark organic-rich layer (Figs. 3, 4) have accumulated because the anoxic bottom waters were unable to support benthic animals and protists (Dickman 1979). It has been proposed that episodic reduction in benthic anoxia at times of reduced productivity and BOD between the two phases of human settlement in the catchment (Chan, C., personal communication 2011, unpublished benthic ostracode data) may have interrupted varve formation, explaining the observation that about 10% of the varves are missing in the Post-Iroquoian Zone when compared to Accelerated Mass Spectrometry–C^{14} dating (Ekdahl et al. 2004, 2007). Nonetheless, varve counting together with carbon dating provides a very precise chronology, allowing the microfossil record to be compared with historic and archaeological data (Fig. 4). Freeze cores allow varves to be recovered, as the sediment freeze onto the hollow aluminum wedge filled with an ethanol and dry ice slurry; the wedge

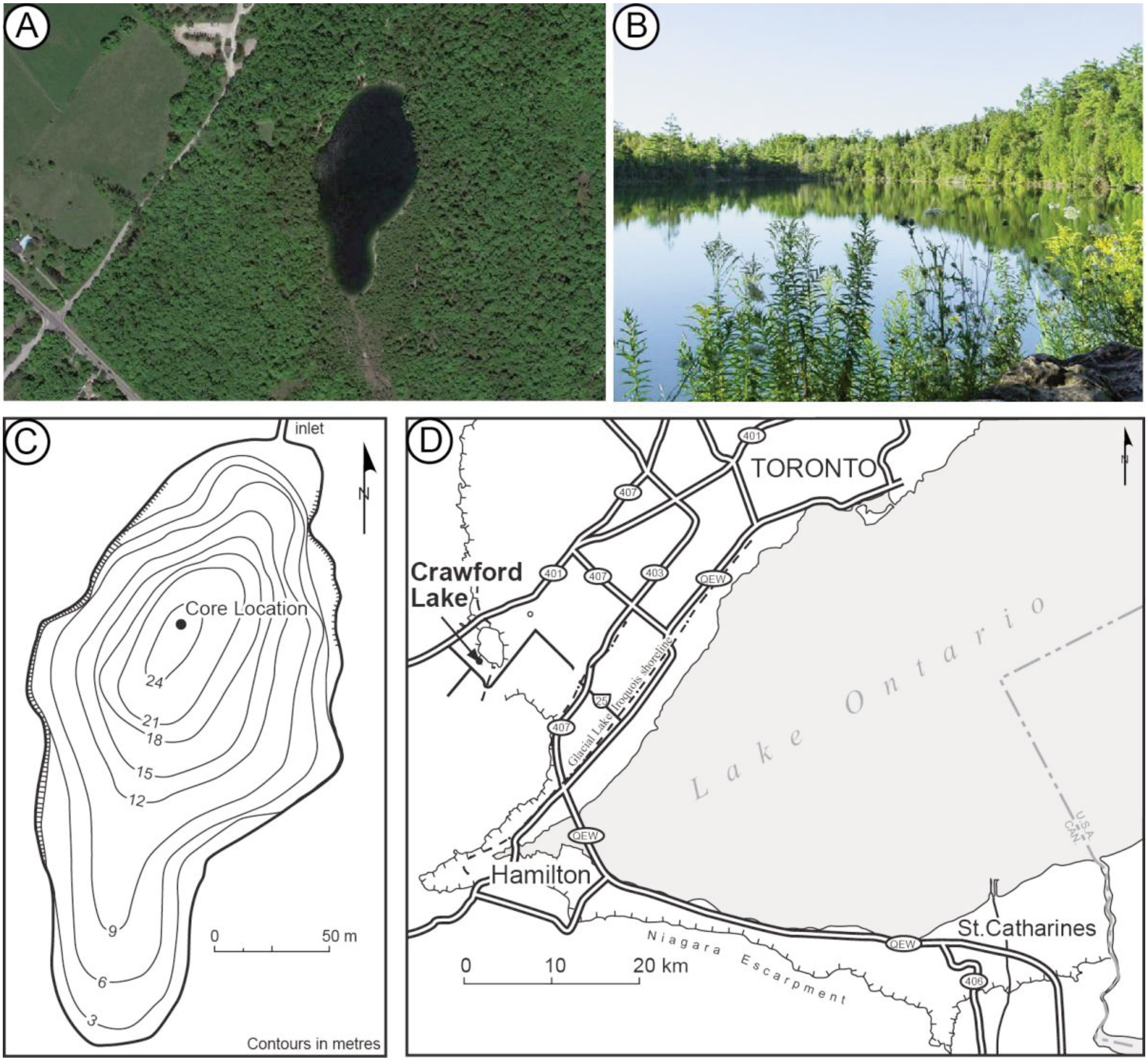

Figure 1. Aerial view (A) and shore view (B) photos of Crawford Lake, Milton, Ontario (Google images 2015). Bathymetry of the small, deep, meromictic Crawford Lake (C) near the edge of the Niagara Escarpment World Biosphere Reserve, about 50 km west of Toronto (D).

shape of the 'frigid finger' sampler allows for easy penetration into the sediments.

EXCEPTIONALLY PRESERVED DINOFLAGELLATES

In addition to commonly preserved pollen (Boyko 1973; Byrne and McAndrews 1975; McAndrews and Boyko-Diakonow 1989; Byrne and Finlayson 1998), fungal spores like corn smut (*Ustilago maydis*; McAndrews and Turton 2010), and diatoms (Ekdahl et al. 2004, 2007), rarely preserved microfossils are also found in varves deposited in the deep basin of Crawford Lake over the last 800 years. Turton and McAndrews (2006), for instance, reported common rotifer loricae that show a clear response to the increase in nutrients and abundance of algae during the Iroquoian and Euro-Canadian zone (Fig. 2). Fossil remains of these pseudocoelomate microscopic aquatic 'wheel animals' of the Phylum Rotifera are rare except for their resting eggs (van Geel 2001), but other body parts can accumulate under exceptional circumstances that inhibit oxygen, such as preservation in amber (Waggoner and Poinar 1993), in rapidly accumulating early Holocene sediment (Swadling et al. 2001), and a rare example of a complete rotifer in Permian sediment from India (Jha et al. 2011).

Rarely preserved cellulosic thecae of the dinoflagellate *Parvodinium [Peridinium] inconspicuum* (Lemmermann) Carty (Fig. 5A–C) were found together with abundant resting cysts in palynological preparations from varves deposited during the

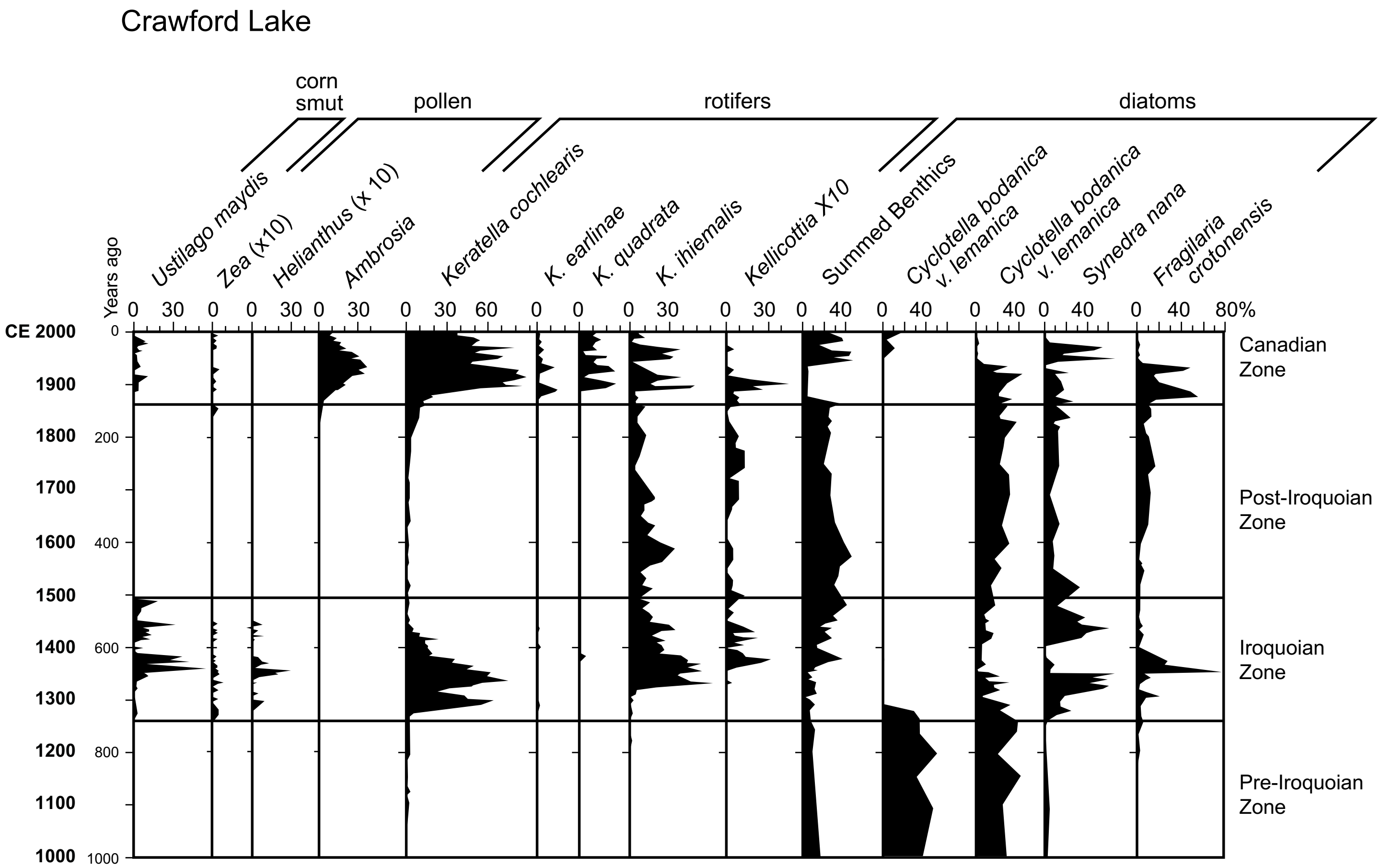

Figure 2. Summary of microfossil occurrence in varved sediments from Crawford Lake showing two separate phases of human settlement in the catchment indicated by peaks in abundance of spores of *Ustilago maydis*, a pathogenic fungus that attacks corn ('corn smut') and pollen associated with agriculture and land disturbance, e.g. corn (*Zea*), sunflower (*Helianthus*), and ragweed (*Ambrosia*) (McAndrews and Turton 2007, 2010). Eutrophication of the lake is illustrated by peaks in rotifer loricae (Turton and McAndrews 2006) and diatoms (Ekdahl et al. 2004, 2007). Although there is microfossil evidence of improved water quality since the site was taken over by the Halton Region Conservation Authority (Conservation Halton) in 1972, the lake has not returned to pre-disturbance conditions.

early Iroquoian period (13th century CE) and from the Euro-Canadian Period (Fig. 6). Dinoflagellates are common components of the phytoplankton in lakes, with approximately 350 species of the Phylum Dinoflagellata Bütschli inhabiting freshwater environments (Popovsky and Pfiester 1990; Mertens et al. 2012; Carty 2014). They have large, unusual dinokaryotic nuclei in which the chromosomes have unmasked DNA fibrils and are more or less continuously condensed (Fensome et al. 1993). The large nuclei contain the red pigment responsible for 'red tides;' they are bright red just prior to mitosis (McCarthy et al. 2011) and thus impart a red colour to the water during algal blooms. The life history of most dinoflagellates consists of a motile (vegetative) stage in which armored thecae composed of several cellulosic plates whirl through the water column using their two flagellae – one transverse, along the cingulum (belt), and one longitudinal along the sulcus (groove) – and at least one nonflagellated benthic stage (cyst) (Bravo and Figueroa 2014). Fossilizable (long-term) resting cysts are composed of dinosporin, a complex biomacromolecular substance composed of phenolic, alcoholic and/or carboxylic hydroxides, fatty acids with tocopherols, and sterols (Kokinos et al. 1998; Versteegh et al. 2012). These are produced by some, but not all, species, and to date are known for only about 20% of fresh water species (Mertens et al. 2012), a percentage comparable to marine taxa (Head 1996).

Unlike marine taxa, however, cyst-theca relationships are known for very few freshwater dinoflagellate taxa (Wall and Dale 1968; McCarthy et al. 2011; Mertens et al. 2012; Drljepan et al. 2014). Even in studies where both phycological and palynological approaches are combined (e.g. Chu et al. 2008), it has proven difficult to definitively relate thecae in the water column with dinoflagellate cysts preserved in sediment on the lakebed (Popovský 1983; McCarthy and Krueger 2013). As a result, few detailed paleolimnological studies have been published using dinocysts since Traverse (1955) recorded the first known fossil freshwater dinoflagellates (*Peridinium hansonianum*) from Oligocene lignite. Most of these are monospecific or very low diversity assemblages from sites exhibiting exceptional preservation, such as varved lacustrine deposits of the Miocene Clarkia lake succession in northern Idaho (Batten et al. 1999), the Upper Oligocene Enspel *Lagerstätte* in the Westerwald area of Germany (Köhler and Clausing 2000), rapidly deposited Holocene sediment from the alpine Lake Nero di Cornisello, Italy (Tardio et al. 2006), and Holocene microlaminated sediments from Lake Xiaolongwan in northeastern China (Chu et al. 2008). Drljepan et al. (2014) reported a relatively high diversity Holocene record from the deep basin of a meromictic lake in Massachusetts, particularly at times of natural and cultural eutrophication during the dry mid-Holocene 'hemlock minimum' when low lake levels are recorded

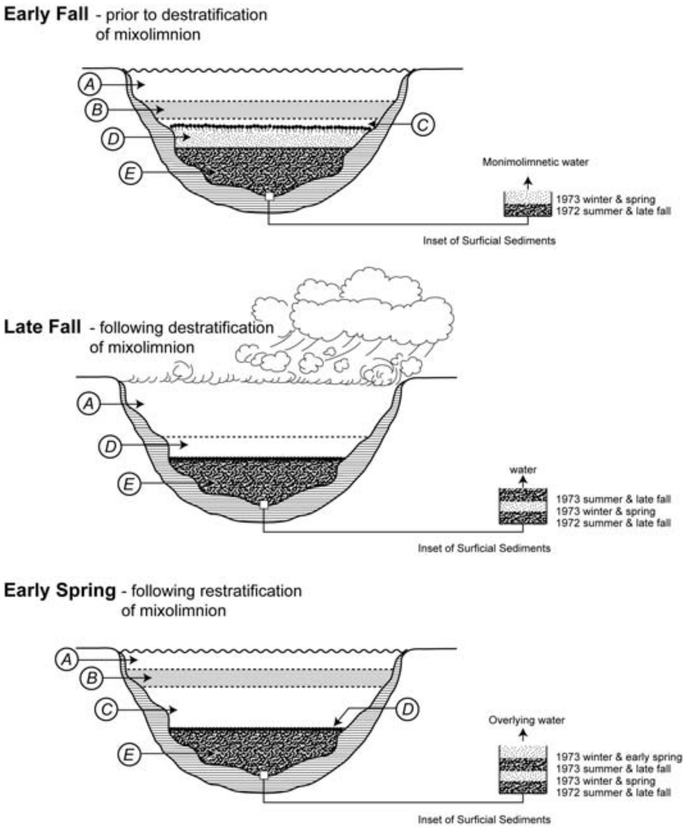

Figure 3. Mechanism of varve formation in Crawford Lake (modified from Dickman 1979). Wind mixing of the mixolimnion, surface waters, during fall turnover introduces oxygen into the chemocline and resulting mass mortality of photosynthetic anaerobic bacteria produces a dark organic-rich lamina; when water temperatures rise in spring, calcite starts to precipitate, forming a white calcium-rich lamina. (A) Upper mixolimnion; (B) thermocline; (C) lower mixolimnion (partially aerated zone); (D) lower mixolimnion (anaerobic zone); (E) monimolimnion. Sediment oxygen demand (SOD) produces bottom water anoxia, inhibiting bioturbation and promoting preservation of rare microfossils such as cellulosic thecae of dinoflagellates.

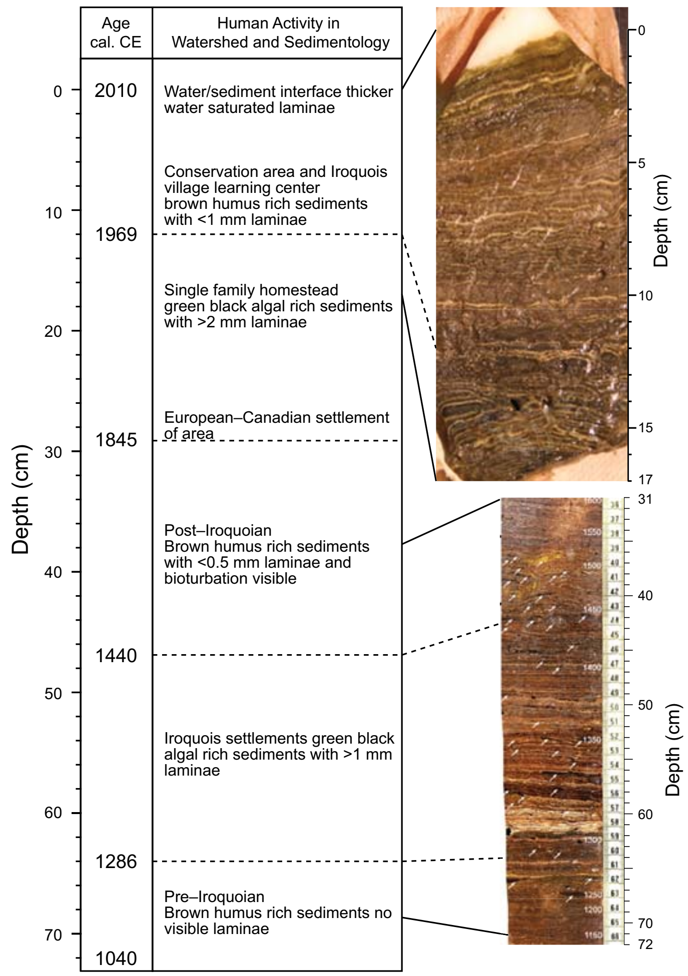

Figure 4. Varve counting provides a very precise chronology, allowing the microfossil record to be compared with historic and archaeological data. Both phases of human settlement, by the Iroquois (between 1268–1486 CE) and historic Euro-Canadians (since around 1820 CE), are associated with a change in colour and increase in the thickness and continuity of laminae (from Krueger 2012).

throughout New England, and over the last four centuries in response to anthropogenic impact.

Cellulosic dinoflagellate thecae are typically reported to be non-fossilizable, but rare examples of preservation have been reported from amber collected from a Late Albian/lowermost Cenomanian black paralic deposit in southwestern France (Masure et al. 2013) and from anoxic Recent sediment from another meromictic eastern North American lake (Drljepan 2014; Drljepan et al. 2014). The exceptional preservation of thecae of *Parvodinium inconspicuum* in several samples from Crawford Lake allowed Krueger (2012) to infer the affinity of the abundant tiny (about 16–20 μm in diameter), spherical, unornamented cysts with visible cell contents (illustrated in Fig. 5E with a rotifer lorica) in the same palynological preparations from varved sediments from a freeze core collected in February, 2011. The affinity of these tiny, spherical, unornamented cysts to *Parvodinium inconspicuum* was also confirmed by comparison with illustrations of the characteristic 'peanut-shaped' cell during reproduction in Pfiester et al. (1984), when five samples dating from about 1920 to 1845–1860 CE (20 cm to 29 cm) germinated during an unplanned hiatus in palynological processing (McCarthy and Krueger 2013). A 72 cm-long freeze core was recovered on January 25, 2011, from the deepest point in Crawford Lake (up to 22.5 m) using a frigid fingernail sampler. The core was brought back to Brock University where it was kept in a freezer wrapped in dry ice awaiting further processing that occurred in late February 2011. Inadvertent culturing occurred when samples were left in test tubes for a week after processing with a weak HCl solution and rinsed with distilled water. The samples were kept at room temperature (about 22°C) under fluorescent lights. This allowed the various stages of the dinoflagellate life cycle to be observed in the resulting slides (Fig. 7), including meiosis and mitosis showing the characteristic lack of breakdown of the nuclear envelope during mitosis (Fig. 5D). Excystment allowed us to suggest that the cysts inferred by Chu et al. (2008) to be cysts of *Parvodinium inconspicuum* are actually cysts of *Parvodinium [Peridinium] umbonatum* (Stein) Carty (McCarthy and Krueger 2013), probably because the thecae in the water column were incorrectly identified. Both the thecae and cysts of *P. umbonatum* were identified in sediment from a meromictic lake in Massachusetts (Drljepan et al. 2014) and the cysts resemble those illustrated by Tardio et al. (2006). The abundance of cysts of *P. inconspicuum* in Crawford Lake at times of anthropogenic impact is consistent with the tolerance of this

Figure 5. Small, thick-walled cellulosic thecae of *Parvodinium [Peridinium] inconspicuum* (Lemmermann) Carty with visible nucleus (A, B) and plate tabulation (C), and a hypnozygote of this taxon undergoing meiosis (D) (from Krueger 2012). A rotifer lorica (genus *Keratella*) with tiny cysts assigned to *Parvodinium inconspicuum* (E); note the large dinokaryotic nuclei.

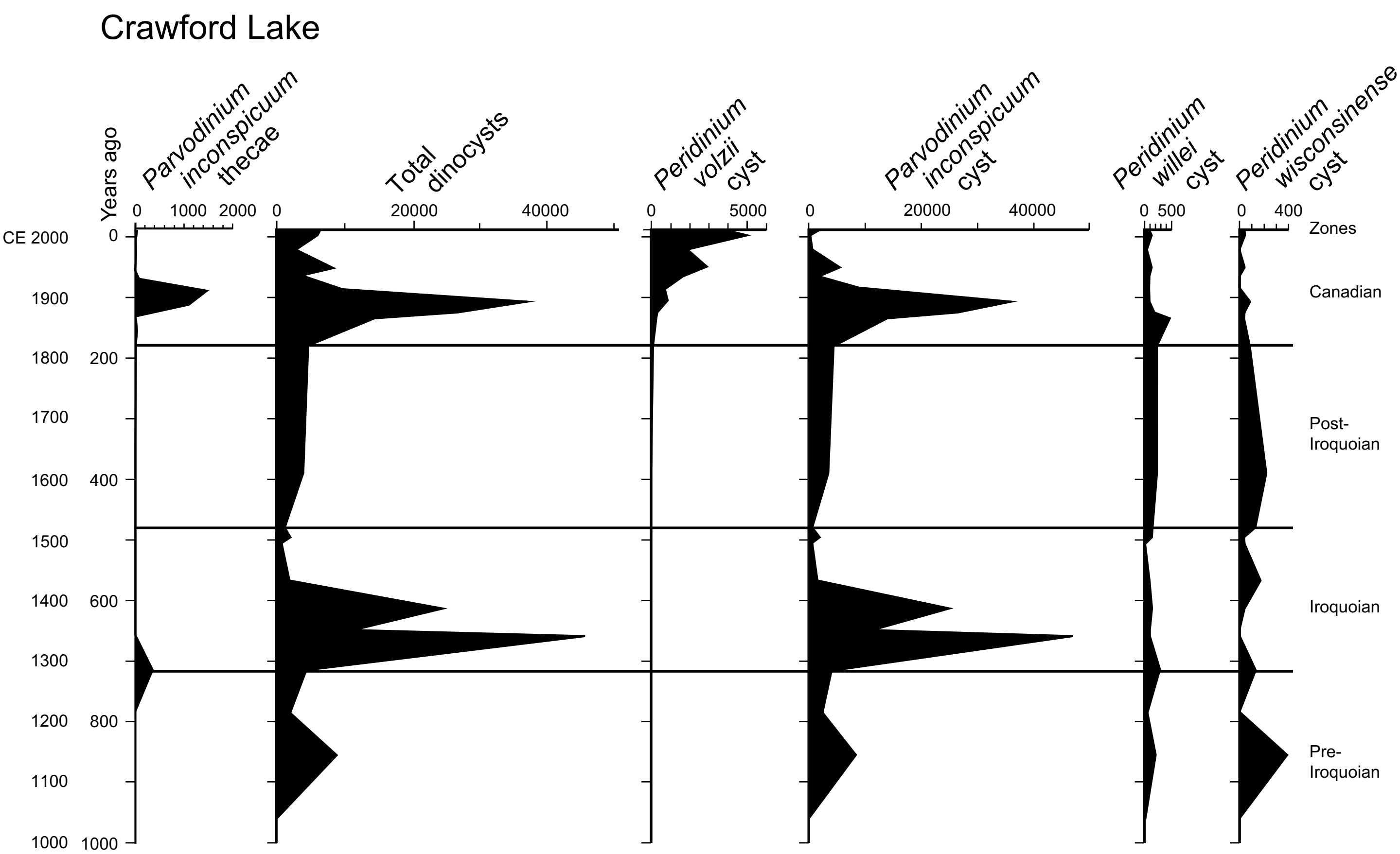

Figure 6. Cysts and rarely fossilized thecae of dinoflagellates (shown as absolute abundances per ml sediment measured by liquid displacement) in varved sediments from a freeze core collected in February 2011. Peak dinocyst abundances near the base of the Iroquoian zone suggest that the peak impact on the lake ecosystem was shortly after the village was settled and peak impact in the Euro-Canadian phase coincides with operation of the lumber mill. The presence of thecae in varves dated to the early 13th century and mid-19th to early 20th century suggests extreme anoxia at these times and a slightly earlier date for occupation of the Iroquoian village than previously published.

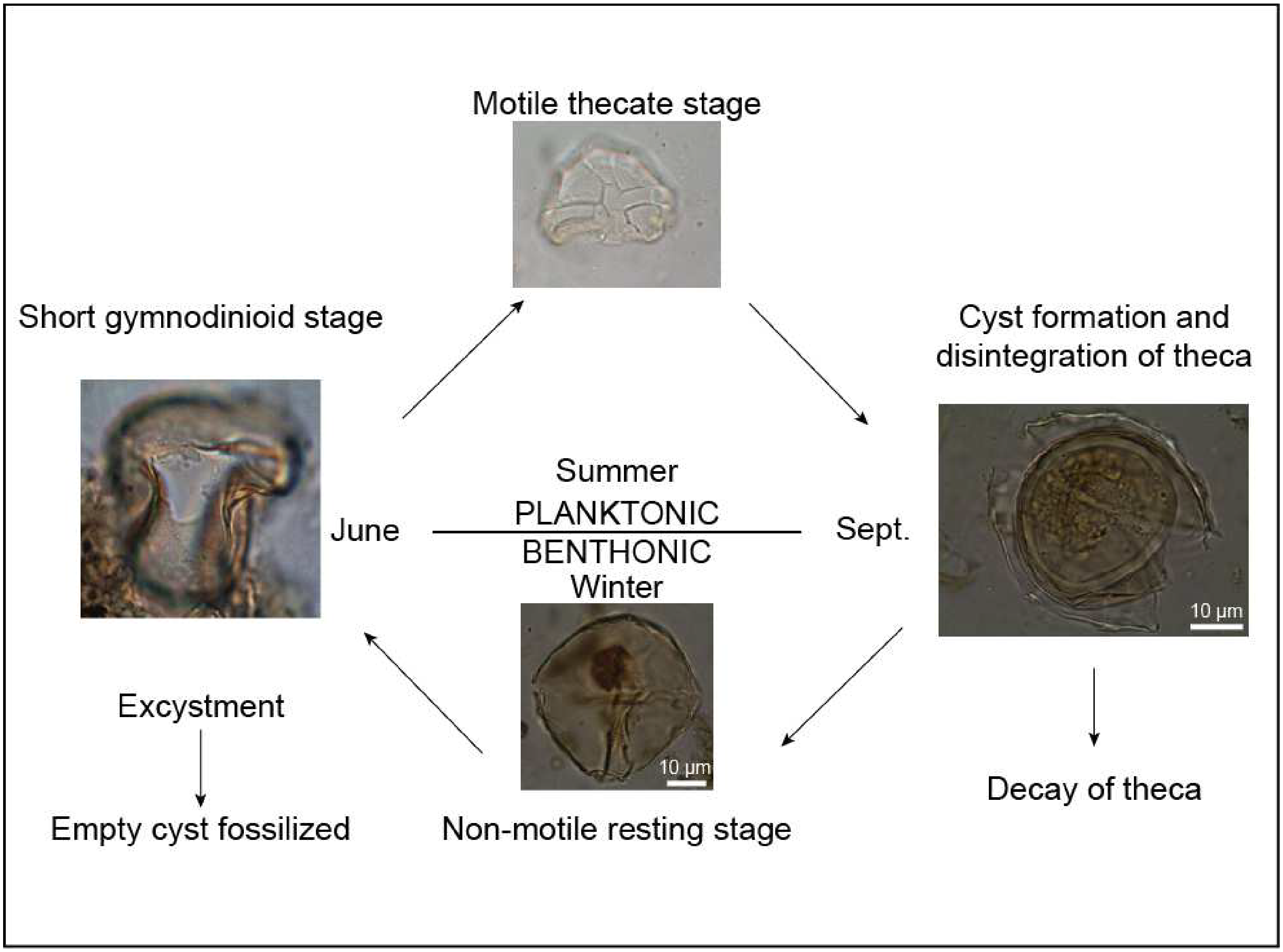

Figure 7. Two samples germinated during an unplanned hiatus in palynological processing, allowing all stages of the life cycle to be observed, as illustrated by Krueger (2012) for *Peridinium volzii* Lemmermann. Counter-clockwise from bottom: a resting cyst showing viable cell contents, an empty cyst with an archeopyle from which the cell excysted, the epitheca of the motile stage made of cellulosic plates, and an encystment and sloughing of the theca to avoid adverse conditions.

species to eutrophic conditions (Koryak 1978; Moiseenko 2005), particularly when pH is above 6 (Perez et al. 1994), as it is in this dolomitic basin.

The oldest dinoflagellate to excyst was from varves deposited in Crawford Lake around AD 1820; just as the Crawford family began clearing land in the catchment to build their homestead according to McAndrews and Boyko-Diakonow (1989). The cysts of *P. inconspicuum* that germinated are nearly twice as old as the oldest cysts of *Pentapharsodinium dalei* Indelicato et Loeblich that Ribeiro et al. (2011) were able to germinate from sediment cores retrieved from a low-oxygen sill fjord, and much older than previous reports of cyst germination following decades of dormancy (Keafer et al. 1992; McQuoid et al. 2002; Mizushima and Matsuoka 2004). Anoxic conditions in the deep basin of Crawford Lake appear to have promoted the long-term viability of the resting cysts that may have contributed to the survival of these cyst-forming genera during times of ecological catastrophe like the K–T boundary event (Ribeiro et al. 2011).

The inadvertent excystment during processing also allowed small (approximately 30 × 40 µm) slightly ovate non-motile dinosporin resting cysts previously recorded as *Peridinium willei* ('small') in sediments from Georgian Bay (McCarthy et al. 2011) to be assigned to *Peridinium volzii* Lemmermann (Krueger 2012). The restriction of cysts of *P. volzii* as well as the loricae of *Keratella earlinae* and *Keratella quadrata* to varves deposited since about 1880 CE (Figs. 2, 6) suggests that these organisms were incidentally introduced when the naturally fishless lake was stocked with fish (Turton, C., personal communication 2011; Krueger 2012), around the same time that a lumber mill was erected by the south end of the lake (Crawford Lake Conservation Area 2011).

CULTURAL EUTROPHICATION, ENHANCED PRODUCTIVITY AND PRESERVATION

An increase in absolute abundance of aquatic microfossils (biomass) and a transition from oligotrophic to eutrophic species assemblages is evident in the fossil record of phytoplankton (diatoms – Ekdahl et al. 2004, 2007, and dinoflagellates – Krueger 2012; McCarthy and Krueger 2013) as well as herbivores like rotifers (Turton and McAndrews 2006) that thrived in response to the increase in food supply during the two separate human settlement phases (Fig. 2). The exceptional preservation of cellulosic thecae and the unparalleled longevity of cell contents is attributed to especially pronounced bottom water anoxia resulting from cultural eutrophication-induced sediment oxygen demand (SOD) (Hargrave 1972; Walker and Snodgrass 1986), evident in the suppression of benthic diatoms (Fig. 2) (Ekdahl 2004, 2007) and benthic ostracodes that was only episodically interrupted (Chan, C.C.H., unpublished data). Peak anoxia appears to coincide with 1) initial settlement and land clearing beginning in 1822 CE and lumbering on the shores of Crawford Lake during the 1880s (Krueger 2012) recorded by thick accumulations of woody debris near the base of the *Ambrosia* rise near the north shore of the lake (McCarthy et al. 2011), and 2) during the earliest phase of Iroquoian settlement, when the village was established and trees were cut to clear land for the village and corn fields and to provide building material for the longhouses. McAndrews and Turton (2007, 2010) suggested that increased nutrient input from the dung of Canada geese (*Branta canadensis)* that grazed on the cultivated fields and then roosted at Crawford Lake was the main cause of eutrophication during Iroquoian settlement. The peak concentrations of cellulosic thecae (around 1500 thecae per ml) in varves deposited coincident with the establishment of the lumber mill suggests that Euro-Canadian land clearing was the most intense contributor to BOD/ SOD.

It is clear from the increase in algal (diatom and dinoflagellate) and herbivore (rotifer) biomass and from the changes in assemblages to favour eutrophic plankton and nekton (Figs. 2, 6) that the Iroquoian village had a strong and irreversible impact on the lacustrine ecosystem. Although there was resurgence in oligotrophic algae (e.g. *Cyclotella bodanica* var. *lemanica* and *Peridinium wisconsinense*) during the post-Iroquoian interval, the lake did not return to pre-disturbance conditions.

CONCLUSIONS

Preservation of rarely fossilized microscopic organisms in varved sediments from Crawford Lake, notably cellulosic thecae and cysts of dinoflagellates with viable cell contents deposited nearly 200 years ago, allowed reconciliation of the thanatocoenosis with the biocoenosis in this unusual group of organisms. Exceptional preservation of organisms rarely present in lacustrine sediment allows unparalleled insights into the response to perturbation of various trophic levels in a mid-latitude lacustrine ecosystem. The correspondence between the palynological record in the varves from Crawford Lake and the components of the ecosystem is closer than typically found in lacustrine sediment, allowing insights from the phycological and zoological literature into dinoflagellate cyst–theca relationships. Varve counting provides a precise chronology allowing correlation with archaeological and historic records, and the increase in nutrients that accompanied Iroquoian and later Euro-Canadian settlement of the uplands north of the small, deep lake promoted the bottom water anoxia that allowed exceptional preservation of dinoflagellate thecae and rotifer loricae. The existence of an interpretive centre managed by Conservation Halton in this Area of Natural and Scientific Interest (ANSI) on the edge of the Niagara Escarpment World Biosphere Reserve provides an opportunity to promote *Konservat–Lagerstätten* to the general public in a highly populated region. In addition, the insights into the various trophic levels in this temperate lake as extant primary producers and consumers twice responded to cultural eutrophication can assist in linking the fields of limnology and paleolimnology allowing for improved management of important fresh water resources.

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SERIES

Igneous Rock Associations 20. Pearce Element Ratio Diagrams: Linking Geochemical Data to Magmatic Processes

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SUMMARY

It has been nearly fifty years since Tom Pearce devised a type of element ratio diagram that isolates the effects of crystal fractionation and accumulation (sorting) hidden in the chemistry of a suite of igneous rocks. Here we review the guiding principles and methods supporting the Pearce element ratio paradigm and provide worked examples with data from the Mauna Ulu lava flows (erupted 1970–1971, Kilauea Volcano, Hawaii). Construction of Pearce element ratio diagrams requires minimum data; a single rock analysis can suffice. The remaining data test the model. If the data fit the model, then the model is accepted as a plausible or likely explanation for the observed chemical variations. If the data do not fit, the model is rejected. Successful applications of Pearce element ratios require the presence and identification of conserved elements; elements that remain in the melt during the processes causing the chemical diversity. Conserved elements are identified through a priori knowledge of the physical-chemical behaviour of the elements in rock-forming processes, plots of weight percentages of pairs of oxides against each other, or by constant ratios of two elements. Three kinds of Pearce element ratio diagrams comprise a model: conserved element, assemblage test, and phase discrimination diagrams. The axial ratios for Pearce ratio diagrams are combinations of elements chosen on the basis of the chemical stoichiometry embedded in the model. Matrix algebra, operating on mineral formulae and analyses, is used to calculate the axis ratios. Models are verified by substituting element numbers from mineral formulae into the ratios. Different intercepts of trends on Pearce element ratio diagrams distinguish different magma batches and, by inference, different melting events. We show that the Mauna Ulu magmas derive from two distinct batches, modified by sorting of olivine, clinopyroxene, plagioclase and, possibly, orthopyroxene (unobserved).

RÉSUMÉ

Il y a près de cinquante ans Tom Pearce a conçu un genre de diagramme de ratio d'éléments qui permet d'isoler les effets de la cristallisation fractionnée et de l'accumulation cristalline (tri) au sein de la chimie d'une suite de roches ignées. Dans le présent article, nous passons en revue les principes et les méthodes étayant le paradigme de ratio d'éléments de Pearce, et présentons des exemples pratiques à partir de données provenant de coulées de lave du Mauna Ulu (éruption 1970–1971 du volcan Kilauea, Hawaii). La confection des diagrammes de ratio d'éléments de Pearce requière un minimum de données; une seule analyse de roche peut suffire. Les données restantes servent à tester le modèle. Si les données sont conformes au modèle, alors le modèle est accepté comme explication plausible ou probable des variations chimiques observées. Si les données ne correspondent pas, le modèle est rejeté. Les applications réussies des ratios d'éléments de Pearce requièrent la présence et l'identification d'éléments conservés; éléments qui demeurent dans la masse fondue au cours des processus causant la diversité chimique. Les éléments con-

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servés sont identifiés par la connaissance a priori du comportement physico-chimique des éléments dans les processus de formation des roches, le positionnement sur la courbe des pourcentages pondérés de pairs d'oxydes les uns contre les autres, ou par des ratios constants de deux éléments. Trois types de diagrammes de Pearce de ratio d'éléments constituent un modèle: élément conservé, test d'assemblage, et diagrammes de phase discriminant. Les ratios axiaux pour les diagrammes de ratio d'éléments de Pearce sont des combinaisons d'éléments choisis sur la base de la stœchiométrie inhérente au modèle. L'algèbre matricielle, appliquée à des formules minérales et à des analyses, est utilisée pour calculer les ratios axiaux. Les modèles sont vérifiés en utilisant les nombres d'élément des formules minérales dans les ratios. Différentes intersections dans les diagrammes de ratios d'éléments de Pearce distinguent différents lots de magma et, par inférence, différentes coulées. Nous montrons que les magmas de Mauna Ulu proviennent de deux lots distincts, modifiés par l'extraction de l'olivine, de clinopyroxène, de plagioclase et, éventuellement, orthopyroxène (non observé).

Traduit par le Traducteur

INTRODUCTION

Pearce element ratios and diagrams are effective and efficient methods for extracting information on mineral accumulation and loss in magmas. Grounded in mineral stoichiometry, Pearce element ratios and diagrams faithfully depict the chemical variations in geochemical data sets collected from rocks in a volcanic field or from an intrusive suite. This article serves as a review, intended to demonstrate the power of the methods to recover igneous processes from geochemical data sets and to provide a blueprint for students to follow in order to apply the methods to their own rocks.

Pearce element ratios were first conceived by Pearce (1968) and subsequently further developed by Russell and Nicholls (1988), Oviatt and Nash (1989), Nicholls and Russell (1990), Russell et al. (1990), Russell and Stanley (1990a, b), Nicholls and Russell (1991), among many others. More recently, the concepts and methods developed by Pearce (1968) have been expanded and applied to altered rocks (Stanley 1993, 2003, 2006a, b) and to sulfide deposits (Beswick 2002, 2013).

Pearce element ratio diagrams are rectilinear plots featuring combinations of elements cast into ratios (Fig. 1). By definition, Pearce element ratios use a common element or combinations of elements in their denominators. That element in the denominator must be *conserved* (Nicholls 1988). A conserved element is any element essentially excluded from the differentiation processes; it remains sequestered in the melt. The effectiveness of Pearce element ratio diagrams derives from two main factors:

1. The geochemical data sets are converted to element ratios using a conserved element as the denominator of the ratios (Fig. 1). This transformation removes the effects of closure, rendering the resulting geochemical patterns as a direct and true record of the differentiation processes.
2. Differentiation involving igneous minerals, with their chemical stoichiometry, leaves an imprint on the associated melt compositions. Pearce element ratio diagrams are designed to compare the chemistry of model processes against the actual chemical variations recorded by the rock compositions.

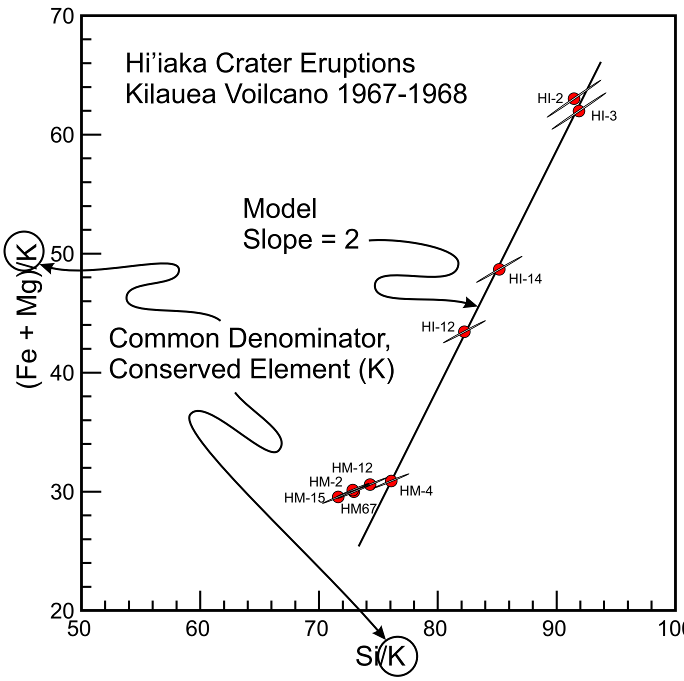

Figure 1. Pearce element ratio diagram and its parts. Plot of (Fe + Mg)/K versus Si/K. The model line has a slope of 2. If the data are related by the fractionation or accumulation of olivine, they should fall on a trend with a slope of 2. Five of the lava flows (HI02, HI03, HI14, HI12, and HM04) have compositions that supply ratios that fall close to the line. The other four samples (HM12, HM02, HM15, and HM67) fall on a trend with a slope less than two. Potassium is the conserved element and the intercept at X = 0 is off the graph.

For example, sorting (i.e. loss or gain) of olivine phenocrysts is a common explanation for the chemical diversity in basaltic melts. Furthermore, K represents an element that is expected to be conserved throughout basaltic differentiation. Because ideal stoichiometric olivine contains two Mg + Fe atoms for every Si atom, a plot of (Mg + Fe)/K versus Si/K on a Pearce element ratio diagram prescribes a slope of 2 for the model. The Pearce element diagram (Fig. 1) allows for an easy graphical comparison of the model line to the distribution of real data. Figure 1 displays the graphical implications of olivine loss or accumulation in a suite of co-magmatic olivine-rich basaltic lava flows erupted at Hi'iaka Crater, Kilauea in 1968. Several of the ratio values plot on (or very near) the line with a slope of 2 and are fully explained by sorting of olivine phenocrysts; several data points do not, however, and these data points require a different model to explain the chemical variations.

The values of the ratios, the number pairs (X, Y) (Russell and Nicholls 1988), that plot on a Pearce element ratio diagram come from a rock analysis. The weight percent of the constituent in the analysis that contains the element in question is divided by the formula weight of the constituent and multiplied by the number of elements in the constituent. These numbers are then used to calculate the X- and Y-values for the ratios. The same procedure is followed for each analysis in the data set. The simple element ratios for the rock analyses listed in Table 1 are set down in Table 2.

Here, our goals are three-fold. 1) To provide a review of the basic Pearce element ratio paradigm which comprises three main types of diagrams: i) conserved element diagrams, ii) assemblage test diagrams, and iii) phase discrimination diagrams. 2) To provide detailed instructions on how to design Pearce element ratio diagrams to explore or test specific processes or models. These simple matrix operations allow readers to develop their own diagrams to address their specific situations. 3) To describe the importance of the intercept in Pearce element ratio diagrams as they provide a way to discriminate between individual magma batches and, by inference, melting events.

We will demonstrate features of Pearce element ratios and diagrams using data collected on lava flows from the 1970–1971 Mauna Ulu eruptions from Kilauea Volcano, Hawaii. The samples come from lava flows erupted from 9 April, 1970 through 19 April, 1971 (Wright et al. 1975). The trace element data are from Hofmann et al. (1984). The data are listed in Table 1 for those wanting to calculate their own diagrams.

Table 1. Oxide (wt. %) and trace element (ppm) concentrations for the Mauna Ulu lava flows from Wright et al. (1975) and Hofmann et al. (1984), respectively.

Oxide	70-25	70-35	70-41	70-62	70-83	71-127	71-134	71-136	71-137
SiO_2	49.91	49.51	49.74	49.14	49.43	49.38	50.48	49.73	49.16
TiO_2	2.44	2.30	2.38	2.15	2.21	2.13	2.31	2.21	2.10
Al_2O_3	13.52	13.00	13.14	12.18	12.63	12.48	13.63	12.91	12.20
Fe_2O_3	1.39	1.08	1.07	1.15	1.13	1.16	1.27	1.20	1.16
FeO	10.07	10.53	10.44	10.62	10.57	10.54	10.06	10.37	10.67
MnO	0.18	0.18	0.17	0.17	0.17	0.18	0.17	0.18	0.18
MgO	8.55	10.01	9.57	12.02	10.92	11.33	8.14	10.33	11.96
CaO	10.85	10.41	10.60	9.86	10.19	10.06	11.05	10.31	9.85
Na_2O	2.27	2.21	2.20	1.98	2.11	2.02	2.22	2.10	2.20
K_2O	0.47	0.41	0.43	0.40	0.40	0.39	0.41	0.40	0.37
P_2O_5	0.23	0.21	0.23	0.21	0.22	0.21	0.22	0.21	0.20
Total	99.88	99.85	99.97	99.88	99.98	99.88	99.96	99.95	100.05
					Trace elements				
Ce	32.60	30.70	31.10	28.50	29.20	27.90	30.30	28.00	27.20
Nd	21.20	19.90	20.10	18.40	19.00	18.30	19.60	18.60	17.60
Sm	5.43	5.19	5.21	4.75	4.96	4.76	5.16	4.83	4.64
Eu	1.84	1.79	1.80	1.65	1.71	1.66	1.80	1.68	1.64
Dy	5.01	4.78	4.83	4.45	4.62	4.54	4.94	4.65	4.42
Er	2.45	2.37	2.38	2.20	2.26	2.25	2.49	2.31	2.22
Yb	1.95	1.86	1.90	1.75	1.77	1.81	2.04	1.85	1.79

Table 2. Single element ratios calculated for the analyses reported in Table 1.

Ratio	70-25	70-35	70-41	70-62	70-83	71-127	71-134	71-136	71-137
Si/K	83.240	94.657	90.673	96.298	96.866	99.249	96.511	97.454	104.148
Ti/K	3.060	3.307	3.263	3.168	3.257	3.219	3.321	3.257	3.346
Al/K	26.575	29.293	28.231	28.131	29.170	29.563	30.712	29.817	30.462
Fe/K	15.970	18.606	17.588	19.323	19.211	19.698	18.118	18.982	20.996
Mn/K	0.254	0.291	0.262	0.282	0.282	0.306	0.275	0.299	0.323
Mg/K	21.258	28.530	26.007	35.115	31.902	33.948	23.200	30.178	37.773
Ca/K	19.388	21.324	20.703	20.702	21.395	21.664	22.635	21.647	22.358
Na/K	7.340	8.192	7.776	7.523	8.017	7.872	8.229	7.979	9.037
P/K	0.325	0.340	0.355	0.348	0.365	0.357	0.356	0.348	0.359

CONSERVED ELEMENT SELECTION

Trends on a Pearce element ratio diagram will be petrologically significant only if the common denominator is conserved during the physical-chemical processes that produced the chemical variations in the data. The first task is to determine whether a conserved element exists in the data set. There are three ways to do this.

1. Our a priori knowledge of the physical-chemical behaviour of the elements in rock-forming systems may suggest conserved element status. This criterion, knowledge of the physical-chemical behaviour, is probably the most important one. Unless an element is likely to be conserved, there is no point in using that element as the common denominator to the Pearce element ratios. For example, in most igneous rocks, P is expelled from the melt only in the late stages of crystallization when apatite forms. In volcanic rocks, apatite almost always occurs as tiny, unnoticeable crystals in the groundmass. In plutonic rocks, apatite often occurs as scattered, small subhedral to euhedral crystals, too small to be fractionated in silica-rich melts. Consequently, the physical-chemical behaviour of P in igneous systems suggests that it is likely a conserved element.
2. A plot of the weight percentages of pairs of oxides against each other will define a single linear trend having a zero intercept if the elements in the oxides are conserved (Stanley and Madeisky 1995; see Fig. 2A, B, C). Figure 2D shows the contrasting case where the oxides of two non-conserved elements are plotted against each other. The data plotted on Figure 2 come from the 1970–1971 Mauna Ulu lava flows (Table 1).
3. The ratio of two conserved elements (e.g. P/K) should be constant. Constant ratios indicate that both elements are conserved constituents; only by chance can the ratios be constant and the elements not conserved. The variations in the ratios of these elements within a single data set should not be significantly greater than the variation that can be attributed to analytical uncertainty. Figure 3 plots Ti/K vs. P/K for the Mauna Ulu eruptive products. If all 3 elements are equally conserved, and the 1970 and 1971 lava flows derive from a single chemical system, the entire geochemical data set should plot in a single cluster (see below and Fig. 3A). The dispersion in the data around the mean value should not be larger than can be explained by analytical error.

TYPES OF PEARCE ELEMENT DIAGRAMS

Several models have been put forward to explain the diversity found in the Mauna Ulu magmas. Crystal sorting, magma mix-

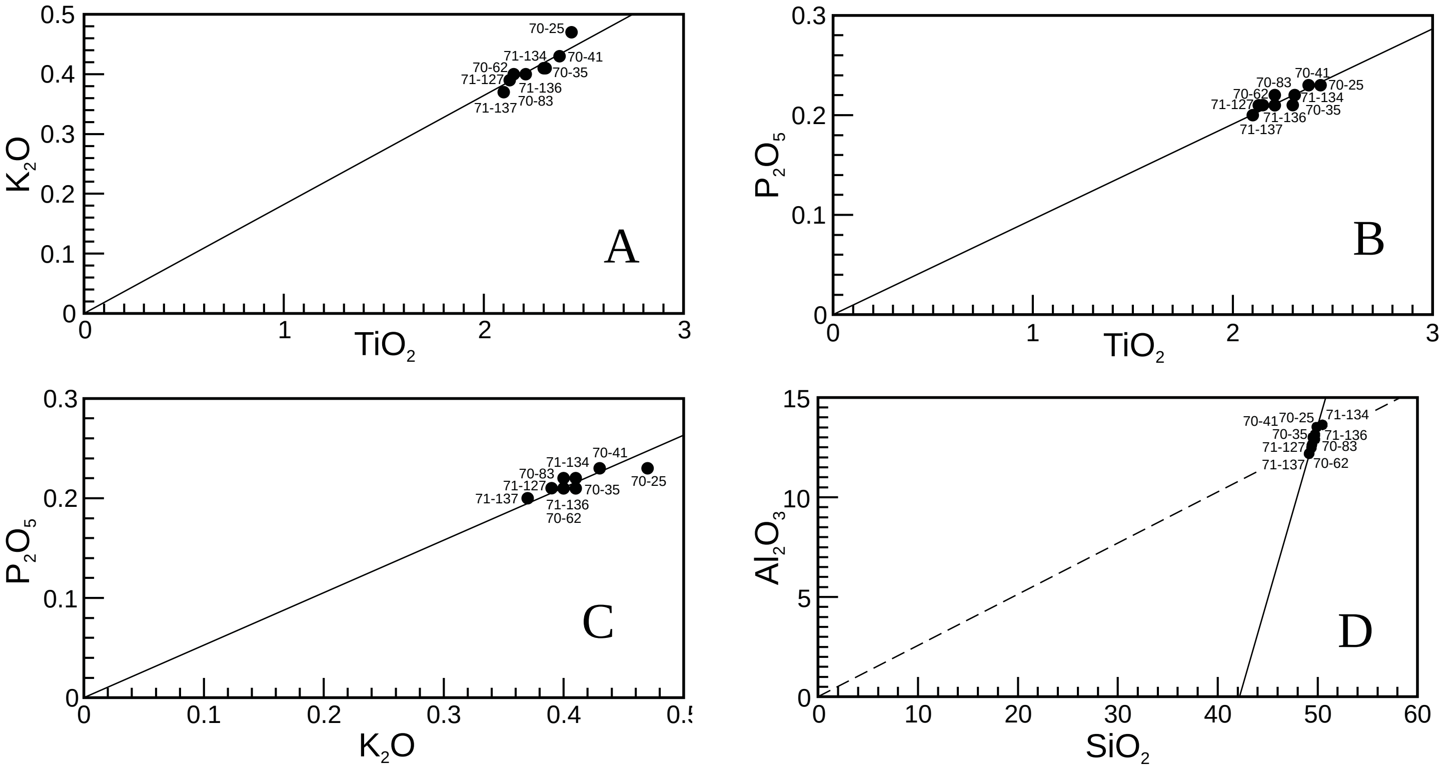

Figure 2. An empirical method for discovering conserved elements (Stanley and Madeisky 1995). Weight percentages of oxides containing potential conserved elements plotted against each other. Data for the Mauna Ulu 1970–1971 lava flows. (A) K_2O–TiO_2, (B) P_2O_5–TiO_2, (C) P_2O_5–K_2O. If the elements are potentially conserved they will fall along a trend through the origin. (D) Contrasting behaviour for elements that are not conserved. The latter fall on a line that does not pass through the origin (solid line).

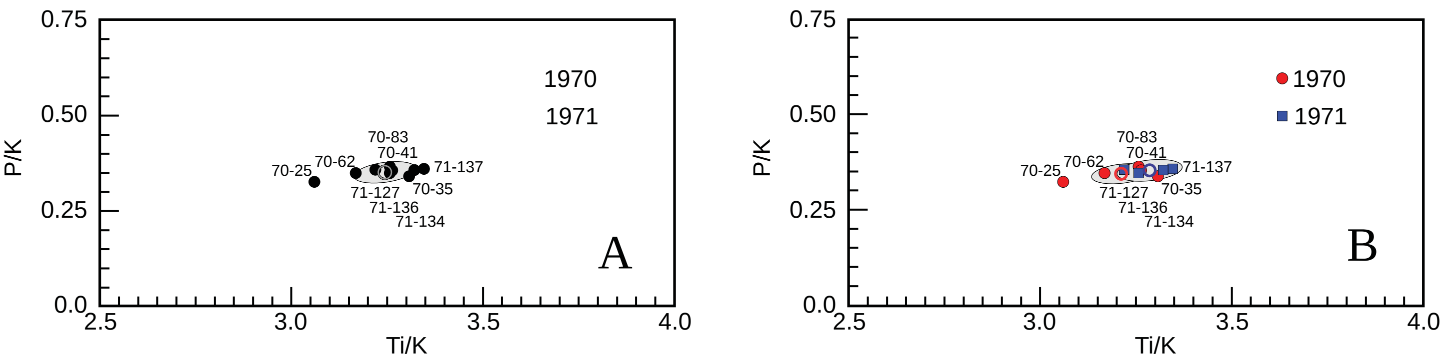

Figure 3. Conserved element plots for the 1970–1971 Mauna Ulu lava flows. Plotted are two ratios formed from three elements likely to be conserved in basaltic systems: P/K and Ti/K. Mean values are indicated by open circles. The shaded ellipses represent the expected variation in location of the mean values due to analytical uncertainty. (A) Distribution of the data points for the entire 1970–1971 data set. Several points fall outside the expected uncertainty about the mean, especially along the Ti/K axis. (B) Distribution of data points grouped by date of eruption. The 1971 data points fall within their uncertainty ellipse, whereas two of the 1970 data points (70-25 and 70-35) do not.

ing, and compositional variations in the source regions of the magmas have been invoked, either singly or in combination, as models (see Hofmann et al. 1984 and Vinet and Higgins 2010, for further description and discussion). Pearce element ratio diagrams can help discriminate between these competing ideas.

Conserved Element Diagrams

We begin with conserved element diagrams because they provide information about consanguinity of magmas. The 1970–1971 Mauna Ulu lava flows are basalt made of olivine, plagioclase, augite, opaque minerals, and variable amounts of glass. The bulk composition of the Mauna Ulu magma, the mineral assemblage, and the typical physical-chemical behaviour of the mineral phases leads us to expect that at least three elements could be conserved: Ti, K, and P. In our analysis of the Mauna Ulu data we will use K as the conserved element. The propagated analytical uncertainties (Nicholls 1990; Halleran and Russell 1990) depend on the analytical method and the concentration of the substance. Usually K_2O has a higher concentration than P_2O_5 and a smaller uncertainty, making it the preferred denominator.

The remarkable feature of Figure 3A is the near uniformity in P/K values compared to Ti/K. The variation or scatter in P/K ratios for the combined data from both the 1970 and 1971 lava flows is explicable by analytical uncertainty alone. However, the range in Ti/K values exceeds that expected from analytical uncertainty (grey ellipse, Fig. 3A). If the data are segregated by time of eruption (Fig. 3B, 1970 versus 1971 data), the data points more closely conform to the dispersion about the mean expected from analytical uncertainty. The P/K and Ti/K data points for the 1971 Mauna Ulu samples are enclosed by the analytical uncertainty ellipse centred on the mean value (open circle). However, the 1970 data set shows greater dispersion in Ti/K values and two data points (70-25 and 70-35) fall outside the corresponding ellipse (Fig. 3B). The dispersion in Ti/K values suggests minor sorting of a Ti-bearing phase, likely a Fe-Ti oxide. Obviously, we must consider models that distinguish between the two populations.

Assemblage Test Diagrams

A first and logical model to explain the geochemical diversity in the Mauna Ulu lava flows is sorting of the phenocrysts typically found in basalt: olivine, augite, and plagioclase.

The Pearce element ratio diagram (Fig. 4) uses combinations of elements on the two axes to represent the proposed model. Specifically, the coefficients for the elements are chosen to exactly mimic the stoichiometric effects of sorting of the proposed mineral assemblage comprising any modal combination of olivine, clinopyroxene and plagioclase. This type of Pearce element ratio diagram is termed an Assemblage Test diagram (Stanley and Russell 1989, 1990); the methods used to find these effective, but non-intuitive, coefficients are discussed in detail below. The coordinates of the Mauna Ulu data points plotted in Figure 4 are listed in Table 3. For the moment we simply use the diagram to explore the chemical diversity of the Mauna Ulu lava flows.

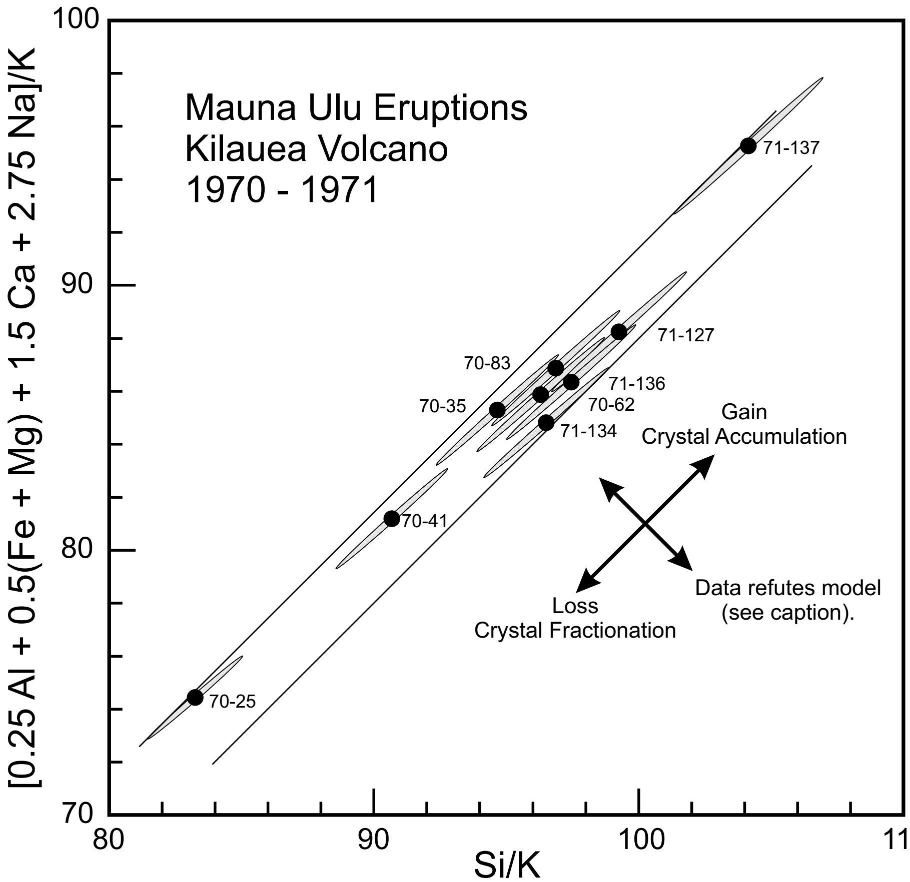

Figure 4. Assemblage test diagram to determine whether the chemical variations in the 1970–1971 lava flows from Kilauea Volcano, Hawaii, can be explained by sorting olivine, clinopyroxene, and plagioclase. The two lines with slopes of one straddle the data. The shaded ellipses represent the expected variation in location of the data points due to analytical uncertainty. The arrows show how data points should be distributed if one particular process dominates. Scatter away from a line with a slope of one caused by processes or factors not considered in the model design, such as multiple source compositions, magma mixing, non-conserved element in the denominator, gain or loss of a phase not included in the model.

Figure 4 is constructed such that lava flows from a single batch of basaltic magma that record the effects of differentiation by sorting combinations of olivine, clinopyroxene, and plagioclase will define a single straight line having a slope of one and, ideally, a non-zero intercept. Data seldom fit models perfectly but if the model is adequate, we expect the compositions of the lava flows to plot within analytical uncertainty of a single model line with unit slope. The ellipses on Figure 4 illustrate the analytical uncertainty that can be ascribed to each data point.

Data points representing rocks with accumulated minerals will plot on the model line at higher ratio values. Data points representing rocks that have fractionated (lost) minerals will plot on the model line at lower ratio values. Data points that scatter off the model line represent rocks related in other ways (Fig. 4).

What is absolutely clear is that the combined 1970–1971 Mauna Ulu data set (Figs. 1, 4) does not conform to a single straight line of any slope (compare Fig. 4 with Fig. 1) let alone a slope of one. Nor will two model lines with slopes of one fit the 1970 and 1971 Mauna Ulu compositions separately. Consequently, the differentiation model as stated above is inadequate; sorting of olivine, clinopyroxene, and plagioclase fails to explain all the chemical variations. Rather, some other or additional processes must play a role and this fact has led to the myriad of alternate explanations in the literature on Mauna Ulu magmas (see Hofmann et al. 1984; Vinet and Higgins 2010).

Trace element ratios provide insight into other processes that can contribute to, or limit, the chemical diversity of the Mauna Ulu magmas. Although partition coefficients control trace element concentration instead of mineral stoichiometry, ratios of trace elements can be integrated into Pearce element ratio diagrams (Halleran and Russell 1990; Russell and Halleran 1990). Figure 5 shows the ratio of two incompatible elements, Yb and Ce, projected onto the assemblage test diagram of Figure 4. The trace element data define two chemically distinct groups: (1) the 1970 flows (70-25, 70-41, 70-35, 70-62, and 70-83), and (2) the 1971 flows (71-127, 71-134, 71-136, and 71-137); evidence consistent with a model encompassing two separate chemical systems.

Analogous plots of ratios for the rare earth elements Er/Ce, Dy/Ce, Eu/Ce, Sm/Ce, and Nd/Ce are shown on Figure 6. With two exceptions, the REE data are consistent with two magma batches in the 1970–1971 data. The Nd/Ce ratios for 71-134 and 71-137 fail to fall at higher values than the high-

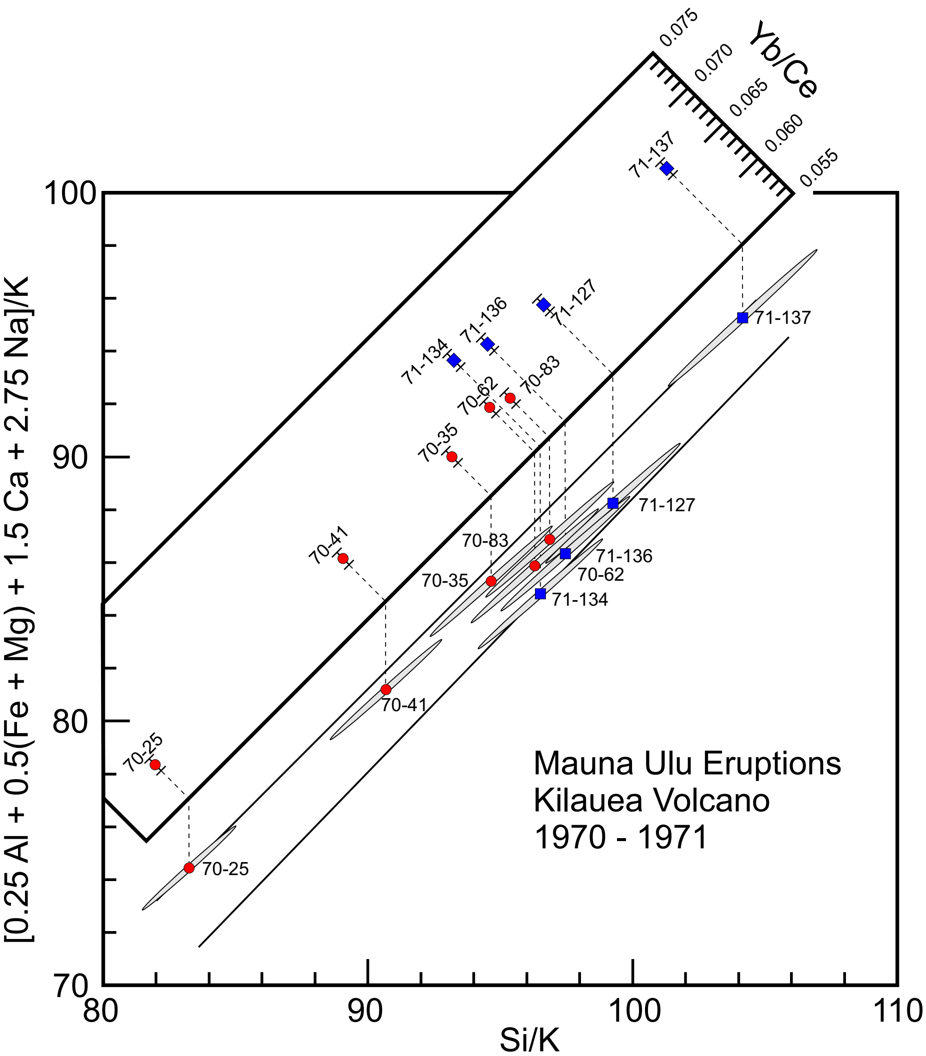

Figure 5. Same diagram as Figure 4 but with the ratios of two incompatible trace elements (Yb and Ce) projected on the diagram. The distribution of the trace element ratios distinguishes the flows erupted in 1970 from those erupted in 1971, indicating the presence of two chemical systems among the eruptive products. The shaded ellipses represent the expected variation in location of the data points due to analytical uncertainty.

est values of the 1970 ratios although some are within our estimates of analytical uncertainty.

Phase Discrimination Diagrams

The 1970–1971 Mauna Ulu lava flows belong to two distinct chemical systems, one represented in the 1970 lava flows and the other in the 1971 lava flows (Figs. 4, 5). The assemblage test diagram designed to test a model of sorting of olivine, clinopyroxene, and plagioclase in any combination, showed that the chemical variations within and between the two lava groups are inconsistent with simple sorting of the common basalt phenocryst assemblage. Furthermore, the ratios of most of the rare earth elements are distinct and coherent for the 1970 versus 1971 Mauna Ulu lava flows (Figs. 5, 6). This precludes simple mixing of the two chemical systems as an explanation for the diversity.

What other possibilities make physical-chemical sense? The natural choice is to add another phase to the sorted assemblage. An Fe-Ti oxide and/or orthopyroxene crystallize in many basaltic magmas and are likely candidates.

The conserved element ratio diagram (Fig. 3) suggests Ti is not conserved in all the samples, especially sample number 70-25. An assemblage test diagram that incorporates the possibility of an Fe-Ti oxide having a composition equal to 75% ulvospinel, 25% magnetite is shown on Figure 7. Four of the five 1970 data points fall close to a line with a slope of one (70-41, 70-35, 70-62, and 70-83). 70-25, however, falls more than one unit of analytical uncertainty from the line. None of the 1971 data points fall on the same line with its slope of one nor do they fall on a different line with a slope of one. Sorting of an Fe-Ti oxide may be a factor in creating chemical diversity in the 1970 data but it is an incomplete explanation at best. It fails to explain the scatter in the 1971 data.

Orthopyroxene (or another low-calcium pyroxene, e.g. pigeonite) occurs in the phenocryst assemblages of some basaltic rocks along with plagioclase, olivine, and clinopyroxene (Deer et al. 2013). Below, we give reasons for including orthopyroxene in the sorted assemblage that go beyond the simple fact that it is found in some basalt suites. Here, our purpose is to introduce another type of Pearce element ratio diagram, the phase discrimination diagram. This diagram isolates the effects a rival phase would have on a trend caused by sorting. Orthopyroxene will be the rival phase. The coefficients of such diagrams are designed to force the greatest deviation from a line with slope of one if sorting of the rival phase occurs (Stanley and Russell 1989, 1990). Again, the methods for the calculation of the coefficients are discussed below. The phase discrimination diagram shown in Figure 8 is designed to test the model of sorting of olivine ± clinopyroxene ± plagioclase, but has the property such that sorting of orthopyroxene will have a maximum discernible effect; orthopyroxene sorting causes a trend to develop at right angles to the trend caused by sorting of the other phases.

In this phase discrimination diagram (Fig. 8), the Mauna Ulu data show increased scatter compared to Figures 4, 5, and 7. The nature of the scatter is consistent with orthopyroxene sorting contributing to the chemical variations within the data sets. The 1970 Mauna Ulu lava flows could have fractionated orthopyroxene with the other three phases; this conclusion follows from the data defining a trend with a slope greater than one. Orthopyroxene accumulation accompanied by fractionation of the other three phases is suggested by the trend defined by the 1971 data where the slope of the trend is less than one. However, in both cases, the total chemical effect of orthopyroxene sorting is subordinate to the effects of sorting of olivine ± clinopyroxene ± plagioclase. The slopes of the lines through the trends (Fig. 8) lead to estimates of 0.15–0.25 for the ratios of orthopyroxene to olivine ± clinopyroxene ± plagioclase in the sorted assemblages.

Table 3. Element ratios for the 1970–1971 Mauna Ulu eruptions as plotted on Figures 6 and 7 with X = Si/K and Y = [0.25 Al + 0.5 (Fe + Mg) + 1.5 Ca + 2.75 Na]/K. Also listed are the Y-intercepts for lines drawn through each data point (Y_0) and having a model slope of 1.0 and the corresponding mean values, the standard deviations (s) and the analytical uncertainty associated with the data set and subsets (s_A).

Sample	X-axis Ratio	Y-axis Ratio	Intercept (Y_0)
70-25	83.24	74.435	-8.804
70-41	90.673	81.191	-9.482
70-35	94.657	85.297	-9.359
70-62	96.298	85.882	-10.416
70-83	96.866	86.877	-9.989
71-134	96.511	84.817	-11.694
71-136	97.454	86.338	-11.116
71-127	99.249	88.243	-11.006
71-137	104.148	95.267	-8.882
Mean	95.455	85.372	-10.083
s	5.8147	5.5568	1.0367
s_A	4.7362	4.2512	0.7072
70- Mean	92.347	82.736	-9.61
70- s	5.6371	5.121	0.6169
70- s_A	4.4348	3.9857	0.5696
71- Mean	99.341	88.666	-10.675
71- s	3.4003	4.6183	1.2325
71- s_A	5.0879	4.5613	0.6512

DESIGNING DIAGRAMS WITH LINEAR ALGEBRA

So, how does one calculate the complex, non-intuitive, elemental coefficients used in the assemblage test and phase discrimination diagrams (i.e. Figs. 4, 5, 7, 8)? The challenge is to find combinations of ratios for the axes of the Pearce element ratio diagram that will cause the geochemical data points to plot as a line with a prescribed slope. The slope of the line is prescribed by the model and by the mineral stoichiometry of the sorted phases. The expectation that the data points will fall on the line is a consequence of the model. The slope most commonly prescribed is one.

Matrix algebra provides the most efficient methods for determining the ratios and the methods are straight-forward if the slope is one. Stanley and Russell (1989, 1990), and Nicholls and Gordon (1994) provide extensive descriptions of the requisite matrix methods.

Two types of matrix equations are used to derive the ratios for a Pearce element ratio diagram that tests the consequences of a model: assemblage test equations and phase discrimination equations (Stanley and Russell 1990). As used above in our analysis of the 1970–1971 Mauna Ulu lava flows, assemblage test diagrams are used to determine whether the variations in the data can be explained by sorting of an assemblage of one or more phases, whereas phase discrimination diagrams are used to determine whether a particular phase is required to explain the variations in the data.

Designing Assemblage Test Diagrams

The starting point is a matrix equation that can be written:

$$\mathbf{C} \cdot \mathbf{A} = \mathbf{P} \qquad (Eq.\ 1)$$

where **C** is the (M x N) matrix of the compositions of the phases causing differentiation. M is the number of phases in the system (for example, M = 4 for the assemblage olivine, albite, anorthite, and clinopyroxene). N is the number of distinct elements in the phases being sorted (N = 5 in our example: Si, Al, Fe + Mg, Ca, and N). The rows of **C** are the compositions of the phases and the columns are the elements in each phase. These numbers come from the mineral formulae of the phases we think caused the chemical variations.

A is an (N x 2) matrix of unknown coefficients of the elements that appear in the numerators of the ratios. The two columns are themselves matrix vectors, **X** and **Y**. **X** contains the coefficients of the elements in the numerator of the ratio plotted on the X-axis and **Y** contains the coefficients for the other axis ratio. The components of **X** and **Y** are the unknowns we want to find by solving the matrix equation (Eq. 1).

The column vectors of matrix **P**, which is an M x 2 matrix, are the displacement vectors: **u** and **v**. The M rows of **P** (i.e. the mathematical elements of **u** and **v**) are the relative displacement vectors for each of the M minerals on the two axes of the Pearce element ratio diagram. The relative displacement vectors are set by the slope of the line we choose to assign to the hypothesis. If we want a slope of 1 for each of the M minerals involved in a sorting hypothesis, then the corresponding row elements of **u** and **v** for each phase will be set equal (e.g. $u_i = v_i$). If for some reason a slope of 2 were preferred then all row elements would be adjusted accordingly: $u_i = 0.5\ v_i$, where v_i is an arbitrary number. The magnitude of v_i chosen dictates the length of the resulting displacement vector for each model phase; it is common to set v_i to 1.0 so each phase will have the same relative displacement on the Pearce element ratio diagram.

For the assemblage: plagioclase, olivine, clinopyroxene, the matrix equation, (Eq. 1), can be written:

$$\begin{array}{cc} & \mathbf{C} \\ & \begin{array}{ccccc} \mathrm{Si} & \mathrm{Al} & \mathrm{FM} & \mathrm{Ca} & \mathrm{Na} \end{array} \\ \begin{array}{c} \mathrm{An} \\ \mathrm{Ab} \\ \mathrm{Ol} \\ \mathrm{Cp} \end{array} & \begin{bmatrix} 2 & 2 & 0 & 1 & 0 \\ 3 & 1 & 0 & 0 & 1 \\ 1 & 0 & 2 & 0 & 0 \\ 2 & 0 & 1 & 1 & 0 \end{bmatrix} \end{array} \begin{array}{c} \mathbf{A} \\ \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \\ x_5 & y_5 \end{bmatrix} \end{array} = \begin{array}{c} \mathbf{P} \\ \begin{bmatrix} u_1 & v_1 \\ u_2 & v_2 \\ u_3 & v_3 \\ u_4 & v_4 \end{bmatrix} \end{array} \qquad (Eq.\ 2)$$

Because the two matrices, **A** and **P**, each consist of two column vectors, the last equation (Eq. 2) can be split into two:

$$\mathbf{C} \cdot \mathbf{X} = \mathbf{u} \qquad (Eq.\ 3)$$

$$\mathbf{C} \cdot \mathbf{Y} = \mathbf{v} \qquad (Eq.\ 4)$$

If the desired slopes for all the phases represented by the displacement vectors are 1, then the constraints on the slopes, as reflected in the displacement vectors, **u** and **v**, can be written:

$$\mathbf{u} = \mathbf{v} \qquad (Eq.\ 5)$$

or for each i, $u_i = v_i = 1$.

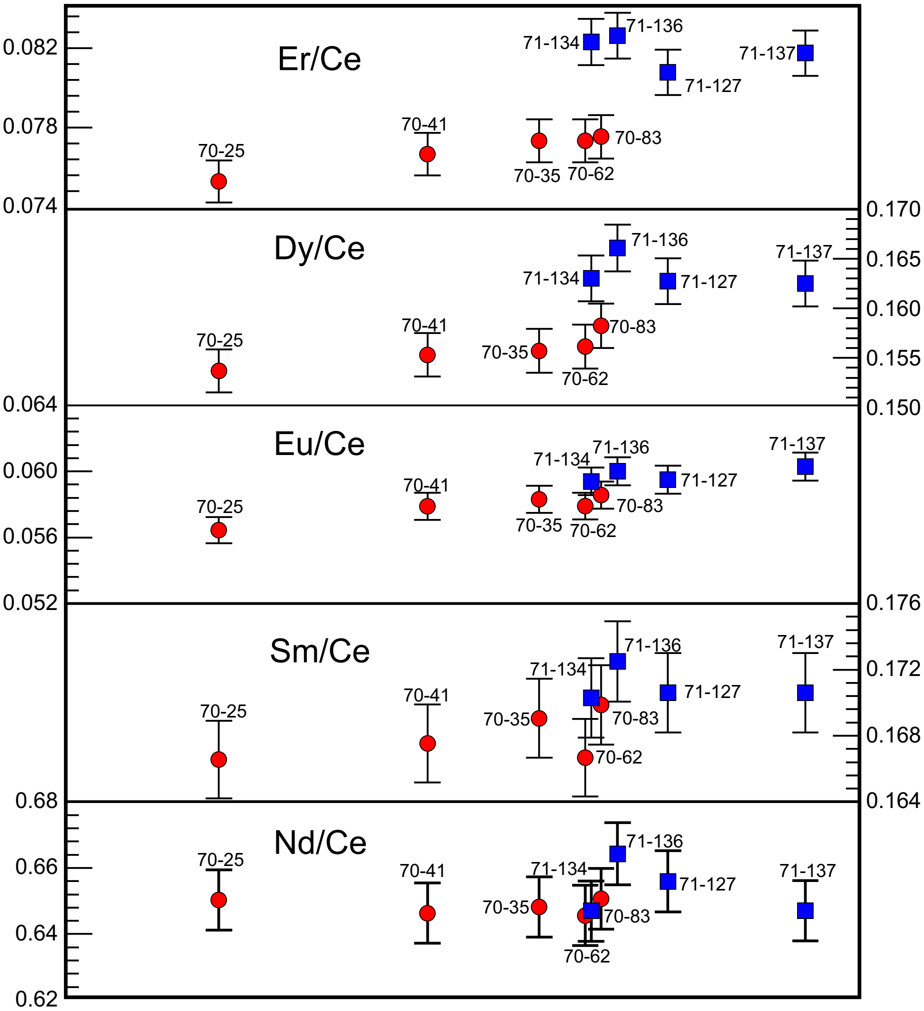

Figure 6. Rare earth element ratios for the 1970–1971 Mauna Ulu lava flows. The horizontal scale is the same as that shown on Figure 7 for Yb/Ce.

For a slope of one, the displacement along the X-axis must equal the displacement along the Y-axis.

Hence:

$$\mathbf{C} \cdot (\mathbf{X} - \mathbf{Y}) = \mathbf{0} \qquad \textit{(Eq. 6)}$$

If the number of phases, M, is less than the number of elements in the phases, N, then the rank of **C** must be less than N and there may be a non-trivial solution to Equation 6 (i.e. a useful set of coefficients). The solution vectors of Equation 6 can be obtained by various methods, such as singular value decomposition, outlined in matrix algebra texts (Press et al. 1992) or by successive row operations. A calculator for doing the latter process can be found on-line at: www.math.purdue.edu/~dvb/matrix.html. The elements of the solution vector can be normalized, if desired, so that the coefficient of at least one of the chemical elements in the numerator of the X-axis ratio, say, is equal to one.

If the conserved element is K, the ratio pair derived by solving Equation 2 – Equation 6 is:

$$[0.25\ \mathrm{Al} + 0.5\ (\mathrm{Fe} + \mathrm{Mg}) + 1.5\ \mathrm{Ca} + 2.75\ \mathrm{Na}]/\mathrm{K} \text{ versus } \mathrm{Si}/\mathrm{K} \qquad \textit{(Eq. 7)}$$

A given model may lead to more than one set of coefficients and more than one Pearce element ratio diagram will provide additional tests. In fact, the number of valid Pearce element ratio diagrams that can be derived from a matrix of phase compositions, **C**, is equal to the column size of the matrix, N, minus the rank of the matrix, a number called the nullity of the matrix (Ayres 1962). In the example above (Eq. 4), the column dimension of the matrix **C** is five and its rank is four; thus, there is a single solution.

Suppose, however, that the hypothesis called for only three phases or end members: albite, anorthite, and olivine. The system of equations then becomes:

$$\overset{\mathbf{C}}{\begin{array}{c|c} & \mathrm{Si}\ \ \mathrm{Al}\ \ \mathrm{FM}\ \ \mathrm{Ca}\ \ \mathrm{Na} \\ \begin{array}{c}\mathrm{An}\\ \mathrm{Ab}\\ \mathrm{Ol}\end{array} & \begin{bmatrix} 2 & 2 & 0 & 1 & 0 \\ 3 & 1 & 0 & 0 & 1 \\ 1 & 0 & 2 & 0 & 0 \end{bmatrix}\end{array}} \overset{\mathbf{A}}{\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \\ x_5 & y_5 \end{bmatrix}} = \overset{\mathbf{P}}{\begin{bmatrix} u_1 & v_1 \\ u_2 & v_2 \\ u_3 & v_3 \end{bmatrix}} \qquad \textit{(Eq. 8)}$$

an equation for which the number of columns (5) minus the number of rows (3) equals 2, indicating that there are two Pearce element ratio diagrams that can test the same model against the data. The solutions to Equation 8 can be cast into the ratios that we plot on the X-axis and Y-axis.

$$(\mathrm{Si} + 0.333\ \mathrm{Ca})/\mathrm{K} \text{ versus } [1.167\ \mathrm{Al} + 0.5(\mathrm{Fe} + \mathrm{Mg}) + 1.833\ \mathrm{Na}]/\mathrm{K} \qquad \textit{(Eq. 9)}$$

and:

$$\mathrm{Al}/\mathrm{K} \text{ versus } (2\ \mathrm{Ca} + \mathrm{Na})/\mathrm{K} \qquad \textit{(Eq. 10)}$$

In vector form, the two solutions to the matrix equation (Eq. 8) are:

	$(\mathbf{X}-\mathbf{Y})_1$	$(\mathbf{X}-\mathbf{Y})_2$
Si	1.0	0.0
Al	-1.167	1.0
Fm	-0.5	0.0
Ca	0.333	-2.0
Na	-1.833	-1.0

We arbitrarily assign positive values in the solutions to coefficients of elements in the numerator of the ratio plotted on the X-axis whereas negative values, with the minus sign dropped, are assigned to coefficients in the numerator of the ratio plotted on the Y-axis.

Generally, if the number of phases, M, is equal to the number of elements, N, the rank of **C** will also equal N. In such instances, the set of homogeneous equations:

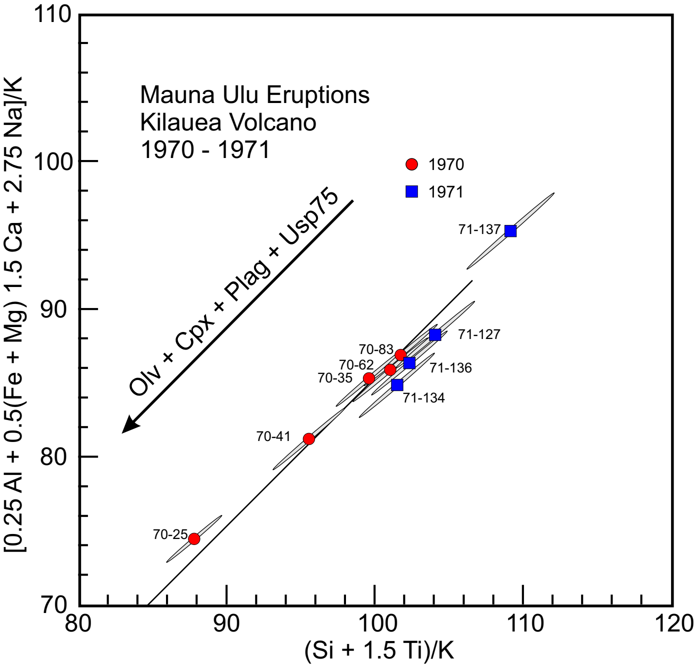

Figure 7. Assemblage test diagram to determine if a model with sorting of olivine, clinopyroxene, plagioclase, and a Fe-Ti oxide (Usp75) accounts for the distribution of the data points (compare Fig. 5). The shaded ellipses represent the expected variation in location of the data points due to analytical uncertainty. The solid line with a slope of one line touches all the 1970 error ellipses except 70-25.

$$\mathbf{C} \bullet (\mathbf{X} - \mathbf{Y}) = \mathbf{0} \qquad \textit{(Eq. 11)}$$

will only have the trivial solution ($\mathbf{X} - \mathbf{Y}$) = $\mathbf{0}$ or, in other words, the X-axis ratio is the same as the Y-axis ratio. This will produce a plot with a perfect straight line but it will also contain no information. Exceptions to this point occur if the rank of the coefficient matrix is less than *N*. If the composition of one (or more) of the phases is a linear combination of some of the other phases, then the rank of **C** will be less than *N*.

Suppose, for example, the hypothesis is that the variations are due to sorting of plagioclase, clinopyroxene, olivine, ulvospinel and apatite. The number of phases or end members, *M*, is 8: An, Ab, Fo, Fa, Di, Hd, Up, and Ap. The number of elements to be placed in the ratios, *N*, is also 8: Si, Al, Ti, Fe, Mg, Ca, Na, and P. The rank of the coefficient matrix, **C**, is less than 8 because there is a linear combination relating the compositions of four of the end members, fayalite, diopside, hedenbergite, and forsterite:

$$\tfrac{1}{2}\,Fe_2SiO_4 + CaMgSi_2O_6 = CaFeSi_2O_6 + \tfrac{1}{2}\,Mg_2SiO_4 \qquad \textit{(Eq. 12)}$$

A pair of ratios that will provide a slope of one on a Pearce element ratio diagram, if the variations are due to sorting of plagioclase, clinopyroxene, olivine, ulvospinel, and apatite are:

$$\begin{gathered}(2.25\ \mathrm{Al} + 0.5\ \mathrm{FM}\ 1.5\ \mathrm{Ca} + 2.75\ \mathrm{Na})/K \text{ versus} \\ (\mathrm{Si} + \mathrm{Ti} + 2.5\ \mathrm{P})/K\end{gathered} \qquad \textit{(Eq. 13)}$$

Assemblage test diagrams need not have axial ratios defining a slope of one if sorting of the model assemblage produced the chemical variations. The matrix equation, Equation 1, however, reduces to a system of homogeneous equations, Equation 7, only if the model slope is equal to one.

Designing Phase Discrimination Diagrams

In our analysis of the geochemical diversity of the 1970–1971 Mauna Ulu lava flows, we considered whether or not orthopyroxene may have been involved in the differentiation process. To test this model, we designed a phase discrimination diagram (Fig. 8) to test for potential sorting of the rival phase, orthopyroxene [$(Mg,Fe)_2Si_2O_6$], versus sorting only of olivine, clinopyroxene, and plagioclase.

For this rival phase we want the displacement vectors to point in a direction at a high angle (i.e. perpendicular) to the model trend, which usually has a slope of 1. As a result, the right side of Equation 6 will not be a zero vector and the system of equations will not be homogeneous.

The components of the displacement vectors for orthopyroxene (Op) must be such that the orthopyroxene vector has a slope of –1 on a Pearce element diagram. Such a feature will occur if $\mathbf{u}_{Op} = -\mathbf{v}_{Op}$.

If we assign the coefficients of the elements in the numerator of the left-ratio to **X** and the coefficients of the elements in the numerator of the right ratio (Eq. 8) to **Y**, then one can show that the resulting vectors satisfy the equation:

$$\mathbf{C} \bullet (\mathbf{X} - \mathbf{Y}) = \mathbf{0} \qquad \textit{(Eq. 14)}$$

Note that the components of the column vectors corresponding to orthopyroxene have opposite signs.

Again, because of equality in number of elements in the vectors **X** and **Y** and in the vectors **u** and **v**, this last equation can be written as two:

$$\mathbf{C} \bullet \mathbf{X} = \mathbf{u} \qquad \textit{(Eq. 15)}$$
$$\mathbf{C} \bullet \mathbf{Y} = \mathbf{v} \qquad \textit{(Eq. 16)}$$

The coefficients for the **X** and **Y** vectors for these non-homogeneous systems of equations can be extracted by solving for **X** and **Y** separately. Solving Equation 15 will provide the coefficients for the numerator of the ratio plotted on the X-axis, whereas solving Equation 16 provides the coefficients for the numerator of the ratio plotted on the Y-axis. These two equations are, in general, enough to give a ratio pair with the desired properties. There are several numerical techniques for solving such equations, such as singular value decomposition or row reduction methods. A web site that features and explains the latter process is:
www.math.odu.edu/~bogacki/cgi-bin/lat.cgi?c=sys.

Incorporating Mineral Analyses in Pearce Element Diagrams

Pearce element ratios are often calculated for the stoichiometry of ideal mineral formulae or end members. The compositions of minerals actually sorted in rock-forming processes deviate to a greater or lesser extent from the compositions of end members. At best, these deviations will cause small amounts of scatter from the predicted trends on Pearce element ratio diagrams. At worst, they can produce significant deviations from the predicted trends.

Olivine and plagioclase are two commonly occurring minerals in mafic igneous rocks whose compositions are close enough to ideal to not cause scatter greater than analytical uncertainty. On the other hand, augite often contains Al, Ti,

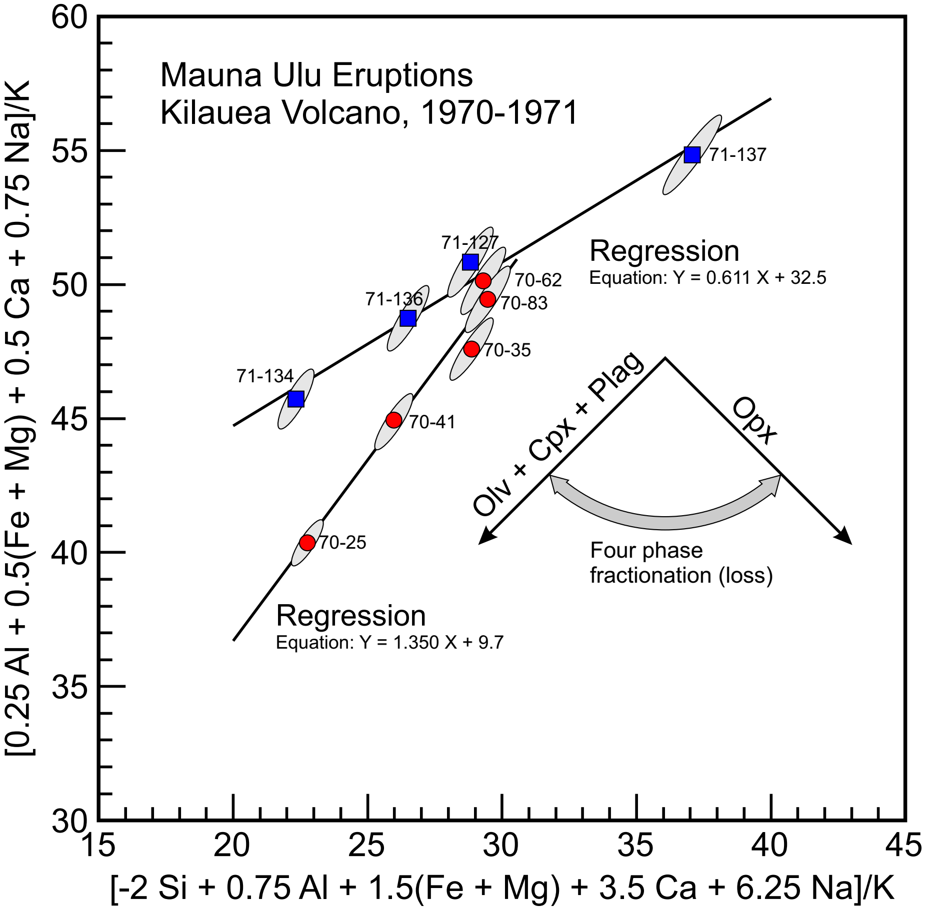

Figure 8. Phase discrimination diagram to best test whether sorting of orthopyroxene in addition to olivine, clinopyroxene, and plagioclase would affect the dispersion of the data compared to the diagrams in Figures 5, 6. The small arrows in the middle right contrast the trends successive melts would follow if fractionation of olivine, clinopyroxene, and plagioclase separated from the melts compared to separation of orthopyroxene. Separation of both olivine + plagioclase + clinopyroxene and orthopyroxene would create a trend between the two (broad grey arrow). The solid lines are the best fit, least-squares lines through the 1970 and 1971 data points. They approximate the paths in Pearce element ratio space that fractionation (all four phases, 1970 data) or accumulation (orthopyroxene) and fractionation (other three phases, 1971 data) would create. The tangents of the angles between the three-phase direction and the orthopyroxene directions are an estimate of the relative importance of the two processes, three-phase separation versus orthopyroxene separation or accumulation.

and excess Mg, deviating from the ideal. For some minerals, minor components can contribute substantial scatter to the data and a significant departure from the slope for an ideal end member. Table 4 lists the slopes expected from ideal solid solutions of olivine, plagioclase, and clinopyroxene and the analogous slopes calculated from analyses of typical basaltic minerals. The worst case is an error in slope of approximately 6° for an augite with considerable Al and Ti in solid solution.

Figure 9 shows two models testing whether the phase assemblage olivine, clinopyroxene, plagioclase, and an Fe-Ti oxide (Usp_{75}) can explain the chemical diversity in the 1967–1968 Halemaumau and Hi'iaka eruptions from Kilauea Volcano (Wright et al. 1975; Nicholls and Stout 1988). One model was constructed with an ideal clinopyroxene composition; the other was constructed using the composition of the most femic clinopyroxene-bearing sample (HI-14, Nicholls and Stout 1988, their table 4). The composition matrices (**C**, Eq. 1) are shown in Table 5. The entries in the Cpx row come directly from the formula calculated from the mineral analysis. The matrix methods described above return the same ratio for the X-axis for both models. Only the Y-axis ratio differs between the two models.

The foremost question is if the incorporation of an analyzed mineral composition provides more information on the adequacy of the model as an explanation for the chemical diversity? In this instance, the answer is no. Figure 9 shows that the data fit either model almost equally well. The data plotted with the two separate Y-axis coefficients (ideal solid solutions versus analyzed compositions) describe two lines that are different only in their Y-axis values. The two models describe linear trends of equal quality and allowing for real substitutions in the clinopyroxene do not improve the linearity nor do they reduce the dispersion in the location of the data points.

In other instances, incorporation of analyzed mineral compositions is essential for a successful Pearce element ratio analysis. If the sorted assemblage contains minerals of more variable stoichiometry, such as amphibole, then the deviations from the slopes expected for ideal compositions become more extreme. An innovative example is supplied by the data from the study of the granitic plutons forming part of the Coast Range Batholith in southwestern British Columbia (Cui and Russell 1995). They incorporated measured amphibole compositions into the phase composition matrices to create Pearce element ratio models for several different plutons that outcrop along a transect crossing the southwestern corner of the batholith. Intercepts revealed different source regions for different plutons, information not readily seen in the unmodified analytical data, indicating different chemical characteristics for source regions that supplied the granitic magma.

Verifying Pearce Element Ratio Diagrams

If, by some procedure or by inspiration one devises a ratio pair that is supposed to generate a trend with a slope dictated by a particular model; how, then, can the claim be verified? For example, how can one check that the pair of ratios plotted on Figure 4 will produce a slope of one if each of the phases in the model, olivine, plagioclase, and clinopyroxene, are sorted? This check becomes even more necessary if measured compositions of minerals in the samples are introduced into the phase composition matrix, **C** (Eq. 1, Table 5), or if the ratios come from inspiration. A diagram created through inspiration is shown on Figure 10. Neither sorting of plagioclase ($CaAl_2Si_2O_8$, $NaAlSi_3O_8$) nor clinopyroxene [$Ca(Mg,Fe)Si_2O_6$] will affect the distribution of data points on this diagram. It shows only the distribution caused by sorting of olivine [$(Mg,Fe)_2SiO_6$] and orthopyroxene [$(Mg,Fe)_2Si_2O_6$].

Fortunately, one can check for each phase that a diagram will produce a line with the slope dictated by the model. One

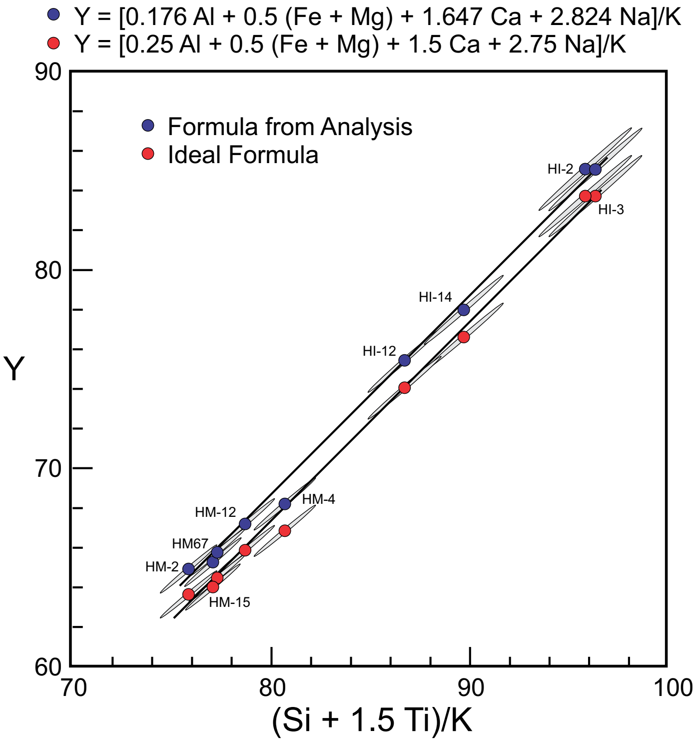

Figure 9. Two Pearce element ratio models to test whether the chemical diversity in the 1968 Kilauea eruptive products (Wright et al. 1975; Nicholls and Stout 1988) can be explained by sorting of olivine, clinopyroxene, plagioclase and Fe-Ti oxide (Usp_{75}). Lines with slopes of one are drawn through HI-3. The model shown in blue uses an analyzed pyroxene in the phase composition matrix (Eq. 1). The other model (shown in red) uses the ideal clinopyroxene formula [Ca(Fe,Mg) Si_2O_6].

does this by calculating the ratio of the components in the numerator of **Y** to those in the numerator of **X**. For the phase assemblage diagram (Fig. 4), the ratios are:

[0.25 Al + 0.5 (Fe + Mg) + 1.5 Ca + 2.75 Na]/K and Si/K

and the calculations that verify the ratios are:

$(Mg,Fe)_2SiO_4$ Olivine:	**Y/X** = [0.5 x 2 (Fe + Mg)]/1 Si = 1/1
$NaAlSi_3O_8$ Albite:	**Y/X** = [0.25 Al + 2.75 Na]/3 Si = 1/1
$CaAl_2Si_2O_8$ Anorthite:	**Y/X** = [0.25 x 2 Al + 1.5 Ca]/2 Si = 1/1
$Ca(Mg,Fe)Si_2O_6$ Cpx:	**Y/X** = [1.5 Ca + 0.5 Fe + Mg]/2 Si = 1/1

Given a mineral of known stoichiometry or composition, this procedure will return the slope of the trend that sorting of that phase will generate on the diagram. For example, on Figure 8, the arrows in the lower right corner show the directions loss of olivine, clinopyroxene, plagioclase, and orthopyroxene would impart to a trend caused by fractionation. Performing the exercise for orthopyroxene gives:

$(Mg,Fe)_2Si_2O_6$ Opx:
Y/X = ½[2(Fe + Mg)]/[-2(2Si)+1½ 2(Fe + Mg)] =1/-1

In other words, orthopyroxene sorting alone would generate a trend with a slope of –1.

Intercepts of Trends on Pearce Element Ratio Diagrams

Usually, geochemical trends are analyzed with regression methods and the trend is evaluated and interpreted on the basis of its slope, intercept, and the associated correlation coefficient. Pearce element ratio diagrams suggest an alternate strategy wherein the slope of the trend is dictated by the model. The slope is not extracted from the data; rather the model slope, representing a specific hypothesis, is compared directly against the data itself. Consequently, we can draw a line with the model slope through each data point on the diagram. Each data point will then define a unique intercept value. It is this set of intercepts that provides insight into the nature and uniqueness of the chemical system. Co-genetic rocks plotted on assemblage test diagrams ideally should have equal intercepts. In practice they will not because of analytical uncertainty. The intercepts will have a mean and a standard deviation consistent with the expected analytical uncertainties.

Significantly different intercepts in and between data sets distinguish different magma batches and, by inference, different melting events (Russell and Nicholls 1988; Russell and Stanley 1990a, b; Nicholls and Russell 1991; Cui and Russell 1995).

ORIGINS OF CHEMICAL VARIATIONS WITHIN THE 1970–1971 MAUNA ULU LAVA FLOWS

Our analysis of the geochemical compositions of the 1970 and 1971 Mauna Ulu lava flows with Pearce element ratios reveals several patterns and insights. First, the elements that are likely candidates for conserved behaviour in basaltic magmas show mixed results (Fig. 3). The data fall on a trend compatible with crystal sorting but with considerable scatter off the model trend (Fig. 4). Ratios of incompatible trace elements (Yb/Ce, Er/Ce, Dy/Ce, Eu/Ce, and Sm/Ce; Figs. 5, 6) separate the data into distinct sets that correlate with time of eruption.

Table 3 lists the values of the mean and variance for the ratios and intercepts for the full data set from the 1970–1971 Mauna Ulu eruptions. The values derive from the ratio pair used to create Figure 4:

[0.25 Al + 0.5 (Fe + Mg) + 1.5 Ca
+ 2.75 Na]/K versus Si/K

Also listed is the expected variation in the mean intercept values due to analytical uncertainty. The variation attributable to analytical uncertainty is less than the standard deviation of the data; a consequence expected if more than one chemical system is included in the data set (see Figs. 4, 5, 6). Three of the 1971 data points plot at values smaller or larger than the mean plus or minus the standard deviation whereas only one 1970 data point (70-25) has this distinction. Further, four of the five 1970 intercepts have values greater than the mean and three of the four 1971 data points have values less than the mean, again suggesting two magma batches.

Table 3 also lists the means and standard deviations for the ratios and intercepts for the two data groups separately, as delineated by the trace elements, along with the expected variations due to analytical uncertainty. The expected variation in analytical uncertainty for the 1970 samples is slightly larger than the standard deviation for the data. The 1971 data scatter considerably more than the expected analytical variation.

The question, therefore, is how to explain the chemical diversity expressed within and between the 1970 and 1971 Mauna Ulu lava flows? We consider four possible models:

Table 4. Comparison of slopes (*M*) calculated from mineral analyses to slopes for end members.

Ratio Pair	Mineral	*M* (Mineral Analysis)		*M* (Ideal Mineral)	
(**Fe** + **Mg**) vs. **Si**	Olivine	1.980 ± 0.033	63.2º ± 0.4º	2	63.4º
	Augite	0.638 ± 0.037	32.4º ± 1.5º	½	26.6º
(**2 Ca** + **Na**) vs. **Al**	Plagioclase	1.054 ± 0.015	46.4º ± 0.4º	1	45.0º
	Augite (N = 15)	13.473 ± 3.347	85.8º ± 1.2º	∞	90.0º

Table 5. Phase composition matrices for end member minerals and from a clinopyroxene calculated from a mineral analysis (Nicholls and Stout 1988).

End Member Matrix:

$$\begin{array}{l} \text{An} \\ \text{Ab} \\ \text{Fo} \\ \text{Fa} \\ \text{Di} \\ \text{Hd} \\ \text{Usp} \end{array} \begin{bmatrix} 2 & 0 & 2 & 0 & 0 & 1 & 0 \\ 3 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 2 & 0 & 0 \\ 1 & 0 & 0 & 2 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 1 & 1 & 0 \\ 2 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0.75 & 0 & 2.25 & 0 & 0 & 0 \end{bmatrix}$$

Mineral Analysis Matrix:

$$\begin{array}{l} \text{An} \\ \text{Ab} \\ \text{Fo} \\ \text{Fa} \\ \text{Cpx} \\ \text{Usp} \end{array} \begin{bmatrix} 2 & 0 & 2 & 0 & 0 & 1 & 0 \\ 3 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 2 & 0 & 0 \\ 1 & 0 & 0 & 2 & 0 & 0 & 0 \\ 1.869 & 0.042 & 0.197 & 0.211 & 0.867 & 0.792 & 0.019 \\ 0 & 0.75 & 0 & 2.25 & 0 & 0 & 0 \end{bmatrix}$$

1. The chemical diversity of the Mauna Ulu samples arises through sorting of olivine, clinopyroxene, and plagioclase.
2. The diversity arises through sorting of the phenocryst phases combined with mixing of two chemically distinct magmas, the 1970 and the 1971 magma batches.
3. The diversity arises through sorting of olivine, clinopyroxene, and plagioclase plus another phase such as Fe-Ti oxide or orthopyroxene.
4. The diversity arises through melting of source regions with distinct differences in major element chemistry.

The 1970 and 1971 data sets define general trends expected from sorting olivine, clinopyroxene, and plagioclase (Model 1). However, in both cases, the dispersion in the Pearce element ratios is greater than can be ascribed to analytical uncertainties (Table 3). Consequently, we conclude that the scatter is too large for sorting to be the sole cause of the diversity, especially in the 1971 data. Although one could argue that the dispersion in the 1970 data is not large enough to definitely rule out the sorting model.

A model involving mixing between two magma batches represented by compositions within the 1970 and 1971 lava suites (Model 2) would be consistent with the major element dispersion shown on Figures 4 and 5. The end-member compositions involved in mixing could, for example, be the extreme compositions that fall on the extremes of the trends shown. The mixing model fails, however, because of the distinct separation in the trace element data between the 1970 and 1971 lava flows (Figs. 5, 6). If mixing occurred, the trace element ratios should show a dispersed pattern analogous to the dispersion of the major elements shown on Figure 4.

Model 3, which involves sorting of orthopyroxene, is questioned or rejected by many scientists because orthopyroxene has not been reported in any of the Mauna Ulu lava flows (Wright 1971; Wright and Fiske 1971; Wright et al. 1975; Hofmann et al. 1984). In fact, orthopyroxene phenocrysts are rarely found in recent Kilauea lava flows. The only exceptions among the modern eruptions are the lava flows erupted in 1955 (Ho and Garcia 1988), which contain orthopyroxene phenocrysts. It sporadically occurs in trace amounts in the groundmass of lava flows erupted on the flank of the volcano (Richter and Murata 1966). By contrast, lava flows erupted from neighbouring Mauna Loa typically contain orthopyroxene phenocrysts (Russell 1987). In some Mauna Loa flows they are overgrown by clinopyroxene (Nicholls and Stout 1997).

We view this problem from two perspectives: 1) Are there circumstances and conditions where orthopyroxene could be sorted and leave no physical indication of its presence but only a pattern in the chemical data? 2) Are there other tests for its participation?

To counter the rarity argument, one can consider thermodynamic modeling with MELTS (Ghiorso and Sack 1995). Such modeling shows that:

1. Basalt melts commonly have orthopyroxene as the first phase to crystallize with falling temperature at pressures corresponding to deeper parts of the Earth, depths below those of the mid-crust. Examples can be found in Russell (1987), Stout et al. (1989), Nicholls and Stout (1997), and Nicholls (2013). Figure 11 shows an example from the Mauna Ulu compositions. If sorting takes place at high pressure, say during transport, then it is conceivable that orthopyroxene would be part of the fractionated assemblage. At lower pressures, olivine and/or clinopyroxene and/or plagioclase crystallize first. If the melt is subjected to lower pressures on ascent and if the ascent rate is such that there is time for the orthopyroxene to dissolve, then no physical trace would remain. At the lower pressures, the high-pressure phases will be most out of equilibrium and the heat to dissolve them will come from the melt, lowering its temperature until the lower pressure phases (olivine and clinopyroxene) saturate again. The larger the pressure drop, the more the high-pressure phase is out of equilibrium, increasing the affinity for the dissolution reaction (Edwards and Russell 1996). The rate of dissolution increases with the affinity of reaction, increasing the likelihood that high-pressure phases will dissolve on ascent. Recent estimates of residence times in shallow magma reservoirs beneath Kilauea (30–200 years, Pietruszka and Garcia 1999) are times enough to dissolve early-formed orthopyroxene. The phase diagram on Figure 11 shows that a melt with the composition of the Mauna Ulu basalt 71-137 has this property.

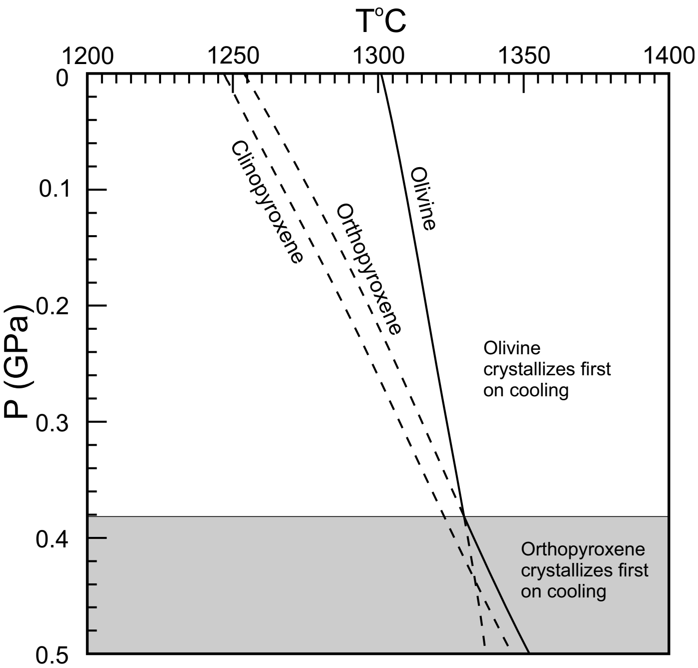

Figure 10. Pseudo-liquidus diagram computed for the bulk composition of a Mauna Ulu basalt 71-137 showing the curves of first saturation for the three phases: olivine, orthopyroxene, and clinopyroxene as a function of pressure and temperature. Curves calculated with MELTS (Ghiorso and Sack 1995). Curves are dashed where metastable.

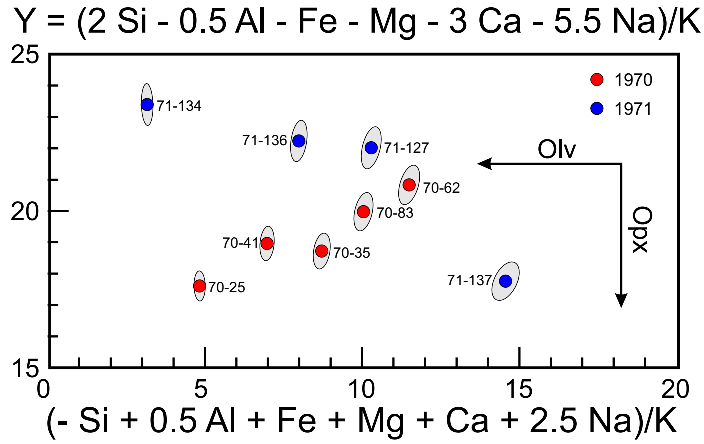

Figure 11. Pearce element ratio diagram that contrasts the pattern expected from olivine fractionation with the pattern expected from orthopyroxene fractionation. One can verify that plagioclase ($CaAl_2Si_2O_8$, $NaAlSi_3O_8$) and clinopyroxene [$Ca(Mg,Fe)Si_2O_6$] would produce a zero-length vector on the diagram. The arrows point in the direction fractionation (loss from system) would distribute data points.

2. Figure 8 shows the pattern expected for orthopyroxene sorting, although the data points for the 1970 data deviate little from the distribution expected for olivine, clinopyroxene, and plagioclase sorting (see Fig. 5). The variance expected from analytical uncertainty is slightly smaller than the variance in the data (Table 3). Another Pearce element ratio diagram is shown on Figure 10 that confirms the pattern shown by Figure 8: fractionation of orthopyroxene (and olivine) in the 1970 magmas and accumulation of orthopyroxene (and fractionation of olivine) in the 1971 magmas. Clinopyroxene and plagioclase sorting will produce no effect on the pattern displayed by the diagram (see Verifying Pearce Element Diagrams above).

For Model 4, chemical differences in the source regions, source processes, and chemically different source compositions provide the opportunity for creating chemical heterogeneity in magmas that are bound to have the chemical imprint of orthopyroxene (and other mantle mineralogy). The chemical diversity could arise from magma batches that result from different degrees of melting of the mantle source, or from incremental melting of the source, or from wall rock reaction attending transit through the overlying mantle. However, this model leaves little to be tested. Calls to coincidence to explain patterns will always provide the means for getting the pattern but such calls should be embraced only when all other explanations are totally inadequate.

THE LOGICAL STRUCTURE OF PEARCE ELEMENT RATIO DIAGRAMS

Pearce element ratio diagrams offer a rigorous and scientific means of testing our best ideas (i.e. models) concerning magmatic differentiation against geochemical data sets. Models are propositions, constrained by logic, with testable consequences (Greenwood 1989). Pearce element ratio diagrams test the geochemical consequences of model ideas.

Models that are independent of the data are more powerful than those dependent on the data for their construction. In this regard, Pearce element ratio diagrams are ideal as they can be designed, independently of the geochemical data set, to represent specific models. For example, models of olivine sorting are expressed as a single straight line with a slope of 2 on a Pearce element ratio diagram of (Fe + Mg)/K versus Si/K (Fig. 1). The model can then be tested against the geochemical data. If the data are consistent with a single line of slope 2 the model is not rejected, and remains an adequate explanation of the variable olivine distributions within the lava flows and the geochemical data; otherwise the model is rejected.

It is over 40 years since publication of Pearce's original idea and over 25 years since a group of us put together a summary of how to use Pearce element ratio diagrams as petrologic tools (Russell and Stanley 1990). In that time there have been modifications and refinements to the paradigm (Russell et al. 1990) but the basic logical structures have remained the same. Consequently, we can confidently infer more about the 1970–1971 Mauna Ulu lava flows than we could in 1990. Dare we say that revisiting the same rocks in another twenty five years, possibly with additional data, would show even further improvement? We think so, which is what makes igneous petrology fun, satisfying, and, sometimes, frustrating.

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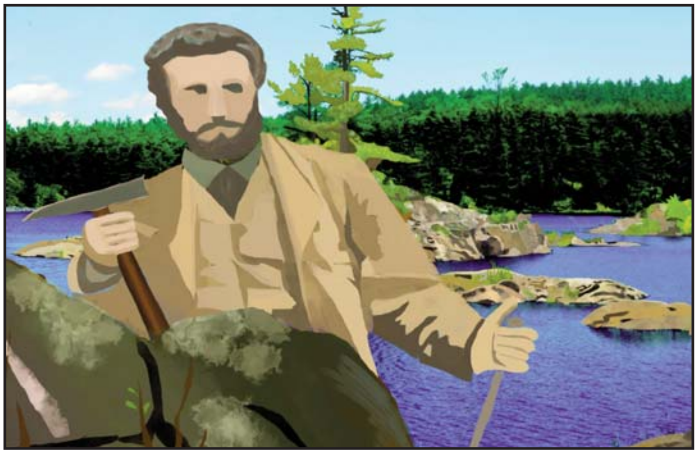
Access to the Excel spreadsheet of the Pearce element ratio program is available through the GAC's Geoscience Canada Data Repository, Igneous Rock Associations series link at: http://www.gac.ca/wp/?page_id=12081.

ARTICLE



"ALL THAT GLITTERS...:" The Scientific and Financial Ambitions of Robert Bell at the Geological Survey of Canada

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[+] Ian Brookes, passed away February 13th, 2015, and is missed by the Canadian Geoscience Community. This paper was submitted, reviewed and revised prior to his passing, and was finalized for publication by the generous efforts of his colleagues Ian Spooner and Antony R. Berger.

SUMMARY
In Canada, the 19th-century development of sciences with a geographical component was marked by individuals whose contributions were remarkable for their details, their geographical coverage, the originality and longevity of their ideas. Collectively, these individuals could be called the 'inventors of Canada.' Among them was Robert Bell. Early in his career at the Geological Survey of Canada and during an interval of part-time service while he taught at Queen's University (1864–68), Kingston, Ontario, Robert Bell (1841–1917) involved himself in several commercial schemes that he hoped would lead to the development of mineral occurrences in the British colony of Newfoundland (various minerals), Canada East and West (petroleum), and Nova Scotia (gold), developments that he hoped would also raise his financial as well as his scientific stature. Here, the circumstances of these ventures and their outcomes and his unencumbered achievements in later life are reviewed.

RÉSUMÉ
Au Canada, au 19e siècle, le développement des sciences comprenant un volet géographique a été marqué par des individus dont les contributions ont été remarquables par leurs détails, leur couverture géographique, leur originalité, et la longévité de leurs idées. Collectivement, ces personnes pourraient être appelées les «inventeurs du Canada». Parmi elles se trouvait Robert Bell. Tout au début de sa carrière à la Commission Géologique du Canada, et pendant son service à temps partiel alors qu'il enseignait à l'université Queen's à Kingston, Ontario (1864–1868), Robert Bell (1841–1917) s'est impliqué personnellement dans plusieurs programmes commerciaux qu'il espérait mener au développement des richesses minérales de la colonie britannique de Terre-Neuve (divers minéraux), du Canada-Est et Canada-Ouest (pétrole), et de la Nouvelle-Ecosse (or). Il espérait que ces développements augmenteraient son statut financier ainsi que scientifique. Dans cet article, la situation de ces entreprises et leurs résultats, et ses accomplissements scientifiques indépendants, sont passés en revue.

Traduit par le Traducteur

INTRODUCTION
Objective
Robert Bell's 50-year career with the Geological Survey of Canada (GSC) left him with a dual reputation in the history of Canadian Geology; on the one hand, as the farthest-travelled explorer of Canada of his times and author of a landmark synthesis: On Glacial Phenomena in Canada (Bell 1890); on the other hand, as a fractious schemer against Director William Logan's successors, Alfred Selwyn and George Dawson, and knowing seeker of financial gain in ventures stemming from his and others' geological investigations. The paper examines this duality.

Young Bell at the Geological Survey of Canada
In 1857, shortly before his 16th birthday, Robert Bell (1841–1917; Fig. 1) was recruited into the Geological Survey of Canada (GSC) by its Director, Sir William Logan (1798–1875), following the early death of his father, Andrew, a Presbyterian minister and noted amateur geologist. Bell met with early

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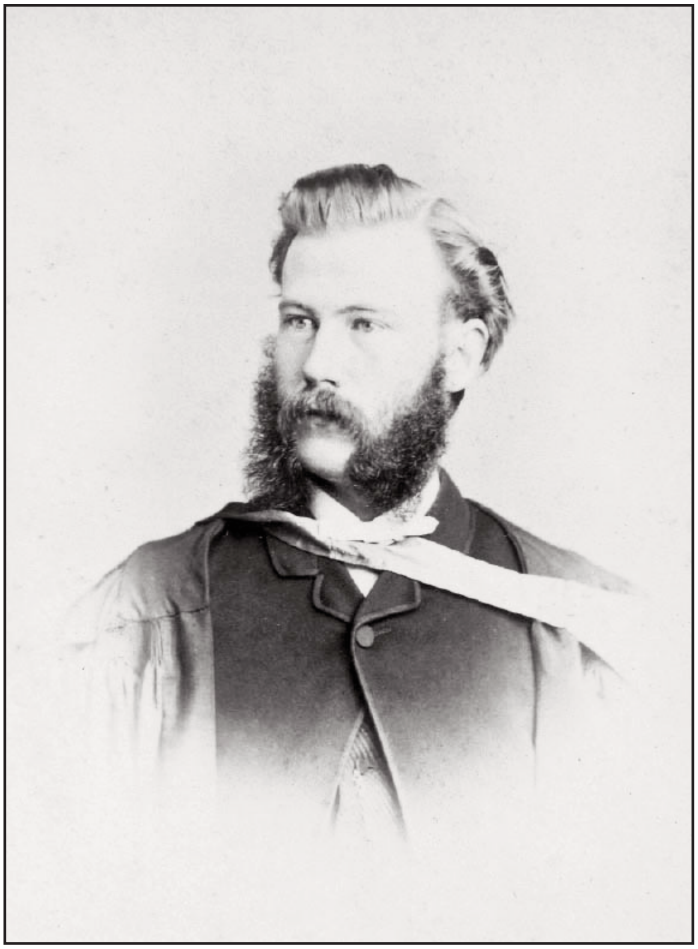

Figure 1. Robert Bell, Montreal, QC, 1865. McCord Museum, McGill University, Notman Collection, catalogue no. I-17981.1

approval at the Survey, then based in Montréal. Although his duties were those of assistant to field parties, he published eight articles in his first four years on Natural History materials collected on his first two explorations (Bell 1858, 1859a, b, 1861a, b, c, d, e).

Such was that early approval that in 1858, with Logan's encouragement, Bell enrolled part-time at McGill University, where, for a year, there being no Geology program, he studied for the certificate in Civil Engineering. At the same time, and for the following two years, he attended lectures in Geology given by McGill's recently appointed Principal, J. William Dawson (1820–1899). He graduated in Civil Engineering in 1861, with as much Geology as an established degree program would then have been able to offer, but no degree.

Prior to his studies, Bell would have known of Logan's embrace of the Glacier Theory (first announced officially in Logan 1847), while Principal Dawson was a life-long adherent to the Drift Theory (e.g. Dawson 1866). Admiration of Logan was general amongst Survey staff, including young Bell, for more than scientific reasons, which may have influenced him to follow Logan's glacier leanings on his field explorations. After Bell's first three years as assistant, Logan was confident enough in him that he assigned him solo fieldwork. As well, in 1862, burdened with administration, fundraising, and international exhibitions, Logan assigned Bell the task of writing a section on 'Superficial Deposits' for the volume being prepared to summarize the Survey's first 20 years' work (Logan et al. 1863). The volume was published just as Bell took up a five-year professorship at Queen's University at Kingston (1864–68; Brookes 2011), establishing him then as one of the few authoritative Canadian adherents to 'Glacierism.'

Seeking Status

I posit several influences on Bell's early-career pursuit of financial as well as scientific status. First, his concern for the reputation of the GSC as an engine of Canada's economic development, which lay at the root of its establishment in 1842, the year following the constitution at Westminster of the Province of Canada from the former 'Upper' and 'Lower' Canadas. The Industrial Revolution had by then been in progress for two generations; the United States was expanding rapidly on its rich (and richly surveyed) resource endowment (e.g. Pennsylvania coal and Superior iron ore). North of the border the search for the Carboniferous system above the Devonian rocks had drawn blanks, while iron ore in the crystalline 'Azoic' (Precambrian) rocks occurred only as small bodies of sulfide, which could not be smelted at large enough scale until the Bessemer process arrived in North America in the 1860s.

On Manitoulin Island, in Georgian Bay of Lake Huron (Fig. 2), Logan's lieutenant, Alexander Murray (1810–1884), recognized the association of petroliferous seeps with low-amplitude anticlines in the Paleozoic limestone–shale sequence (Murray 1847), while Logan (1846) reported seeps in the Gaspé Peninsula (Fig. 2); both occurrences attracted capitalists. Capitalism was – had to be – to the fore at all levels of society at this time, especially concerning mineral resources, although the American Civil War was depressing the economy north of the border. Although most noted for his glacial and forest studies, economic minerals and mining were never very far down on Murray's 'to-do' list – field and office.

Second, with the fortunes accruing during the California Gold Rush of 1849, and the Silver Boom a decade later, Canada-to-be experienced its own 'rushes' – placer gold in the Fraser Valley in 1858, in the Cariboo District in 1861, in the colony of British Columbia, and, more hesitantly, after 1858 discoveries, vein gold in Nova Scotia. During his years at Queen's University, again as private not public servant, Bell found himself conveniently placed to involve himself in Scotian gold.

Third, while again as private citizen, Bell sought financial gain from mineral developments in Newfoundland. Relations between the Province of Canada and Britian's oldest colony became close geologically when, in response to a British request in 1864, Logan seconded Alexander Murray to head a geological survey of the Island. Formal institutional heft behind discovery of mineral resources in Newfoundland, in Logan's mind to Canada's advantage, was seen as an enticement to Newfoundland's joining the Canadian confederation being formulated that year in conferences at Charlottetown and Québec.

With these institutional encouragements, identification of personal influences on Bell's monetary pursuits must necessarily be loaded with subjectivity. Nevertheless, three such influences are posited here.

First, Bell's upbringing was in no way moneyed; his father was a poorly paid, intellectual cleric who was married as

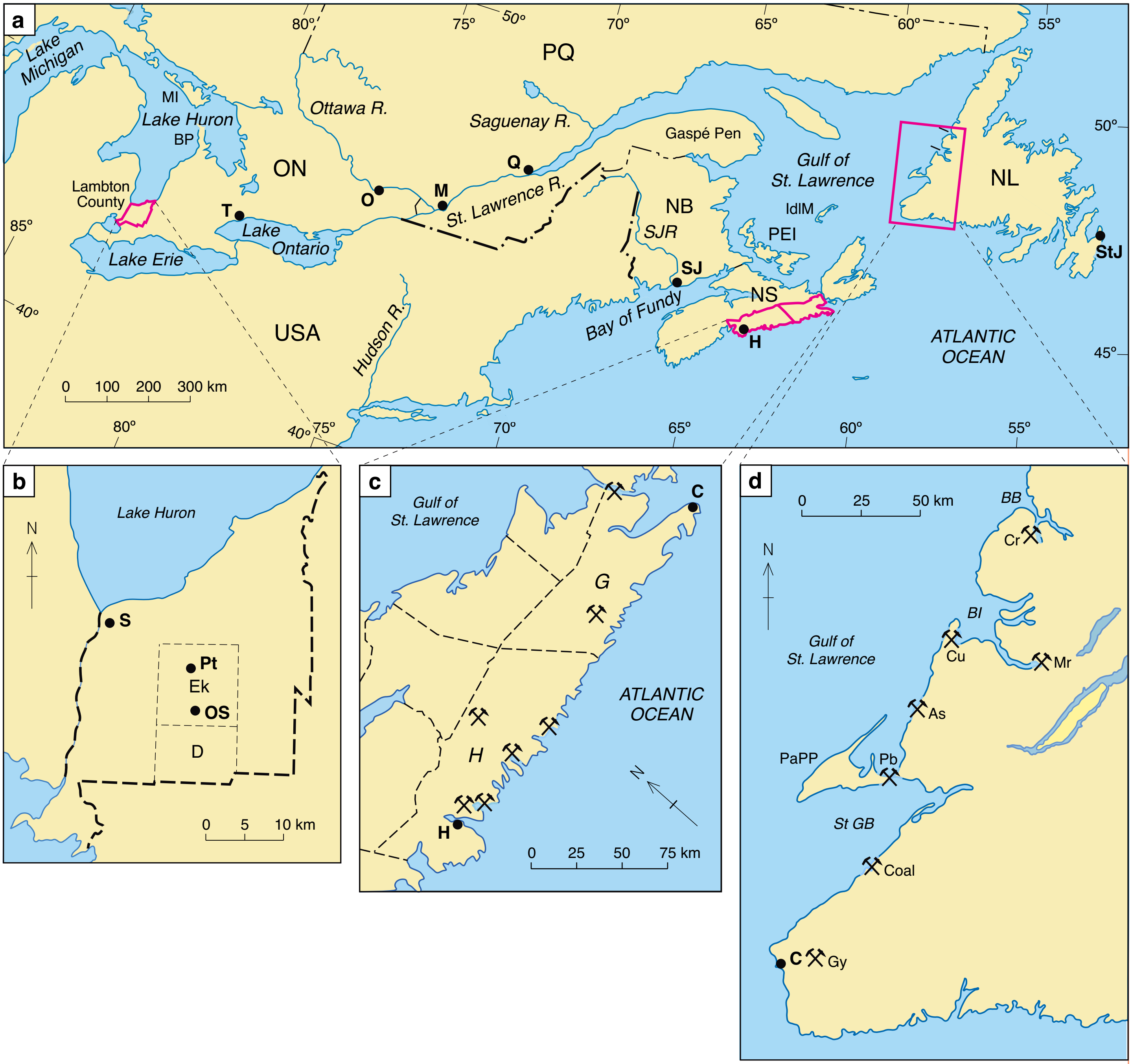

Figure 2. (a) Eastern Canada, showing (red outline) locations of mineral occurrences in which Robert Bell was involved. Cities mentioned in text: T (Toronto), O (Ottawa), M (Montréal), Q (Québec), H (Halifax), SJ (Saint John), St.J (St. John's), IdlM (Iles de la Madeleine), MI (Manitoulin Island), SJR (Saint John River). (b) Historical oil-producing region of Canada West: S (Sarnia), Lambton County (dashed boundary); Ek (Enniskillen Township), D (Dawn Township), Pt (Petrolia), OS (Oil Springs). (c) 1860's gold mining in Nova Scotia (hammer symbols), H (Halifax), C (Canso); county boundaries: H (Halifax County), G (Guysborough County). (d) Southwest Newfoundland, places visited by Richardson's Geological Survey of Canada party, 1867: C (Codroy), St GB (St. George's Bay), BI (Bay of Islands), BB (Bonne Bay), PaPP (Port au Port Peninsula); mineral occurrences (hammer symbol): Gy (gypsum), Coal, Pb (lead sulfide), As (chrysotile asbestos), Cu (York Harbour copper sulfide), Mr (Humbermouth marble), Cr (Bonne Bay chromite).

strongly to his Natural History pastimes as to his ministry. He instilled Presbyterian as well as scientific values in Robert and his younger brother, John. His mother was a lawyer's daughter, who must originally have seen in her suitor both moral and intellectual, rather than financial, comfort – a functional partnership at least, curtailed prematurely after 18 years by Andrew's death from one of the common and incurable bronchial infections then so prevalent. Natural History, therefore, was to be Bell's intellectual and (small 'r') religious path.

Bell practiced his Presbyterianism as professional pursuits allowed; for example, in scores of letters home from his explorations there is no mention anywhere of religious observances by him, or exhortations to the family. At home for the 'office' part of the year he regularly attended St. Andrew's church with the family, and was thought of highly enough there to have a wall-plaque dedicated to his memory. Then, while Darwin's 'The Origin of Species' first appeared (1859) during his McGill studies, and was one of his graduation prizes, its thesis was never evident in Bell's writings. He taught at Queen's University from 1864–689 (Brookes 2011); in a 'Prologue' written for his Natural History course at Queen's he clearly saw 'Creation' as 'Divine,' but, nevertheless, 'Nature' revealed herself to 'Science.'

Second, his first years at the Survey (the late 1850s), he received (irregularly) the equivalent of about $2.00 a day from Logan's pocket it seems, which was enough only to feed him. Robert, therefore, must early have sensed that maintenance of both social and financial status was going to depend on belonging to the upper middle-class, and that this had implications to income. Brother John obtained the Medical Doctorate degree from McGill at age 21, and thus was not going to suffer financially, although he early showed an humane concern for patients from the working poor of Montréal. John died in 1878, aged 33, of a bronchial affliction, but likely remained to Robert an example of secure social status. In that year (1878) Robert himself was awarded the MD from McGill, which is seen by most as his response to sicknesses among Native peoples, whom he respected as guides, canoe men, and victuallers of his Survey explorations.

Third, in 1864, at 23, Robert visited a Glasgow family, to the matriarch of which his mother, a Notman, was distantly related. The Smith family, with 14 children, was headed by the successful owner of an engineering company with local and Caribbean customers, particularly for railway rolling stock, rails, and bridges. Nine years later (1873) Bell married into this family, approaching 32 – 13 years the senior of his spouse, Agnes – and would have wished to keep her in the comfort in which she was raised. This took some time; for instance, it was 20 years before home ownership replaced rental, six years before a child arrived, a second more than two years later, eventually growing to four. The Bells employed live-in girls as domestic help or for childcare. Even then, on his superannuation from the Survey in 1908, Bell's wealthy son-in-law, of the Douglas family (known to McGill for Douglas Hall, and to Queen's for the Douglas Library), agreed to assume the mortgage on the Bell home at 136 MacLaren Street, Ottawa (one street south of Somerset Street).

FINANCIAL PATHWAYS

Newfoundland

In 1839–40, Joseph Beete Jukes undertook a geological survey of Newfoundland for the British Government, in which he identified several mineral occurrences, those on the island's west coast being more exploitable, if only for their coastal exposure (Jukes 1840, 1842; Martin 1983; Cuff and Wilton 1993). Then, in 1860, James Richardson of the GSC had surveyed the coasts of southern Labrador and the northwest of the Island. In 1867, therefore, Richardson was the natural leader of a party to follow-up Jukes' discoveries. The roles of the GSC and private interests in this expedition were intertwined. Montréal banker, Donald Ross, who was interested in the occurrence of coal in the hinterland of St. George's Bay (Fig. 2d), funded commission of a Gaspé schooner and its victualling, as well as recruitment of crew and labourers. Robert Bell and his freshly-minted physician brother, John (as botanist), made up the complement of seven. Director Logan perhaps felt political influence on his turning a blind eye to this privately funded 'expedition' – after all, it was not to Canada, and no Survey report of it was issued. Aside from banker Ross' commercial interests, the expedition could be seen as a 'private' part of Canada's enticement of Newfoundland to join the Confederation, which was enacted that year. As for Bell's participation, Logan probably also saw it as good experience for him.

With logistics arranged, they sailed from Gaspé, Québec, southeast to Iles de la Madeleine, in mid-Gulf of St. Lawrence (Fig. 2a), but nothing survives of investigations there. From there, the southwestern tip of Newfoundland was due east. Near Cape Anguille, Newfoundland, the southwest extremity of the island, on June 15 they checked on Jukes' report of a cliff exposure of gypsum near Codroy, a French fishing station near the southwest limit of the 'French Shore' (Rowe 1980; Hillier 1996). Murray, then in his third year of Newfoundland Survey, had also visited it (Murray 1866, in Murray and Howley 1881). Jukes had referred to 'vast masses' of gypsum, but the outcrop in the sea-cliff is only about 100 metres wide, and, if its associated karstic dolines define its inland extent, this amounts only to ~100 m. Besides acting as a soil conditioner for the alkaline soils of Canada West, where gypsum was already plentiful, the small size of the Newfoundland occurrence meant that its economic value was not then great, nor would it ever be (although Murray later discovered a huge gypsum body further north, inland of St. George's Bay, Newfoundland, which was worked until 2007 for wallboard manufacture at Corner Brook).

To the north, 2 miles inland of the St. George's Bay shore, Jukes had recorded two seams of coal in the banks of Middle Barachois and Robinsons rivers (Fig. 2d), which had been known from Captain Cook's surveys, exactly a century before the Richardson party's visit. Of the 12 seams eventually known (Howley 1896), Richardson's party sampled two 2-foot seams, and located the adit that Hugh Allan (owner of the shipping line) and Robert Russell (surveyor of Canada East) had driven into Robinsons River bank 10 years earlier.

As with Logan in the Canadas 20 years before, Murray's main mission in Newfoundland was the location of coal to fuel industrial development, marine and rail transport. If enough of it could be proven at the three west Newfoundland localities where it was known, its utility for a trans-island railway was obvious; as well, despite it being shallow and sandy, Bell optimistically praised St. George's Harbour for docking coal-ships, and the neighbourhood of the community there as a fuelling depot for a railway. Although it was surveyed ten years later (1877), a railway was not completed for another twenty (1898). Coal in commercial quantities eventually proved lacking on the island, while mines on Cape Breton Island came to supply most eastern Canadian demand.

Inland of St. George's, during hydrographic survey of Newfoundland, Captain Cook had in 1767 raised a cairn for survey purposes on a dome-shaped hill which later became 'Steel Mountain' (anomalously, 'Cairn Mountain' is named nearby). The Richardson party would have seen that the constituent rock was made almost entirely of feldspar (Bell called it 'labradorite', although it is not iridescent). More to the point toponymically, it contained 'blebs' up to a foot across of pure magnetite, the richest of the iron ores, yielding up to 70% metal. Technological lag in smelting technique, and access to more easily capitalized iron ores, excluded development of this rich but small occurrence – that is, until its high specific gravity and accessibility to St. George's Harbour permitted its exploitation in the late 1990s as ballast for the gravity-based structure of the Hibernia offshore oil platform.

Other small mineral occurrences were revisited by the Richardson party (Fig. 2d) – lead and zinc sulfides at Lead Cove, at the eastern end of the Port au Port Peninsula; to the north, below the Lewis Hills, chrysotile asbestos as beach boulders, derived from outcrops in the cliffs above; copper ore had for decades been staked and intermittently worked at York Harbour, just inside the Bay of Islands; high quality marble outcropping in the gorge of the Humber River at the head of that bay had earlier been claimed by St. John's interests, but other marbles were already being imported into Newfoundland for monuments. Upstream, 'pine-clad hills' noted in Cook's survey, and subsequently exploited for boat-building, had been succeeded by healthy stands of balsam fir, black and white spruces, and larch.

The last occurrence visited by the party had been recorded a few years before by Henry Youle Hind. After successfully fulfilling his geographical mandate on two expeditions on the Interior Plains in 1857 and 1858 (Hind 1860), Hind had semi-retired to Windsor, Nova Scotia, from where he engaged in mineral surveys for promoters eager for enthusiastic appraisals of their prospects (e.g. Hind 1870). Contracted for mineral exploration by the Reid Company of Scotland and St. John's, Newfoundland, he had found chromite associated with ultramafic rocks at Bonne Bay, north of Bay of Islands (Fig. 2d). He had informed Rev. Moses Harvey of St. John's, fierce promoter of the colony's economic and social development in Presbyterian minister's clothing (e.g. Harvey 1873). In response to Bell's announcement of the GSC visit to the west coast, Harvey wrote to him: "… *on the recommendation of Prof. Hind, I took out on my own account, under the old Act, five mining licences, in Bonne Bay, covering 15 sq miles. The licences hold good still as they are on the French shore. I never could get them examined. They are in serpentine rock and Hind had a high opinion of the locality, and drew out the diagram for me. What do you think of having Bay of Islands and Bonne Bay examined?" … I should be willing to transfer my licences to your syndicate…we shall keep all secret"*! (Library and Archives Canada (LAC), Robert Bell Fonds, MG29.15, v. 21.64, MH to RB, 18 April 1867). Bell, it seems, had mentioned to Harvey the organization of a group of investors at Kingston, more of which (below) awaited his involvement in Nova Scotia gold prospects. Bell had done his homework on most of these Newfoundland mineral and timber occurrences. He had corresponded with or knew the lease-holders of some of them, and likely knew of the precarious balance between their development and collapse.

As well as local economic disincentives for development of these several mineral occurrences in west Newfoundland, the most effective barrier was the exclusive right the French claimed through the Treaty of Versailles (1783), to fish and process the catch on this coast – the 'French Shore' – until 1904. This is no place even to outline the convoluted history of political entanglements arising from the various treaties (Utrecht 1713, Paris 1763, and Versailles 1783) aimed mainly at compensating the French for losses of their North American territories (but, see: Rowe 1980; Hillier 1996).

In January 1869, after five years of teaching at Queen's (Brookes 2011), but still six months before he rejoined the Survey, Bell returned to Newfoundland, staying a few months in St. John's, intending to curry favour among prominent businessmen and politicians for development of mineral and timber resources in the colony, in the hope of personal gain as advisor to and/or go-between for capitalists and government (Brookes 2010).

The circumstances of his visit to St. John's are cloudy; much was necessarily unspoken, conducted privately, and/or hastily. First, as soon as he arrived (January 21) Moses Harvey presented him with an invitation to himself 'and Friend' to a Robert Burns Supper to be held four days later. Harvey followed this immediately with an introduction to a young lady, who, however pretty or well-connected, could, of course, not be refused as the 'Friend.' Another invitation soon appeared: for him and 'companion' to attend a dinner at Government House, where local confederates had arranged for him to give a pro-Confederation address to the St. John's Athenaeum. Some months later the House of Assembly voted 21 to 9 against the confederation question, the attitude being 'Come Near At Your Peril, Canadian Wolf,' the anti-confederate ditty (http://www.heritage.nf.ca/articles/politics/anti-confederate-song.php).

As the originator of both of these invitations to Bell, Moses Harvey was probably repaying him for his earlier successful recommendation of his two sons to McGill University's Civil Engineering course. Then, there would have been his gratitude for Bell's supportive boost of the colony's economic development. Alexander Murray's position, meanwhile, as Director of the Newfoundland Geological Survey, prevented him from actively supporting Bell's commercial objectives, but he was, as always, ready to advertise his surveys' discoveries of minerals, timber, and land for settlement. Bell balanced these efforts, joining by request a covey of British doyens of Geology (Murchison, Archibald Geike, Ramsay, Bigsby) in recommending to a select committee of the colonial government the continuation and augmented funding of Murray's praiseworthy first five years of survey. But, discussions with politicians in the town (who were usually business leaders as well) did not go well, as a majority were more interested in retaining Newfoundland resources for development by Newfoundlanders, as well as mindful of the international consequences of contesting the French interpretation of the aforementioned treaties.

Bell stayed three months in St. John's, but it is hard to imagine he was engaged in these discussions the whole time. The space might be filled with reference to a letter Harvey wrote to Bell 20 months later, telling him of the disappointment, dismay, and ultimate depression suffered by Bell's young lady 'companion' at his departure, when, so it would seem, she had thought she had cause to hope for a continuing relationship (Brookes 2010).

Petroleum

Canada East – Québec

Logan's early unsuccessful search for coal in the Gaspé region (Logan 1846) had noted oil seeps around Gaspé Bay with which local people, as everywhere it was found, caulked their boats and/or lighted their homes. By the 1860s, oil had attracted the attention of Montréal banker Donald Ross and others, while Bell was never far from discussions. He recorded the gist of an evening's conversation at Kingston in February 1866 with Willis Russell, then a mining engineer, later Surveyor-General of Québec. The evening included reading of a report on Gaspé petroleum geology by the noted American geologist, J. Peter Lesley, according to whom Gaspé offered prospects as good as any of the regions of eastern North America then being prospected for petroleum, Pennsylvania included. Lesley's reasons for this judgment read as modern as any that would be given today, but was he being honest? Had he agreed to 'talk up' Gaspé oil for personal gain?

Gaspé was ripe for investment and would produce 1–5 barrels of oil a day. Miniscule as this seems today, before its use to fuel the internal combustion engine, petroleum mainly lighted and lubricated, so this output could be seen, at least in the short term, as economically viable, particularly as it could replace diminishing whale-oil supplies. Engineer Russell urged Logan to press ahead with surveys and assays which would excite more attention – a typical attitude, when his remuneration depended on production. Logan, however, was circumspect, perhaps because the source of the oil seeps was invisible, so that the factors which so encouraged Lesley could not be confirmed. A fragment of evidence of Bell's not always transparent dealings in mineral development comes from a letter of 1866 in which he agreed to alter a report he made on Gaspé oil for Gaspé Bay Mining Co. of Belleville, in Canada West, in order to throw a more favourable light on the prospect (LAC, RB Papers, v. 24.98, RB to J. L. Macdonald, n.d., est. 1866). At this time, William B. Fowle, a Boston mining promoter, in a letter to Bell referred to having Bell's 'book' with him in London (Bell 1865a or b), where it would assist in negotiations with potential investors; *"I sincerely trust that our mutual efforts may result in pecuniary success to all interested."* (LAC, RB Papers, v. 19.69 WBF to RB, 20 March 1866).

A century and more later, the continuing refinement of tectonic theory and seismological technique have improved knowledge of the geological structure of on- and off-shore western Newfoundland, Gaspé, and mid-Gulf of St. Lawrence, to the point that these have once more become oil and gas exploration-grounds with the modern accompaniment of political conflict.

Canada West – Ontario

In 1859, Logan assigned Bell the solo task of following up Murray's initial exploration of Manitoulin Island, in Ontario's Georgian Bay of Lake Huron (Fig. 2a; Murray 1847; Bell 1870). The Manitoulin survey brought out in Bell the 'complete natural historian,' reflected in his copious notes on bedrock, glacial grooves, hydrographic patterns in relation to geologic structure, ancient lake terraces, climatic anomalies, and Indian agriculture (Indians had been resettled on Manitoulin from their lands which were taken up for immigrant settlement). For present purposes, the most important influence on Bell was his first encounter with the petroliferous seeps, which Murray had related to low-amplitude anticlinals. The previous year, oil-shale operations had opened at Craigleith, near Collingwood, on the southern shore of Georgian Bay, and Logan was showing interest in small 'gushers' in southwestern Canada West. There, in the 1860's, petroleum substituted for gold as the focus of frenetic speculation. Petroleum was most obvious in Enniskillen and Dawn Townships of Lambton Co. (Fig. 2b), and in Orford Township, Kent Co., Enniskillen produced 82,000 barrels of oil in 1862 (Logan et al. 1863), which put in perspective the estimated 1–5 barrels a day (<1800 bbl p.a.) from the Gaspé. In his brother John's name, Bell purchased 200 acres of land in Enniskillen, Concession 7, Lot 18, where oil was suspected beneath, but he was already trying to sell it in 1864, by which time he had learned that it was not in the oil-rich concessions proven by drilling. As well, the American Civil War was depressing prices. Bell's interest in this oil-field led him to write a popular pamphlet on petroleum (Bell 1865c), which he dedicated to Logan, telling him that it was intended to assure him that his ideas on petroleum occurrence had not been corrupted, and as an example of how the Survey might publish on subjects of public interest. Despite his dismal prospects in Lambton, Bell maintained enough interest in petroleum to purchase lots in Manitoulin's Wikwemikong, Sheguindah and Billings Townships, presumably not in his own name as public servant, but drilling there never showed much promise.

Scotian Gold

The Goldfield

More promising, at least at the outset, were Bell's involvements in gold-mining developments while he was a Queen's University professor between 1864 and 1868. Confederation was an economic shot-in-the-arm for Nova Scotia, although the arm also bled. One of the gains was investment from Ontario in its mines – iron ore, coal, and gold. After the original Gold Rush in California in 1849, and others it spawned, especially in the Middle Fraser and Cariboo District of the colony of British Columbia, gold was to the fore in the minds of speculators everywhere.

Gold-bearing quartz was easily recognized, and peninsular Nova Scotia was full of it. Veins commonly protruded through the forest floor and through the sod of deforested lands, and were easily followed across country. The Scotian gold-field itself occupied a belt of low-grade metamorphic rocks along the Atlantic coast between Halifax and Canso (Fig. 2c), rocks now known as the Meguma Group. They included the Goldenville Series, mainly sandstones, and the Halifax Series, mainly slates, both of Early Paleozoic age, roughly 550–400 Ma, which were deformed, heated and intruded by granitic magmas soon after, during the 'Acadian' orogeny at ~350 Ma. Gold veins are concentrated along the crests of up-folds in the slates, where the rock was stretched, opening fractures penetrated by silica- and gold-rich fluids believed in these early days to have been derived from granitic magma.

1858 is usually taken as the year gold was discovered in Nova Scotia, and Tangier, northeast of Halifax (Fig. 2c), as the place (geological information here is after Heatherington 1868, Selwyn 1872 and Bates 1987; while Hind 1870 is noted as a commercially-driven exaggeration of gold potential). Vein-gold is more abundant by far than placers. Veins are centimetres to metres thick, 100's of metres to kilometres in length, extending up to 200 m below the surface, and are gently inclined, sub-parallel to the original stratification of Meguma sedimentary rocks, which have been over-folded to the northwest. Veins were therefore difficult to mine, especially by inexperienced workers, as shafts had, of course, to follow the veins.

Drainage was always a problem – at worst, costing as much as extraction. Vein-rock had to be crushed, but only found its way to the crusher if gold was visible, so more than half of its content was missed, although it was sometimes regained later when old tailings were crushed finer and more efficiently leached.

Primitive though mining was in Nova Scotia, the economic environment surrounding it was worse. Under-capitalization was the main problem, since machinery had to be purchased, delivered, erected, and worked efficiently, none of which could be performed easily by inexperienced local labour; experienced labour had vanished westward. Interruption of funding was most sorely felt by drainage operations; when they ceased, time and money had to be spent on re-draining before extraction resumed. Water supply was the next problem – too much water below, often too little above for sluicing and washing. Dam a stream – time and money; divert a stream – time and money. Power to drive machinery was next – was stream power close enough to the gold workings? If not, only coal could fuel traction engines to raise rock from the shafts, haul wagon-loads to the crushers; and coal was miles away in Cumberland County.

For eager investors, profits were easy to predict based on simple arithmetic. Costs of crushing were between 50¢ and $3.00 a ton, when the average share cost was $1.50, so large investments were necessary. If a mine attracted 2000 shares (say, $3000), with gold in the world market fetching betweeen $20 and $50 an ounce through the 1860's that investment would have to be matched by only between 3 and 7 tons of rock crushed yielding 20 oz. per ton. Open-air crushing could continue for 10 months of the year – say 250 days – and yield 10 tons crushed per day. If 20 ounces could be extracted from each ton, $1–2.5 million was the potential annual gross revenue. Again, for the potential investor half of that was predicted as profit, after taxes, equipment, and wages.

But this potential was never realized; properties were small and scattered, workers inexperienced, investors were shy; too much went on promotion over extraction and processing. Over all districts average annual yields per worker were $517.32 (Heatherington 1868, p. 90) – around $2000 to $2500 per mine – so, even with 10 mines per district, this was a pitiful 1/1000 of the potential calculated above. While economic prospects did improve throughout the 1860's, the under-performing Nova Scotia 'Gold Rush' ended with a whimper the following decade.

Correspondence reveals that Robert Bell was involved in all ten Nova Scotia gold properties, as geological consultant to a group of Kingston investors comprising Queen's faculty and administrators, as well as lawyers and businessmen in the town. He also consulted for Carlos Pierce, owner of gold mines at Stanstead, Québec, whose New York and Sherbrooke Company acquired, in all, 40 gold properties, containing approximately 25 workable lodes. The Scotian properties were all at places extant today: Sherbrooke and Mulgrave, Guysborough County; Wentworth, Cumberland County (placer); Eureka, Pictou County; Victoria Mines, Cape Breton County; Lawrencetown, Salmon River (-Bridge), Tangier, Montague Gold Mines, and Musquodoboit (placer), Halifax County. None is mined today, although, with gold at more than $1000 an ounce, exploration continues.

Legal Trouble

Throughout the latter 1860's, Bell's geological appraisals and financial intermediations related to the Scotia gold properties landed him in a quagmire of debt, dubiety, and political dirt. He often had to borrow from relatives and friends the funds necessary for the initial development of properties in order to attract investors. A property suddenly went dead when workers walked away for lack of wages, or when the shaft flooded for want of a pump. Loans were called in, promissory notes were written, cheques were refused at banks. Ultimately, all accusing fingers pointed at Bell. One Kingston investor ranted, "*I have been pulled and milked with a vengeance*," calling Bell "*unreasonable*" for demanding more time and more money to oil the wheels of development. "*Mr. Patton and others say that you are playing with me in the matter, and deceiving me as to the true position.*" (LAC, RB Papers, v. 31.60, J. Romanes to RB, 22 December 1869). John Paton, Queen's University comptroller, whose relations with Bell were never very cordial, had slighted Bell's character in an angry communication with Bell's main 'partner,' James Patton, a Kingston lawyer and future partner of another Kingston lawyer, John A. Macdonald. Bell, always quick to turn high dudgeon on an adversary, demanded that Paton withdraw the defamation, or his involvement in the scheme would be revealed (LAC, RB Papers, v. 29.36, RB to Jas. Paton, 16 July 1868). Paton responded meekly: "*The remarks injurious to your character which I heard in connection with your report on the Mulgrave Gold Mine I believe to be untrue and I also believe the source from which they originated to be totally unreliable.*" (LAC, RB Papers, RB's copy of JP's letter, n.d.)

The failure in 1867 of the Commercial Bank, headquartered in Kingston, and source of many of the loans to local investors, contributed significantly to the financial mess in which Bell found himself. His dire financial situation, which was prolonged beyond the climax of speculation in the Scotian goldfield, is best illustrated by the contents of a letter responding to his call for clarification and advice made of his friend the prominent former journalist, now politician, William McDougall:

"*I have papers, writs, bonds &c which show:*

(i) your partnership [with Jas. Patton] began Oct 4 1867, as shown by a co-signed agree-ment between you both, and J. Carruthers and Jas. Romanes [Kingston lawyers],

(ii) that you signed bonds and agreements to third parties jointly with Patton as late as 10 Sept 1868,

(iii) that you gave Patton power-of-attorney October 1, 1868 authorizing him to sign your name to bonds, notes, &c for your joint affairs in Nova Scotia,

(iv) that your agreement for dissolution was not made until 13th January 1869,

writs issued against you and Patton by Romanes, Ferguson, J.A. Macdonald [yes, Him!], *were on account of transactions during the partnership* [i.e. before January 13 1869] *and are not affected in law by any agreement you & Patton have between yourselves. … From all of which, it follows that you are personally liable in respect of all these liabilities still unsatisfied.*"(LAC, RB Papers, v. 25.15, WMcD to RB, 12 May 1876).

One case of Bell's 'enthusiastic' geological appraisals of a Scotian gold property at Eureka is documented, in which Toronto brokers Osler and Pellatt were disappointed at the performance compared with Bell's forecast of success. (LAC, RB Papers, v. 29.3, E. Osler to RB, 26 August 1868).

Some officers at the Geological Survey were concerned by what they were hearing about Bell's involvement in mining affairs. Hugh Vennor, hired to the Survey in 1866 on Bell's recommendation, wrote to Bell: "*Sir William has an idea that you are in some way interested in it* [a mine on Lake Superior, probably Silver Islet, off Port Arthur] *and others* [mines]. *Mr Richardson asked me if you were engaged yourself in mining operations in answer to which I pleaded perfect ignorance. If you are doing anything in that line for yourself, you perhaps had better keep it dark from the Survey office – that is if you care at all for said office.*" (LAC, RB Papers, v. 37, HGV to RB, 14 December 1867); wise counsel, indicative of the loyalty that staff felt towards the Survey and 'The Chief.'

Not that Robert Bell felt differently; he took second place to no-one in institutional loyalty. The situation had, after all, arisen before he joined the permanent staff, during his Queen's professorship. He had found little guidance in the behaviour of many of his colleagues there, as well as that of other prominent citizens of Kingston. He had pursued his social and financial ambitions, striking out on a path he saw leading to relative wealth, from a position which gave him access to many whose like ambitions were more commensurate with their resources. He had been drawn into a tangled web by circumstances which allowed associates to run for cover, leaving him exposed.

A Deal with John A.

Legal 'bat-and-ball' dragged on until 1872, when, if all the foregoing wasn't enough, Bell's career progress at the Geological Survey, which he had rejoined as full-time officer in the Spring of 1869, became a bargaining chip in the resolution of guilt and debt, particularly between him and James Patton, by this time a Member of Parliament. When the colony of British Columbia bid for entry into Confederation in 1871, Bell was among those quick to realize that a geological survey was going to be needed to assess its mineral resources. Bell foresaw the need, and played a part in acquiring for the Survey an additional $19,000 to support the survey of British Columbia and Yukon together as a package (LAC, RB Papers, v. 24.95, RB to JAM, 30 June 1871). Was this another reflection of Bell's drive to pecuniary advantage? He sorely needed to claim as his own some such potentially important territory as British Columbia, as his field experience so far had not been financially promising (in Ontario, with oil and iron ore; in Nova Scotia with gold (and coal?); in Newfoundland with several mineral and timber prospects). GSC Director Selwyn likely found the case for sending Bell to British Columbia unarguable; the farther away, the better, perhaps, considering Bell's early hostility to Selwyn as a British interloper, whose appointment could only discourage young Canadians of scientific bent from opting for geology as a career.

Some believe, but rarely give voice to the claim that after his visit to the western plains in 1873, Selwyn was under threat from Sir William Dawson, who had promised that unless Selwyn reserved the geological survey of British Columbia for his son, George upon his return from London, he would expose (public servant) Selwyn's purchase of land on the western plains (even if in his sons' names), on which on Selwyn's instructions borings were sunk near Fort Pelly in east-central Saskatchewan, intending to locate coal beds, but instead had proven the existence of oil.

In 1872, Principal Dawson's son, George, at the age of 23, had just returned from the Royal School of Mines in London, where he had gained the equivalent of a BSc, as well as prestigious medals. After brief teaching and consultancy assignments, in 1873 he was recommended by Sir William Logan as geologist attached to the Canadian government's survey of the Canada–USA boundary between Lake of the Woods and the Rocky Mountains. Dawson acquitted himself admirably in that work, which occupied him in summer fieldwork in 1873 and 1874, and writing up his findings in 1874–75 (G.M. Dawson 1875). The work also prepared him for the next step – westward to BC – where he was to spend four years forging for himself a sterling reputation within Canadian geology, a reputation that remains largely untarnished to this day (Brookes 2002). Bell, 35 years old in 1876, who had been with the Survey for 18 years, was shut out. This slight was to poison for all time his relations with George Dawson, who under Selwyn became his superior on staff, and in 1895 succeeded Selwyn as Survey Director.

Doubt is thrown upon Wiliam Dawson's threat over Selwyn by evidence that Bell had been turned down for the British Columbia work by mid-1871, before Selwyn's 1873 excursion to the plains. Bell had then written to Prime Minister John A. Macdonald, telling him how disappointed he was with the British Columbia decision (thus, not made with George Dawson on hand, but maybe in mind), and that he felt that knowledge of his dubious dealing with the mining industry was behind his disfavour (LAC, RB Papers, v. 24.95, RB to JAM, 30 June 1871). This seems, rather than involving Dawson Sr., to emphasize Macdonald's role in denying British Columbia to Bell (perhaps because Sir John, too, had been burned in Nova Scotia). There were plainly patronage-related reasons for that; Bell was known as a staunch Liberal, whereas the Dawsons were loyal to Macdonald's Conservatives. Further, it might remove both Dawsons from the equation, unless, as is certain, Dawson Sr. had plans for his son ahead of his return from London.

Even that does not quite settle the matter. Correspondence related to the difficulties Bell faced in Nova Scotia reveals additional bargaining chips he and his lawyers brought to the table in his quest for the British Columbia position. First, at quite a late stage in the proceedings, in order to keep his name off the record, Bell invented a player to whom he gave the name 'J. McNulty' as a 'nom-de-plume' in correspondence concerning legal settlement of scores between himself and James Patton, towards whom Bell had acted in what many would call a reckless manner. Bell (as 'J. McNulty') wrote to his lawyers Osler and Regue, enclosing $5000 in promissory notes he had previously received from Patton, "*to be held by Osler for McNulty as his property and to be returned when called for, until McNulty received the appointment applied for from the Dominion Government as head of the Geological Survey of British Columbia, and in this event you are authorized to give up such notes cancelled and paid to the Hon. James Patton of Kingston.*" (LAC, RB Papers, v. 29.1, 'McNulty' [RB] to BB Osler, 18 February 1872).

Patton, a prominent lawyer, a Member of Parliament, and friend and future law-partner of John A. Macdonald, could not come out of the case with any blemish on his reputation. To this end he enlisted Macdonald to engineer an agreement with Selwyn at the Survey, that Bell would be assigned the British

Columbia work if he would 'take the fall,' leaving Patton blameless in the financial imbroglio. Bell, meanwhile, did some 'engineering' of his own in handing to his lawyers the $5000 in promissory notes made out by Patton to various creditors, on the understanding that they would be called, unless Bell received the British Columbia posting from the Dominion government:"[O]*n receiving this position I will discharge the debt of James Patton … and will assist you* [the lawyers] i*n the discharge of liabilities to Messrs Machar, Romanes, Carruthers* [Queen's University 'worthies'], *and others, for which I am said to be liable.*" (LAC, RB Papers, v. 29.1, RB to BBO, 1 March 1872). Osler recommended to Bell, "*Do as I suggest* [regarding the promissory notes, as above] *and I assure you from confidential sources that your appointment* [to BC] *is secure.*" (LAC, RB Papers, v. 29.1, BBO to RB, 7 March 1872).

Both Patton and Bell, then, appear to have been working to the same end, both ignorant of any influence Dawson pére might have had over Selwyn in filling the British Columbia position. Yet, Bell was not appointed to it, so what went wrong with the proposal engineered by Macdonald? Bell told Osler that he wasn't going through with the deal they had agreed. Osler then reminded Bell that Patton had the upper hand with Macdonald, who, he said, could appoint or dismiss him. Urging Bell to meet Patton halfway, he ended, "*If on receipt of this you continue in the same mind, I wash my hands of the consequences and will at once return the notes and the undertaking to you*" (op. cit.).

A Narrow Escape

With Bell standing down against Patton, Patton was out financially only to the extent of his legal costs, which he recovered from Bell in a Montréal court, away from Kingston and Toronto headlines. Apparently, it was left there, both walking away scathed, but relieved it wasn't worse. Patton had sufficient influence to ride out suspicions and whispers. Bell, however, it is fair to say, was left scarred for life, first by his Nova Scotia dealings, and then by the British Columbia affair. When Dawson Jr. was 'assigned' the British Columbia work in 1875, Bell lost professional territory as well as status. His subsequent difficulties at the hands of Ministers (including Laurier as well as Macdonald) and competitive colleagues (Low and Brock in particular) may have owed something to the fact and legend of the Nova Scotia mining *débacle*, handed down unspoken through the next three decades of his career.

It will be obvious by now that none of Bell's scientific-cum-commercial ventures had succeeded.

CONCLUSION

Scientist Bell

For the remaining 35 years of his career at the Survey, Bell subserviated financial ambition to science, as field evidence accrued. He explored all of the north-draining major rivers of Ontario, (except the Winisk and Severn Rivers), and neighbouring northeast Manitoba (Nelson-Hayes and Churchill) and northwest Québec (Harricanaw, Nottaway, Rupert) (Bell 1872 a, b, 1873, 1874, 1877, 1878, 1879, 1880, 1881, 1883 a, b, 1887, 1901a). On several of these explorations, he recorded drift-filled palaeochannels in riverbanks, which later gained him recognition as the first to posit the existence of a pre-glacial drainage system across boreal Canada (Bell 1895), the stem of which was named 'Bell River' by McMillan (1973, p. 504–505).

Bell's paper, *On Glacial Phenomena in Canada* (Bell 1890), based on evidence obtained on these explorations marked the 'vestibule to modernity' in these studies – a sub-continental synthesis unique at the time and the most significant Canadian advance since Logan's (1847) first acceptance of glacial action in Canada. From those northern explorations Bell offered voluminous evidence from striae and till/erratic provenance of sub-continental ice-sheet flow-fields, leading him to the first identification of the Hudson Bay depression as a collection basin for ice-flows from Québec, Labrador, and Keewatin, delivering that ice southwards into the United States and eastwards in what he called an 'ice stream' through Hudson Strait to the Atlantic (Brookes 2007). The details of westward ice-flows from Keewatin were the purview of his successors, McConnell (1891) and Tyrrell (1896). On his sea voyages along the Labrador coast in 1884, 1885, and 1897, Bell (1885a, c, 1901b, c) speculated on the unglaciated status of jagged, weathered peaks of the Torngat Mountains of northern Labrador (Bell 1885a), setting off a controversy that simmers today from Baffin Island to Newfoundland.

As a by-product of these extensive travels through Canada's boreal forest, Bell produced maps of the limits of each of its tree species and an interpretive commentary (Bell 1880, 1881). The work of Blodget (1857, 1875) on North American climate had become well-known by this time, particularly for its revelation in isothermal and isohyetal patterns of sub-continental influences of latitude, the western mountains, and Hudson Bay. Bell was thus able to relate the first-order patterns of tree limits to these first-order factors. But, he went further in considering historical competition among different trees, as well as fire history and tree-succession (Bell 1889, 1906). Bell's lesser-known works on forest subjects has earned him Nestorian status; no less a modern authority than Stephen J. Pyne devotes a chapter of his fire history of Canada (Pyne 2007) to joint consideration of Robert Bell and Bernhard Fernow (late of University of Toronto's Forestry Department) as doyens of the subject. For example, on Bell:

"*Robert Bell was … perhaps the last man to have the opportunity to tramp over vast stretches of the Canadian outback while possessing the training to report in scientific language what he saw and commanding the institutional setting to make himself heard…*
– He accomplished for the Canadian north what Humboldt did for the South American tropics.
…he recognized that fire was not merely a seasonal presence, like mosquitoes, but a shaper of the vast northern forests, a force as powerful as the droughts and winds with which it was associated." (p. 147).

By corporate invitation, Bell was also very much involved in plans for a railway from The Pas, Manitoba, to a proposed trading post at Fort Churchill or York Factory on Hudson Bay, for which he surveyed thousands of kilometres of what is now northern Manitoba, including detailed plans of the Nelson-Hayes and Churchill River systems (Bell 1879, 1880). For this project he also made terrestrial and marine observations while acting as scientific and medical officer on three of four Canadian government shipboard expeditions commissioned to investigate sea-ice conditions affecting navigation in Hudson Strait and Bay (Bell 1885, 1901b). His case in support of the opening of a port at Churchill (Bell 1910) is a model of sub-continental economic geography, at the dawn of that sub-discipline (Clark et al. 2000). He was the first geologist to describe the Athabasca bituminous sands (Bell 1883c, 1885b), and early recognized their economic potential (Bell 1883c, 1908).

Bell authored 32 GSC reports (including four long 'Summary Reports of the Acting Director'), 111 papers in journals (including a few abstracts), 17 solo-authored geological maps (roughly equivalent to GSC's coloured 'A' series), 46 other geological, topographical, and cadastral maps as senior author, 38 maps as junior author, and gave 103 conference papers and lectures to natural history, historical, and charitable societies.

Late Years

GSC Director George Dawson died suddenly in his 52nd year, on March 4 1901, from pulmonary complications of a chest cold. Robert Bell, who turned 60 three months later, and who had then been with the Survey for almost 40 years (accounting for the 5 years at Queen's University), was appointed to replace him. There was no one else on staff with the combined seniority and respect among staff to be considered a candidate. Frank Adams at McGill and Willett Miller at what was then Kingston School of Mining were 'unavailable.' Given, therefore, that Interior Minister Sifton could (grudgingly perhaps) see Bell as the only choice left to him, he also saw sufficient reason to down-grade the position's title to 'Acting Director.' Sifton's reasoning, and Prime Minister Laurier's presumed consent to it (or did the word come down from the PMO?) was not a straight-forward balancing of qualification and choice; there must have been a sense of 'punishment' for the difficulties in Bell's relations with former Directors Selwyn and Dawson, the bad odour of which had pervaded the Survey for at least the past 20 years. As well, there was the suspicion, grown into certainty, of Bell's poor handling of financial affairs, in particular those surrounding the Scotian 'gold-bust,' albeit 30 years before.

Titular dilution of Bell's promotion certainly was a political and personal slight – a festering sore over his final years with the Survey. But, Sifton knew that whatever the title Bell would acquit himself well (and, thus, the Interior Ministry), as a matter of professional and personal pride. On 'The Hill' one imagines chuckles behind closed doors: 'five years as Acting Director and we'll be shot of him.'

Then, in 1902 Sifton found it necessary to mollify relations between Bell and the Liberal Government, whose colours Bell had flown lifelong. He offered Bell a pre-retirement sinecure as Chief Curator of the proposed new Victoria Museum, on the condition that he retire after five years (RBP, v. 33.16, CS to RB, 17 July 1902). Bell refused it, preferring to pursue what he considered his due – the 'Real' Directorship (and the hind-cast deficit in pay compared with Dawson's), while the Museum (now occupied by the Canadian Museum of Nature) was, in the event, not completed until 1912, four years after his superannuation.

'Acting' or not, Director Bell did achieve much by way of hiring scientific staff (including R.A. Daly and W.A.J. Johnston), quick announcement (in Director's reports) and publication (in staff reports) of Survey results, the latter being the only significant recommendation of an 1884 Commons Committee which had investigated Survey affairs. As well, he increased the pay of support staff, and won increased library resources at a time of burgeoning book and journal titles.

At root, Bell's problems throughout his career lay in his mercurial professional nature and behaviour – quite the opposite of the staid, politically malleable official preferred by governments. For all of his burdens, nevertheless, he was fortunate to find relief within the family and its expanded relatives-by-marriage.

In retirement Bell briefly revived his financial ambition in prospecting. For two years, he and his son, who was at the time studying mining engineering at McGill (1908–1912), prospected around Gowganda, Ontario, for extensions of Cobalt silver veins. But then, he was enticed into prospecting for an American company that claimed to have met with success for investors in silver-mining at the Comstock lode, in Nevada. After the first year, whether Bell recognized it or not, he was knee-deep in false claims of a 'Mesabi Range' of iron-ore north of Kingston. To draw attention away from his name, this was when he drew upon his McNulty '*nom de plume*' again, 40 years after the Scotian gold-bust! What must have begun as a natural desire to maintain economic and social status by supplementing his superannuation of two-thirds of his prior income, must have retained some honest rationale – perhaps, at worst, he felt driven to show that 'I'm not finished yet!' When the cruel truth dawned of his (unwitting?) participation in a mining investment fraud, he and Agnes decamped to Europe for two years (1912–14), while a New York court sentenced the American principals to prison terms.

Returned to Canada, Bell lived out his final five years – winters at home in Ottawa at 136 MacLaren, summers at his property overlooking the Assiniboine River near Portage-la-Prairie, Manitoba, which he had purchased in his father-in-law's name in 1873. He and the family sorted, containered, and labelled the huge collection of materials he had amassed over fifty years at the Survey. He died June 18, 1917, six days after a stroke or cerebral hemorrhage – the death certificate called it 'Apoplexy.' He had just turned 76 and was buried temporarily in Winnipeg's Elmwood Cemetery. After settling their Manitoba affairs, his wife Agnes had his remains moved to Montréal's Mount Royal Cemetery, where a prism of polished red granite, engraved with several (not all) Bell family names, lies askew in the grass on a shaded hill slope.

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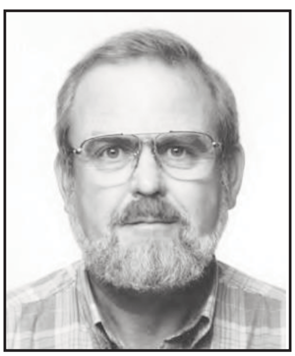
Memories of Ian Brookes*



Ian and I worked together on and off for over 25 years, though I had met him much earlier in Toronto. He often stayed in our house in Woody Point during his many visits to western Newfoundland, where he had many other friends. We conversed about music, literature, history, but mostly about geology and the post-glacial history of Gros Morne National Park. It was Ian who designed the popular and now out-of-print geological map of the Park published by the Geological Survey of Canada in 1992. And it was en route to a workshop on environment monitoring in the Park that I co-chaired in the 1990s that he had his first stroke, which side-lined him for several years.

He emerged from rehab somewhat disabled physically, a source of considerable frustration to him, but he was as alert as ever. He poured his energies then into researching and writing biographies of prominent Canadian earth scientists, but most of all re-working and advancing his extensive knowledge of Newfoundland landscapes. Several projects, a few of which his colleagues are now working to complete, remained unfinished at his death. Ian was a stimulating friend, though he could be crusty and quick to anger when others did not see eye to eye with him. I shall miss him.

Antony Berger
Woody Point, Newfoundland

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