GEOSCIENCE CANADA
JOURNAL OF THE GEOLOGICAL ASSOCIATION OF CANADA
JOURNAL DE L'ASSOCIATION GÉOLOGIQUE DU CANADA

Presidential Thoughts for These Pandemic Times

Can Coeval Cordilleran Carbonatites Constrain Collisions

PGEs, Chalcophiles and Plume Evolution - Insights from the Columbia River Basalts

London 2021 - Virtual and Tangible Field Trips, Workshops and Short Courses

The Lifetime Legacy of R. Frank Blackwood

2020 VOLUME 47

**Publisher/Éditeur**
Geological Association of Canada
Alexander Murray Bld., Rm ER4063
Memorial University of Newfoundland
St. John’s, NL, Canada, A1B 3X5
Tel: (709) 864-7660
Fax: (709) 864-2532
gac@mun.ca
www.gac.ca

Print Edition: ISSN 0315-0941
Online Edition: ISSN 1911-4850

Volume 47

A journal published quarterly by the Geological Association of Canada, incorporating the Proceedings.
Une revue trimestrielle publiée par l’Association géologique du Canada et qui en diffuse les actes.

**Subscriptions**: Receiving four issues of Geoscience Canada per year for $50 is one of the benefits of being a GAC member. To obtain institutional subscriptions, please contact Érudit: www.erudit.org

**Abonnement**: Recevoir quatre numéros par année pour 50,00 $ du magazine Geoscience est l’un des avantages réservés aux membres de l’AGC. Pour les abonnements institutionnels, s'il vous plaît contacter Érudit: www.erudit.org

**Photocopying**: The Geological Association of Canada grants permission to individual scientists to make photocopies of one or more items from this journal for non-commercial purposes advancing science or education, including classroom use. Other individuals wishing to copy items from this journal must obtain a copying licence from Access Copyright (Canadian Copyright Licensing Agency), 69 Yonge Street, Suite 1100, Toronto, Ontario M5E 1K3, phone (647) 503-4664. This permission does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale. Send permission requests to *Geoscience Canada*, at the Geological Association of Canada (address above).

**La photocopie**: L’Association géologique du Canada permet à tout scientifique, de reprographier une ou des parties du présent périodique, pour ses besoins, à condition que ce soit dans un but non-commercial, pour l’avancement de la science ou pour des buts éducatifs, y compris l’usage en classe. Toute autre personne désirant utiliser des reproductions du présent périodique doit préalablement obtenir une licence à cet effet d’Access Copyright (Canadian Copyright Licensing Agency), 69 Yonge Street, suite 1100, Toronto, Ontario M5E 1K3, Tél.: (647) 503-4664. L’autorisation susmentionnée exclut toute autre reproduction, telle la reproduction pour fins de distribution générale, de publicité ou de promotion, pour la création de nouveaux travaux collectifs ou pour la revente. Faites parvenir vos demandes d’autorisation à *Geoscience Canada*, au soin de l’Association géologique du Canada (voir l’adresse indiquée ci-dessus).

Those wishing to submit material for publication in Geoscience Canada should refer to the Instructions to Authors on the journal's website, www.geosciencecanada.ca

**AUTHORS PLEASE NOTE:**
Please use the web address http://journals.hil.unb.ca/index.php/GC/index for submissions; please do not submit articles directly to the editor.

The Mission of the Geological Association of Canada is to facilitate the scientific wellbeing and professional development of its members, the learned discussion of geoscience in Canada, and the advancement, dissemination and wise use of geosciences in public, professional and academic life. Articles in Geoscience Canada are freely available one year after their publication date, unless authors have arranged for immediate open access. Opinions expressed and interpretations presented are those of the authors and do not necessarily reflect those of the editors, publishers and other contributors. Your comments are welcome.

**Cover Image:** View looking south of fieldwork at the Aley carbonatite complex, northeastern British Columbia, with the northern Rocky Mountain Main Ranges (Muskwa Range) in the background. Photo credit: Duncan McLeish

# PRESIDENTIAL ADDRESS

## Changing Trends and Rethinking Geoscience Education in the Context of a Global Crisis

**Kathryn Bethune**

*Department of Geology, University of Regina*
*3737 Wascana Parkway, Regina, Saskatchewan, S4S 0A2, Canada*
*E-mail: Kathryn.Bethune@uregina.ca*

It is somewhat ironic that I am sitting down to compose this Geoscience Canada article one day after Joe Biden was declared the winner of the 2020 US election on the Biden-Harris ticket, and I won't deny that the result of a more forward-looking agenda in regards to safeguarding our planet has inspired me! Under normal circumstances this article would follow from my GAC Presidential address delivered at the annual GAC-MAC meeting in mid-May, but, needless to say, this year has been anything but normal. As it turns out, the annual CSPG-led Geoconvention, in which we, along with MAC, were partnered together with other professional geoscience societies, was significantly delayed and ultimately held in an online format in mid- to late-September. All normal GAC and MAC meeting-related functions, including luncheons, awards, ceremonies and keynote talks, were also postponed with the idea that we could have a double cohort in a future face-to-face (F2F) setting in London, Ontario (Western University), in May 2021.

The circumstances at GAC have been a microcosm of what is happening across society as a whole, with continuous adjustments, delays in plans and new systems put into operation as the situation continually changes and evolves. In short, the global pandemic, felt acutely in almost every region of the world, is forcing us to rethink the ways we do things. In spite of extreme tragedy, including thousands of lives lost, the results have been positive on several fronts. For example, in this time of crisis, many in mainstream society have recognized the need to address several fundamental and persistent problems facing humanity including, but not limited to, the current climate crisis, issues with poverty and the increasing divide between rich and poor, as well as underlying issues of inequity and systemic racism, awareness of which has been enhanced by events in the USA and the 'Black Lives Matter' movement. As global citizens, we all have a role to play in these issues, but as geoscientists we also need to realize our potential to assist in the area of the global climate crisis, an issue I will address toward the end of this article.

One of the areas that have been impacted most by the COVID-19 situation is education, both at the K–12 and college/university levels. At the time of lockdown, all teachers and university professors and instructors had to quickly (within the space of 2–3 weeks) navigate the transition to online teaching, with little or no preparation time. Course platforms were created, learning materials were amassed and distributed to students at short notice (in clever ways, maintaining distance), instructors got up to speed with online platforms such as Zoom and MS Teams. It was a crazy time during which our own Faculty Association urged its members to refer to these as 'emergency teaching measures', recognizing that they by no means approached the requirements of traditional 'distance education' delivery. In addition, while there was breathing room for additional preparation in the summer, serious concerns continue around adequate resources and time to continue to deliver effective online programs.

Speaking to our own discipline, the highly applied nature of geology, across both solid Earth and environmental fields, obviously presents significant challenges for teaching in an online format. There is also a genuine concern, among us all, for the outright loss of experiential (F2F) learning in practical sessions and laboratories. This being said, it has been encouraging to see the enormous spirit of collaboration among geoscience departments, as well as individual like-minded geoscience educators, across the country since the emergency began in mid-March. This underscores the important role of the Council of Chairs of Canadian Earth Science Departments (CCCESD), comprising geoscience heads from across the country, which has been in regular communication on its e-mail network since the pandemic began. Although I am no longer formally a head, as President and now Past-President of GAC, I have remained on this network, recognizing the important linkages it provides. An enormous range of topics has been discussed by this group, from delivery methods and related resources for specific sub-disciplines, to conferring on numbers of classes and protocols for F2F learning.

In April and May, and continuing into the summer, there was also a significant discussion and sharing of ideas on plans for geological field schools in various departments. My sense is that very few departments were able to offer traditional F2F field schools and that many had to improvise, opting for some combination of digital, map-based assignments, coupled with virtual field trips/excursions, or some hybrid of these activi-

*Geoscience Canada,* v. 47, https://doi.org/10.12789/geocanj.2020.47.164 pages 167–169

Students and staff from the Department of Geology, University of Regina, working diligently to prepare 'rock and mineral kits' to be distributed to students in the fall semester. To assist in remote teaching during the Pandemic, such kits have been created and provided to Geoscience students by most departments across the country this year. Photos courtesy of Janis Dale and Jeanette Roelofsen.

ties. In some cases, such as in my own department, some practical F2F sessions could be added into this mix, with appropriate protocols (masks, social distancing) in place. The incorporation of these new forms of technology-based learning has opened our minds to alternative modes of delivery of our geology curricula, and is sure to have some positive spin-offs, including addressing issues of inaccessibility, due to disability and/or prohibitive costs for some students. It was encouraging to see several sessions at the Geological Society of America annual meeting in Montreal (virtual platform), specifically devoted to teaching field geology by innovative, new (online/digital) methods. In short, the pandemic has sped up exploration of alternative teaching delivery methods, not just in our field classes, but in all the sub-disciplines (e.g. mineralogy, petrology, stratigraphy, structural geology, soils, glacial geology, etc.). We have also seen some highly professional remotely delivered seminar series springing up, sourced from both within and outside Canada, including those delivered by the Structural Geology and Tectonics (CTG) and Volcanic and Igneous Petrology (VIP) divisions of GAC; these have been particularly valuable for graduate student training.

Nevertheless, most universities are critically underfunded to put the appropriate technological supports in place to effectively deliver online classes. There are also serious limitations for students, as much of this type of learning requires up-to-date computers (equipped with cameras and microphones), printing capabilities (e.g. for map-based applications), as well as reliable internet connections. Associated costs can prove prohibitive for some students, although are likely to improve over time; however, lack of access to reliable internet in rural areas continues to be a serious impediment, as recently recognized with the internet funding announcement (Nov. 10) by the Government of Canada. Software licensing can also be problematic for universities because of the often excessive and ever-increasing costs, although industry partnership has in some cases proven effective in this area. Regardless, even before the pandemic, Canadian universities appear to have been ill-equipped to invest in current, state-of-the-art equipment to facilitate teaching their Earth Science courses; in some cases, even the most basic items (e.g. petrographic microscopes) have been in short supply, and typically not replaced in a timely fashion.

Aside from this, as experienced Earth Scientists, we are aware of the serious shortcomings of lack of experiential learning in our discipline. Hands-on training has been and continues to be a critical component of academic programs in the

Earth Sciences and is virtually (no pun intended) impossible to replace. Most field-based researchers recognize that university field schools are a bare minimum on the road to becoming a fully-fledged field-oriented geoscientist. Student learning in university-based field courses is commonly augmented by on-the-job training over the summers with geological surveys, resource companies and environmental firms. With continuing concerns about COVID-19, these practical training opportunities have been severely curtailed. In short, we need to start thinking of creative ways to get the current cohort of geoscience students (2020–21 graduating class) up to speed with practical experience. As a first step, university departments may need to offer supplemental programming in the 2021 spring/summer or fall semesters that allows students to catch up on a range of practical skills. This could take the form of a 1–2 week long intensive course that covers practical aspects of all sub-disciplines that were impossible to teach F2F. This might include hands-on aspects of mineralogy, petrology (petrography and microscopic study), structural geology, stratigraphy and sedimentology, and environmental geology. If deemed feasible, in-class instruction could be accompanied by short (day or 1/2 day) field excursions to further advance practical know-how.

It is doubtful that universities will be able to make up entire (normal length) field schools, but I believe that such an intensive, hands-on week to augment skills that were largely taught online could be very helpful and go a long way toward improving student preparation. This academic program could possibly be paired with a collaborative effort between geological societies, universities (including their co-op programs), government organizations and environmental and resource companies to help get student job placements in the summer. All of this would have to be done under safe circumstances, of course, which will depend on how the virus situation progresses through 2021 and if vaccination programs have started up, etc. This being said, it would be prudent to start thinking and planning now.

All this stated, in order to appeal to a wider range of students and to increase equity and diversity within the geosciences, which is much needed, we need increasingly to be aware of other directions students can pursue to make meaningful contributions to our discipline. The COVID-19 pandemic may have fulfilled an important role in this regard, highlighting that there is room for non-field-based pursuits in the Earth Sciences and leading us to re-imagine classical modes of training. For example, we need to be open to the usefulness of new digitally-based lines of inquiry, including applications of modelling (3- and 4-D), artificial intelligence and quantum computing in the Earth Sciences. There are also avenues to pursue in the emerging areas of microanalysis and nanotechnology. Lastly and perhaps more importantly, we need to work toward incorporating 'indigenous ways of knowing' into our approaches to Earth Science education.

As mentioned at the beginning of this article, we are at a critical juncture in society today. The COVID-19 pandemic has accelerated the need to think ‘outside the box’ in order to find solutions to multiple pressing issues. As geoscientists, we are well-positioned to play a key role in helping to mitigate the current climate crisis. From the perspectives of Earth history and deep time, we have unique insights into the Earth system that place us in an excellent position not only to put recent anthropogenic effects on climate in context, and hence better understand them, but to play an active role in developing the needed mitigation measures. The transition to a carbon-free economy in the next 25–75 years will require specialized knowledge of Earth processes that can only be fostered by robust geoscience education programming. Highly qualified Earth Scientists will be needed to, among other things, evaluate sedimentary basins for geothermal potential, evaluate the extent and sustainability of groundwater aquifers and to explore for much sought after rare elements that underpin the electrical vehicle industries, not to mention those needed to support the rapidly growing tech and communications sectors!

The aforementioned are just a few of the wide-ranging applications that require expertise in the Earth Sciences, in conjunction with engineering. We must face the reality that while hydrocarbon resources will continue to be a component of the energy equation, they will be significantly reduced. The inevitable and much needed shift to renewable energy sources such as solar, geothermal and wind, some of these perhaps to be coupled locally with nuclear energy sources, will require the same fundamental skills in geoscience, just applied in somewhat different ways.

In closing, it is our obligation as geoscientists to bring attention to the important role we can play, both within the education system, particularly at the university level, and to the general public, in helping to understand and mitigate climate change. Presently, we also have an enormous obligation to make every effort to bring the current cohort of geoscience students through their degree programs successfully, and to ensure that supplemental programs are created to enhance their practical skills and augment their education. There is no better time to spread the word of the value of Earth Science education and to work on adjusting our academic programs to meet future needs. Now more than ever the world needs highly qualified geoscientists, and we need to be ready!

# GEOLOGICAL ASSOCIATION OF CANADA
# (2020-2021)

## CORPORATE MEMBERS

*PLATINUM*

MEMORIAL UNIVERSITY

*GOLD*

NORTHWEST TERRITORIES GEOLOGICAL SURVEY

*SILVER*

ROYAL TYRRELL MUSEUM

YUKON GEOLOGICAL SURVEY

BRITISH COLUMBIA GEOLOGICAL SURVEY

*NICKEL*

UNIVERSITY OF WATERLOO

*GEOSCIENCE CANADA AND THE GEOLOGICAL ASSOCIATION OF CANADA ARE GRATEFUL TO THE CANADIAN GEOLOGICAL FOUNDATION FOR THEIR FINANCIAL SUPPORT OF THIS JOURNAL*

Canadian Geological Foundation
Fondation Géologique du Canada
1968

## OFFICERS

*President*
Deanne van Rooyen
*Past President*
Kathryn Bethune
*Vice-President*
Alwynne Beaudoin
*Treasurer*
Michael Michaud
*Secretary*
Holly Steenkamp

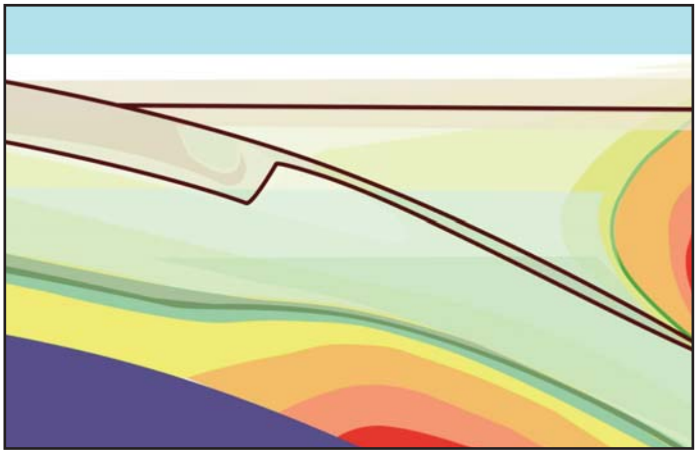
## COUNCILLORS

Paul Alexandre
Andrea Amortegui
Alwynne Beaudoin
Kathryn Bethune
Stefanie Bruekner
Hendrik Falck
Alana Hinchey
Rebecca Hunter
Andy Kerr
Phil McCausland
Michael Michaud
Camille Partin
Roger Paulen
Holly Steenkamp
Deanne van Rooyen
Reg Wilson

## STANDING COMMITTEES

Communications: Rebecca Hunter
Finance: Michael Michaud
GAC Lecture Tours: Stefanie Bruekner
Publications: Roger Paulen
Science Program: Phil McCausland

# ANDREW HYNES SERIES: TECTONIC PROCESSES



## Stratigraphy and U–Pb Zircon–Titanite Geochronology of the Aley Carbonatite Complex, Northeastern British Columbia: Evidence for Antler-Aged Orogenesis in the Foreland Belt of the Canadian Cordillera

**D.F. McLeish[1*], S.T. Johnston[1+], R.M. Friedman[2], and J.K. Mortensen[2]**

[1]*School of Earth and Ocean Sciences, University of Victoria*
*Victoria, British Columbia, V8W 3V6, Canada*
[*]*Present address: Department of Earth and Planetary Sciences*
*McGill University, Montreal, Quebec, H3A 0E8, Canada*
*E-mail: duncan.mcleish@mail.mcgill.ca*

[+]*Present address: Department of Earth and Atmospheric Sciences*
*University of Alberta, Edmonton, Alberta, T6G 2E3, Canada*

[2]*Department of Earth and Ocean Sciences*
*University of British Columbia*
*Vancouver, British Columbia, V6T 1Z4, Canada*

### SUMMARY

The tectonic significance and age of carbonatite intrusions in the central Foreland Belt of the Canadian Cordillera are poorly constrained. Recent work has demonstrated that one of these carbonatite intrusions, the Aley carbonatite, was emplaced as a syn-kinematic sill, coeval with a major nappe-forming tectonic event. Determining the age of the Aley carbonatite thus provides a means of directly dating syn-tectonic magmatism. Attempts at dating carbonatite units failed due to low U–Pb content in sampled zircon; however, a U–Pb titanite age of 365.9 ± 2.1 Ma was obtained from the Ospika pipe, an ultramafic diatreme spatially and genetically related to the carbonatite. This U–Pb titanite age is further supported by respective $^{40}$Ar/$^{39}$Ar phlogopite ages of 359.4 ± 3.4 Ma and 353.3 ± 3.6 Ma for the pipe and a spatially associated lamprophyre dyke. We interpret the Late Devonian U–Pb titanite age of the Ospika pipe to be the minimum possible age of the carbonatite and syn-magmatic nappe-forming tectonic event. The maximum possible age of the carbonatite is constrained by the Early Devonian age of the Road River Group, the youngest strata intruded by carbonatite dykes and involved in the nappe-forming event. Our dating results for the Aley carbonatite closely correlate with U–Pb zircon and perovskite ages obtained for the Ice River carbonatite complex in the central Foreland Belt of the southern Canadian Cordillera, and support the interpretation of carbonatite intrusions of the western Foreland Belt as genetically linked components of an alkaline-carbonatitic magmatic province. Structural, stratigraphic, and geochronological data from the Aley area indicate that deformation was similar in style to, and coeval with, structures attributable to the Antler orogeny, and are consistent with the Antler orogen having extended the length of the Cordilleran margin from the southern United States to Alaska.

### RÉSUMÉ

La signification tectonique et l’âge des intrusions de carbonatite dans le Domaine de l’avant-pays central de la Cordillère canadienne sont méconnus. Des travaux récents ont démontré qu’une de ces intrusions de carbonatite, la carbonatite d’Aley, a été mise en place en tant que filons-couches syn-cinématiques, contemporains avec un événement tectonique majeur de formation de nappe. La détermination de l’âge de la carbonatite d’Aley fournit ainsi un moyen de datation directe du magmatisme syn-tectonique. Les tentatives de datation des unités de carbonatite ont échoué en raison de la faible teneur en U – Pb du zircon échantillonné; cependant, un âge U–Pb de 365,9 ± 2,1 Ma a été obtenu à partir de titanite provenant de la cheminée d’Ospika, une diatrème ultramafique spatialement et géné-

---

*Geoscience Canada,* v. 47, https://doi.org/10.12789/geocanj.2020.47.165 pages 171–186

GC Data Repository for the Andrew Hynes Series: Tectonic Processes at: https://gac.ca/gc-data-repository/

tiquement apparenté à la carbonatite. Cet âge U–Pb sur titanite est en outre soutenu par des âges $^{40}$Ar/$^{39}$Ar sur phlogopite de 359,4 ± 3,4 Ma et 353,3 ± 3,6 Ma respectivement pour la cheminée et un dyke de lamprophyre spatialement associé. Nous interprétons l'âge U–Pb des titanites du Dévonien supérieur de la cheminée d'Ospika comme étant l'âge minimum possible de la carbonatite et de l'événement tectonique syn-magmatique de formation de nappe. L'âge maximum possible de la carbonatite est limité par l'âge Dévonien inférieur du groupe de Road River, les plus jeunes strates traversées par les intrusions de dykes de carbonatite et impliquées dans l'événement de formation de nappe. Nos résultats de datation pour la carbonatite d'Aley sont étroitement corrélés avec les âges U–Pb sur zircon et pérovskite obtenus pour le complexe de carbonatite de Ice River dans le Domaine de l'avant-pays méridional de la Cordillère canadienne, et appuient l'interprétation des intrusions de carbonatite du Domaine de l'avant-pays occidental comme étant des composantes génétiquement liés d'une province magmatique alcalino-carbonatitique. Les données structurales, stratigraphiques et géochronologiques de la région d'Aley indiquent que la déformation était semblable et contemporaine aux structures attribuables à l'orogenèse Antler, et sont compatibles avec l'orogène Antler ayant étendu la longueur de la marge de la Cordillère depuis le sud des États-Unis États jusqu'en Alaska.

## INTRODUCTION

Paleozoic strata in the western Foreland Belt of the Canadian Cordillera are characterized by widely spaced carbonatite and silica-undersaturated alkali intrusive and volcanic complexes (Fig. 1). A detailed structural study of one of the carbonatite complexes, the Aley carbonatite of the Rocky Mountains of northeastern British Columbia (McLeish and Johnston 2019) demonstrated that the carbonatite: (1) forms a sill intruded near the base of a lower to middle Paleozoic stratigraphic sequence that includes, from oldest to youngest, the Kechika and Skoki formations and the Road River Group; and (2) is, together with its wall rocks, overturned, forming the lower limb of a syn-magmatic crustal-scale recumbent nappe. McLeish and Johnston (2019) interpreted the carbonatite and syn-magmatic nappe as manifestations of the Antler collisional orogeny along an active convergent margin.

General questions arising from these findings include: (1) are other Cordilleran carbonatite complexes attributable to the same collisional event; (2) was the collisional orogenic event of continental scope; and, if so (3) can we distinguish correlative structures and identify sedimentary, igneous and metamorphic rocks attributable to the same event elsewhere in the foreland of the Cordillera? Answering these questions requires that we constrain the timing of deformation and syn-kinematic magmatism in the Aley region. Toward this goal, we conducted an integrated field stratigraphic and geochronological study of the Aley carbonatite complex and its wall rocks, including a post-kinematic diatreme, the Ospika pipe; the Lady Laurier volcanic unit, part of the Ordovician Skoki Formation; and a volcano-sedimentary member of the Kechika Formation. Specific questions addressed include: (1) what is the age of intrusion of the syn-kinematic Aley carbonatite and by extension the timing of nappe formation; (2) what is the temporal relationship between the spatially associated silica-undersaturated to alkalic Aley carbonatite, Ospika pipe diatreme, lamprophyre dykes and Lady Laurier (Skoki Formation) volcanic unit; and (3) when was the onset of magmatism, as recorded by the volcano-sedimentary member of the Kechika Formation, in the Aley region of the western Foreland Belt? Here we review the geological setting of the Aley carbonatite and its wall rocks, present the results of our geochronological studies, and attempt, using these data, to address these questions.

## GEOLOGY OF THE ALEY REGION OF THE ROCKY MOUNTAINS OF NORTHEASTERN BRITISH COLUMBIA

### General Information

The study area lies within the Williston Lake area of the western Foreland Belt of the Rocky Mountains and is characterized by lower to middle Paleozoic deep water carbonate rocks and shale (Figs. 1 and 2). These units consist of slope to off-shelf deep-water strata and define the paleogeographic Kechika Trough (Pyle and Barnes 2003). In the Aley region, the north–south trending, 50 km-wide trough is bounded to the west by the Northern Rocky Mountain Trench, which is host to an Eocene dextral strike-slip fault interpreted to have accommodated > 400 km of dextral strike-slip displacement (Gabrielse 1985), and to the east by a facies boundary defined by the western limit of shallow water carbonate rocks of the MacDonald Platform (Aitken 1971; Pyle and Barnes 2003). This facies boundary constitutes the boundary between the western and eastern subprovinces of the Foreland Belt (Fig. 2). North of 59°N latitude, the Kechika Trough widens into the Selwyn Basin. The trough terminates immediately south of the Aley region, where the facies boundary marking the eastern margin of the trough curves around to the west, and is truncated against the Northern Rocky Mountain Trench fault. Thompson (1989) established the regional stratigraphic framework of the MacDonald Platform and Kechika Trough. Additional stratigraphic studies of the Aley region include Pride (1983) and Pyle and Barnes (2001). Intrusive into the Kechika Trough stratigraphic sequence are the Aley carbonatite, the Ospika pipe diatreme and lamprophyre dykes (Fig. 2). In addition to these intrusive rocks, igneous activity in the Kechika Trough is marked by the 10–100 m-thick Lady Laurier volcanic member of the Skoki Formation. Within the study area, the stratigraphic sequence and the Aley carbonatite intrusion all lie within and define the overturned lower limb of a crustal scale nappe (Fig. 3; McLeish and Johnston 2019).

### Structural History of the Study Area

Detailed 1:5000 scale mapping of the carbonatite and Paleozoic host stratigraphy reveals a complex polyphase deformation record preserved within the elliptical complex (McLeish and Johnston 2019). Deformation is manifested by early isoclinal folding and associated shearing ($D_1$) of mineralized apatite and magnetite-rich laminations within the carbonatite, and the development of isoclinal folds ($F_1$), a bedding parallel (axial

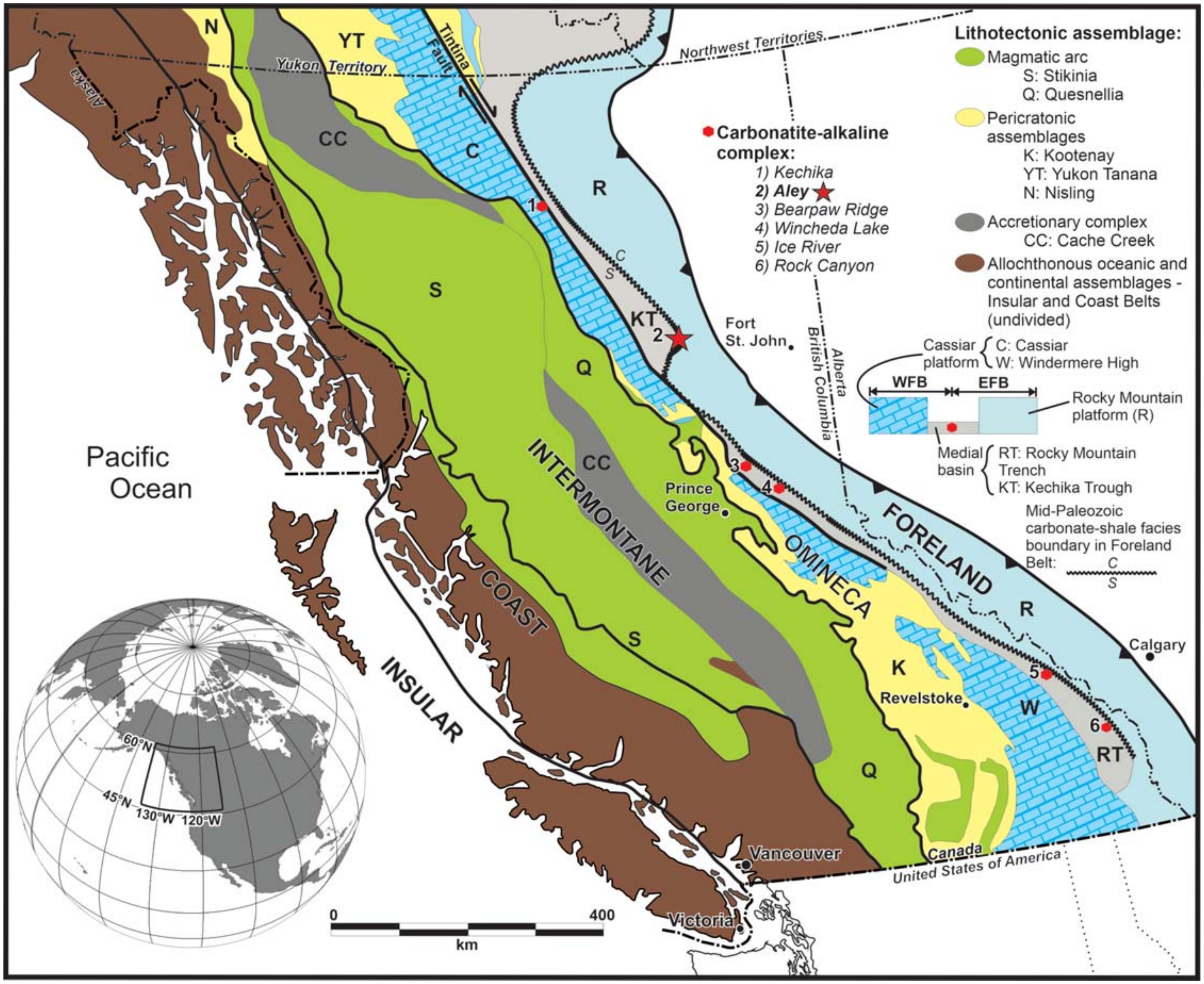


**Figure 1.** First-order morphological subdivisions of the Canadian Cordillera with known Foreland Belt alkaline-carbonatite complexes shown in reference to the transition of early Paleozoic continental platform and slope facies to deep-water basinal facies. This transition is also known as the Carbonate-to-Shale, or C–S, boundary, and is interpreted to separate the western and eastern divisions of the Foreland Belt (WFB and EFB, respectively). Alkaline complex localities in part after Pell (1994); facies boundary after Wheeler and McFeely (1991). The distribution of Paleozoic alkaline volcanic rocks in the Foreland Belt (not shown) closely mirrors that of the carbonatite complexes. Figure after McLeish and Johnston (2019).

planar) cleavage ($S_1$), and low-angle thrust faults within the host stratigraphy. Fabrics generated by the $D_1$ event have been transposed by asymmetric, large-amplitude cascading and chevron-style folds ($F_2$) of the Rocky Mountain orogeny ($D_2$); fold interference between these two deformation events has led locally to the development of mineral fabrics trending approximately E–W, orthogonal to the regional Rocky Mountain trend.

## The Geology of the Antler Orogen

Roberts (1951) first recognized and defined the Antler orogen in southern Idaho and central Nevada. The Late Devonian to Mississippian orogeny involved the eastward emplacement of Cambrian–Devonian sedimentary rocks onto the western margin of the Laurentian craton. The timing of the orogeny is constrained by the oldest (latest Devonian) allochthon-derived synorogenic strata and Late Mississippian successor passive margin strata which unconformably overlie the synorogenic strata (Trexler et al. 2004). Previous to this study, no plutonic rocks have been associated with the Antler orogen, and no occurrences of Antler-aged high-grade metamorphic rocks are known (see Speed and Sleep 1982; Burchfiel and Royden 1991; Linde et al. 2017). It is thought that the Antler magmatic arc was largely or entirely subducted during arc–continent collision (Speed and Sleep 1982).

https://doi.org/10.12789/geocanj.2020.47.165

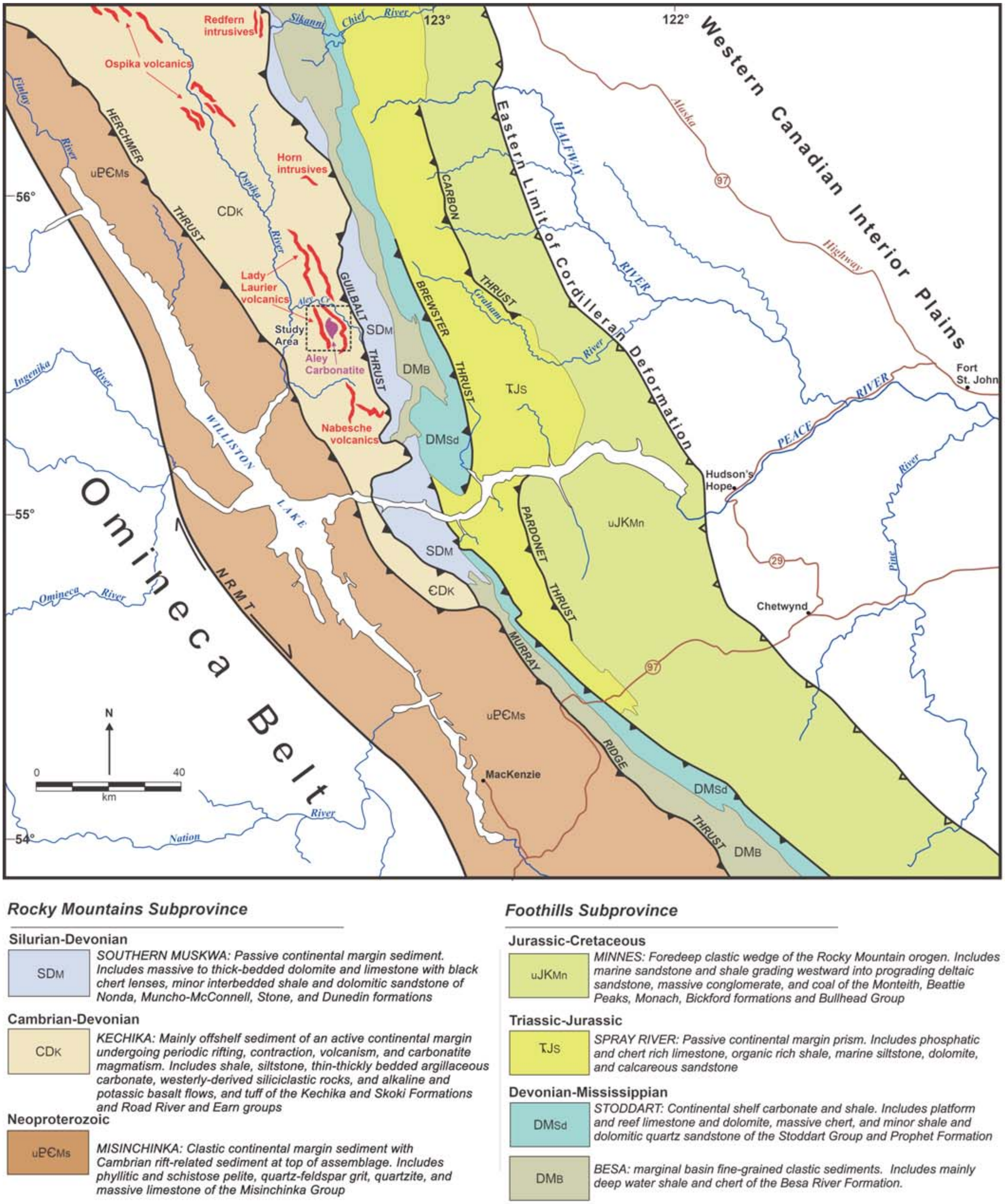


**Figure 2**. Simplified geological map of the Williston Lake area of northeastern British Columbia showing key tectono-stratigraphic divisions (after Wheeler and McFeely 1991). Several alkaline volcanic occurrences (red) and the Aley carbonatite complex (purple) define a strike-parallel belt of Paleozoic igneous activity unseen in Paleozoic continental shelf and margin strata to the east. The location of the carbonate-to-shale facies boundary (not shown) of Wheeler and McFeely (1991) roughly coincides with the Guilbalt Thrust. Note, due to the simplification of geological units on this map, the unit abbreviations and areas covered by the units in this figure differ slightly from Figure 3. NRMT = Northern Rocky Mountain Trench.

## STRATIGRAPHIC UNITS

### Kechika Formation (Late Cambrian to Early Ordovician)

Within the study area, the Kechika Formation is divisible into a lower volcano-sedimentary member, and an upper carbonate and siliciclastic member (McLeish 2013). The heterogeneous lower volcano-sedimentary member consists of interlayered conglomerate, pillow basalt, tuff, volcaniclastic rocks and fragmental volcanic layers. The pebble to boulder conglomerate layers are discontinuous and are of variable thickness. Quartzite, siltstone, granitoid rock and dolostone clasts are rounded to well-rounded. Volcanic layers weather dark to light green. Well preserved pillows are rare; fragmental volcanic layers, tuff and immature, volcaniclastic sedimentary rocks are more common. The exposed thickness of this member in the study area is 200 m. Its total thickness is difficult to constrain as its base has been intruded by the Aley carbonatite, and no pre-Kechika strata are exposed in or adjacent to the study area. Correlative volcanic layers within the lower Kechika Formation (Fig. 2) have been documented 100 km north of the Aley region in the Redfern Lake (Taylor and Stott 1973; Taylor 1979) and Ospika River areas (Taylor et al. 1979; MacIntyre 1998).

Carbonate and siliciclastic strata of the upper sedimentary member of the Kechika Formation include tan-brown and grey planar laminated argillaceous limestone; wavy, banded orange-brown calcareous siltstone; and massive, cream-coloured dolostone. These strata are interpreted to have been deposited in a deep-water, slope to off-shelf environment (Pyle and Barnes 2001). Siliciclastic strata are phyllitic, have a bedding-parallel cleavage, and record low-grade metamorphism. The maximum thickness of the upper member in the map area is 800 m (Fig. 3D).

Age constraints on the Kechika Formation are few. No direct age constraints on the volcano-sedimentary member in the study area are available; however, correlative volcanic strata of the Kechika Group in the Pelly Mountains of south-central Yukon yield Cambrian to Ordovician zircon U–Pb ages (Campbell et al. 2019). Few fossils are preserved in the upper sedimentary member. Pride et al. (1986) and Mader (1986) labelled the Kechika Formation within the study area as Cambrian, whereas Thompson interpreted the age of the formation to extend into the Early Ordovician; conodonts recovered from the uppermost member to the north of the Aley region indicate an Early Ordovician age (Pyle and Barnes 2001).

### Skoki Formation (Early to Late Ordovician)

The Skoki Formation is divisible into lower and upper dolostone members that are separated by a distinct volcanic member informally referred to as the Lady Laurier volcanic unit (Mader 1986; McLeish 2013). The dolostone members consist of cliff-forming, grey weathering, medium to thick-bedded, mottled grey dolostone. Relict primary textures show that the dolostone originally consisted of massive to cross-bedded bioclastic limestone. Fossiliferous layers contain crinoid ossicles, gastropods and, in the upper dolostone member, planispiral (*Maclurites*) gastropods (Mader 1986). Chert lenses and oncolites are rare in the lower dolostone member, but are common toward the top of the upper dolostone member adjacent to the contact with the stratigraphically overlying Road River Group.

Argillaceous, wavy bedded dolostone is present in the lower dolostone member near the contact with the underlying Kechika Formation. The contact between the lower member and the Kechika Formation is commonly faulted; low angle faults that developed along the overturned lower limb of the nappe during nappe formation cut structurally down-section, stratigraphically up-section, from the upper Kechika Formation into the lower dolostone of the Skoki Formation, thinning the overturned stratigraphic sequence (McLeish and Johnston 2019). The thickness of the lower dolostone member is estimated to be 150 m based on exposures in the northwest of the study area where the lower contact with the Kechika is little modified by faults and the contact with the volcanic member is sharp. The thickness of the upper dolostone member is 200 m as constrained by a complete section exposed in the southeast of the study area (Fig. 3D).

The 10- to 100 m-thick middle (Lady Laurier) volcanic member of the Skoki Formation consists of fine-grained submarine volcanic lapilli-to ash-tuff that passes upward into agglomerate and volcaniclastic layers. Metre-thick layers of dark green shale are common, whereas pillow basalt is rare. Carbonatite ocelli have been observed in agglomeratic layers (D. Canil personal communication 2009). Dolostone layers interfinger with volcanic layers near the top of the volcanic member, and the contact with the overlying dolostone is gradual. Structurally thinned (10–20 m) exposures of this member are common. The Skoki Formation, including the Lady Laurier volcanic member, is continuous throughout the Halfway River region (Thompson 1989). Paleontological studies constrain the age of the formation to Early to Late Ordovician (Cecile and Norford 1979; Thompson 1989; Pyle and Barnes 2001). No direct age determination is available for the volcanic member.

### Road River Group (Late Ordovician to Early Devonian)

The Road River Group consists of a > 1 km-thick sequence of off-shelf clastic and lesser carbonate rocks. The contact with the Skoki Formation is sharp, possibly unconformable, and is marked by an abrupt transition from thickly bedded, resistant, chert-rich dolostone to recessive shale. Within the study area, the Road River Group can be divided into two shale-dominated members that are separated by a quartzite unit (McLeish 2013). The lower member consists of fissile, graptolitic shale and planar-laminated to thinly bedded, grey-weathering siltstone and argillaceous limestone. At least four, 10–20 m-thick quartzite beds are present 175 to 300 m above the contact with the underlying Skoki Formation. The quartzite beds are massive, fine- to medium-grained and homogeneous, and form a distinctively resistant section that can be traced throughout the map area; they were recognized regionally as a distinct unit by Thompson (1989). The upper member consists of graptolitic shale and laminated siltstone, but also contains metre-thick dolostone beds with chert lenses. Pride (1983) described an additional dolomitic quartzite unit at the top of the Road River Group. Paleontological collections of Cecile and Norford

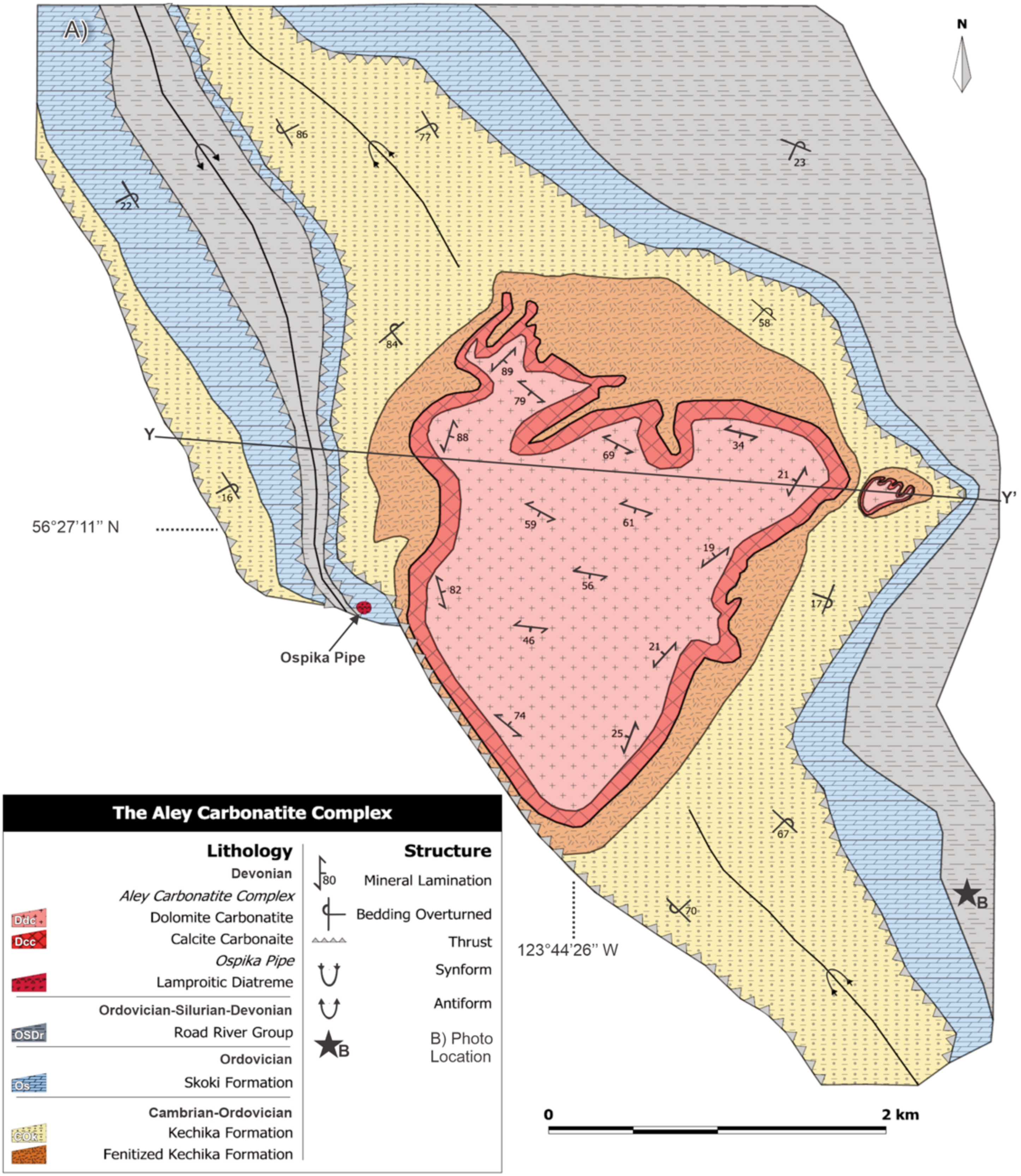


**Figure 3.** (A) Geological map of the Aley carbonatite complex (in part, after Mader 1986 and McLeish and Johnston 2019).

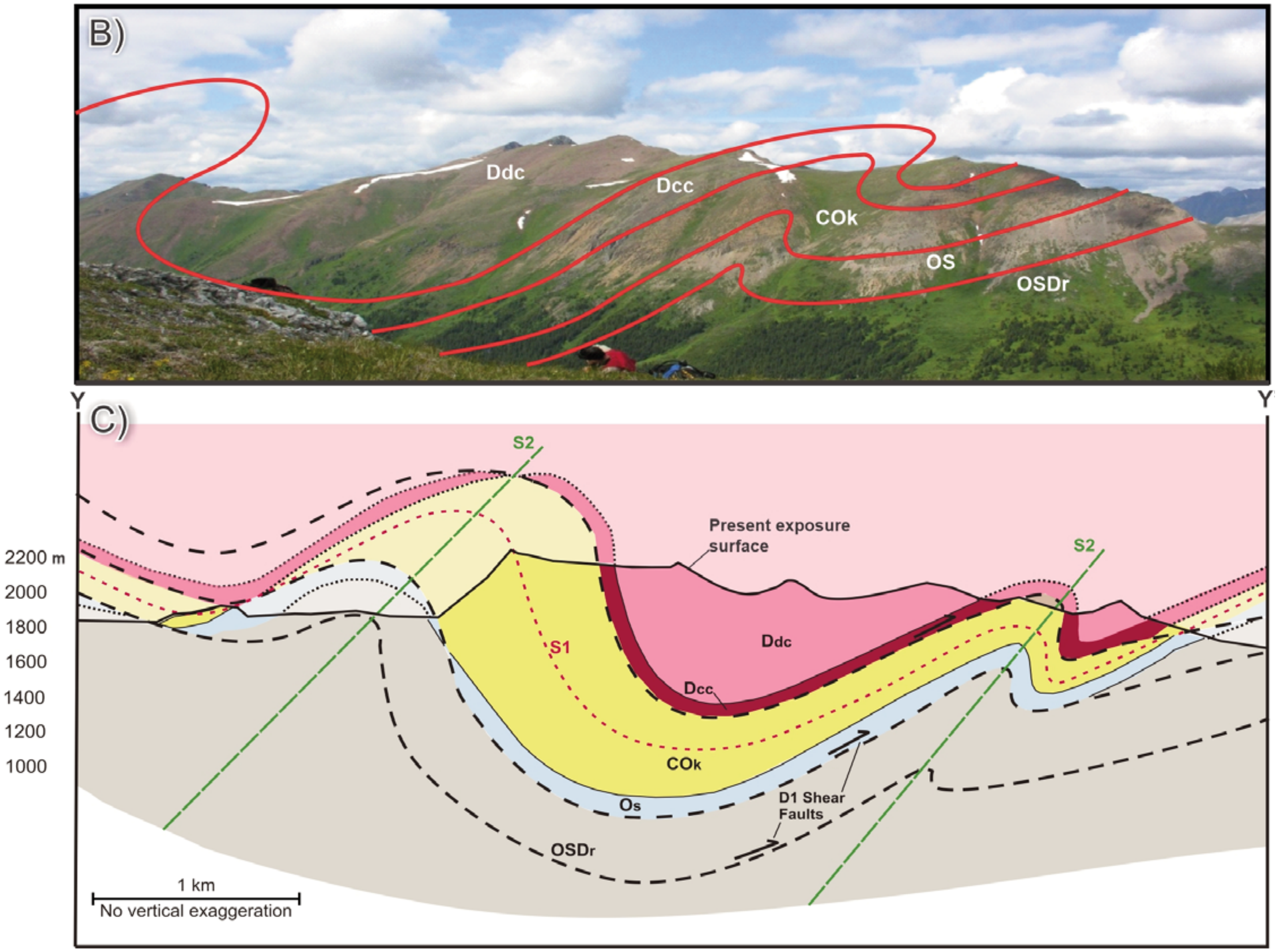


**Figure 3.** *cont'd* (B) East-west profile view of the Aley carbonatite complex showing the distribution of the major map units (after McLeish and Johnston 2019); (C) Geological cross-section Y-Y' from Figure 3A (after McLeish and Johnston 2019). See Figure 3A legend for explanation of rock units. Note, the location of the fenitized Kechika Formation is not shown on the cross-section due to the generally narrow but variable width of the unit.

(1979) and Norford (1979) indicated the age range of the Road River Group in the region to be Late Ordovician to Early Devonian.

## INTRUSIVE ROCKS

Exposures of intrusive rocks in the Aley Creek area include: (1) the Aley carbonatite sill; (2) the Ospika diatreme pipe; and (3) ultrabasic lamprophyre dykes and sills (Fig. 3). The carbonatite has been described by Pride (1983, 1987a, b), Mader (1986), Pell (1994), Chung & Crozier (2008), Crozier (2011, 2013), and Chakhmouradian et al. (2015).

### Aley Carbonatite

The Aley carbonatite intruded as a 1.5 km-thick, layer-parallel sill into or at the base of the lower volcanic member of the Kechika Formation (McLeish and Johnston 2019). The carbonatite now lies structurally above the host stratigraphic sequence and is preserved in the core of an asymmetric, Rocky Mountain deformation-related F$_2$ synform. The synform verges east, with a steeply dipping to vertical west limb, a shallowly west-dipping east limb and a moderately west-dipping axial surface (Fig. 3). To the east, 0.5 km from the eastern margin of the main exposure, a separate 300-metre-wide exposure of the carbonatite sill crops out in a smaller parasitic F$_2$ synform. Three principal units within the carbonatite have been identified: (1) a volumetrically dominant fersmite- and pyrite-bearing dolomite–apatite carbonatite unit that forms the core of the sill; (2) a magnetite, pyrochlore, phlogopite-bearing calcite-apatite carbonatite unit that forms the top of the sill where it is in contact with the Kechika Formation; and (3) a banded magnetite-apatite unit in the dolomite core (Kressall et al. 2010).

Variably developed apatite mineral bands within the calcite and dolomite carbonatite units define a layer-parallel S$_1$ foliation interpreted to have developed during, and provides a record of, D$_1$ plastic flow (McLeish et al. 2010). The S$_1$ folia-

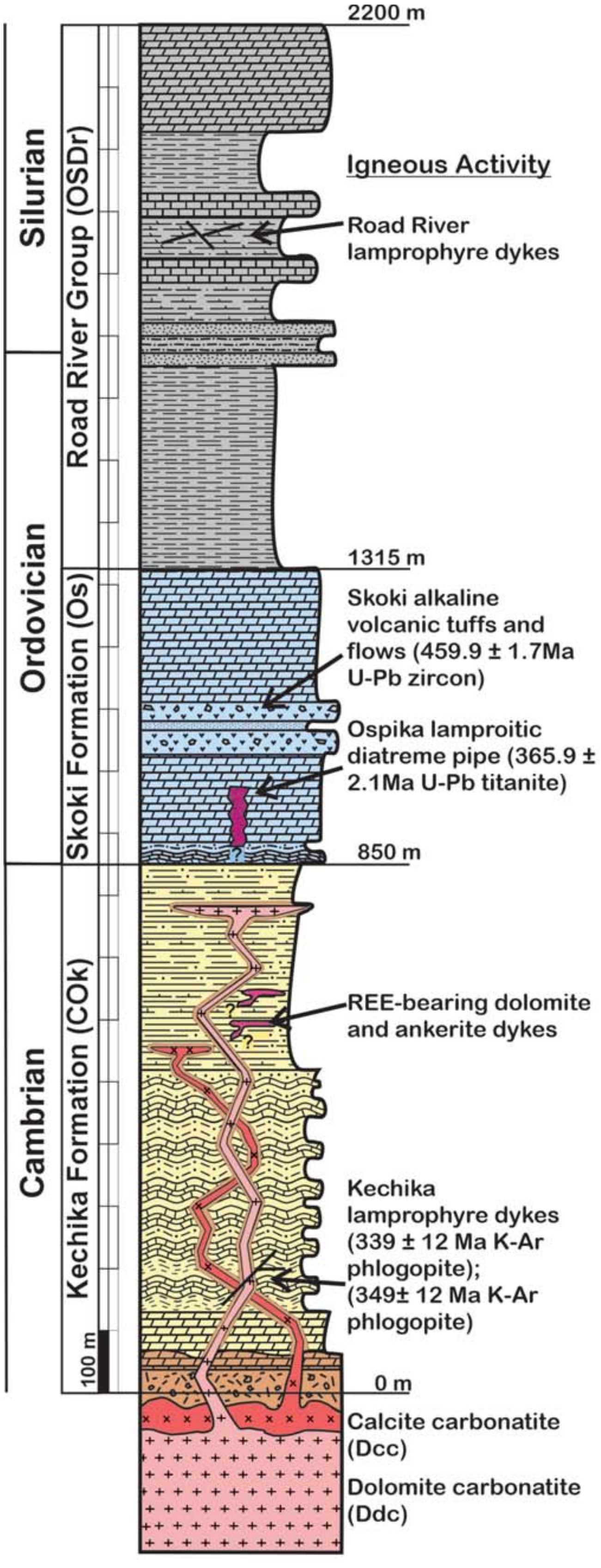


**Figure 3.** *cont'd* (D) Idealized stratigraphic column of the Aley carbonatite map area (in part, after Pride et al. 1986 and McLeish and Johnston 2019).

tion in the carbonatite is concordant with the bedding-parallel $S_1$ cleavage in the country rock and is cut and truncated by late phase dolomite carbonatite dykes, indicating that intrusion of the carbonatite was syn-kinematic with $D_1$ nappe formation (McLeish and Johnston 2019). The banded magnetite–apatite unit is conformable with the $S_1$ fabric and may represent a distinct primary cumulate phase of the carbonatite. Locally, calcite and dolomite carbonatite units contain xenoliths of heavily fenitized siltstone country rock, likely belonging to the Kechika Formation. The abundance of xenoliths increases towards the top margin of the sill, with the peripheral calcite carbonatite unit containing the highest concentration. Numerous dykes and sills of calcite and dolomite carbonatite intrude the Kechika Formation in the fenitized contact aureole where cross-cutting relationships show that the calcite carbonatite preceded intrusion of the dolomite carbonatite (McLeish and Johnston 2019).

A metasomatic fenite aureole extends up to 1 km (apparent thickness) out from the carbonatite–Kechika Formation contact into the upper sedimentary member of the Kechika Formation (Fig. 3). Fenite metasomatism (fenitization) is indicated by replacement of the primary igneous minerals by sodic amphiboles and sodic pyroxenes (arfvedsonite, richterite, aegirine and lorenzenite), and decreases gradationally in intensity outwards from the contact (Mader 1986; Pell 1994). Fenitization is therefore interpreted to have occurred during, and is attributable to, intrusion of the Aley carbonatite and explains previous mapping (Mader 1986; Pride 1987a; Pell 1994) of volcano-sedimentary rocks in the lower member of the Kechika as 'amphibolite' or 'syenite' (Chakhmouradian et al. 2015).

Pre-existing geochronological data for the carbonatite include a single K–Ar date of 339 ± 12 Ma on phlogopite from a sample of an amphibolitized, siltstone xenolith-bearing calcite carbonatite breccia from the western margin of the main carbonatite exposure (Pride et al. 1986). U–Pb dating of zircon separates from the dolomite carbonatite was also attempted by Pride et al. (1986) but failed due to low U–Pb content in sampled zircon. More recently, Chakhmouradian et al. (2015) obtained a high-resolution ion microprobe U–Pb baddeleyite age of 372 ± 8 Ma for the main dolomite phase of the carbonatite.

## Lamprophyre Dykes

Multiple thin (0.5–2.0 m) ultrabasic sills and dykes, including some that are enriched in rare-earth carbonate minerals and which bear distinctive purple fluorite, occur throughout the map area in the host stratigraphy (Fig. 3D) but are most common in the metasomatic fenite aureole peripheral to the carbonatite. Similar dykes intrude the dolomite carbonatite near the core of the western synform (A. Chakhmouradian personal communication 2010). The sills and dykes range in colour from reddish-orange to deep chocolate-brown and are primarily composed of ankerite (Pell 1994). The dykes cut bedding ($S_0$) and the bedding-parallel cleavage ($S_1$), and truncate and post-date the fenite metasomatized rocks of the carbonatite contact aureole, indicating that the ultrabasic intrusions post-date $D_1$ tectonism and carbonatite magmatism. A single K–Ar date of 329 ± 12 Ma was obtained from a sample of biotite lamprophyre talus collected near the carbonatite Kechika Formation contact (Pride 1986).

### Ospika Pipe Diatreme

The Ospika pipe is a 50 m-wide ultramafic diatreme pipe intruding the Skoki Formation 500 m west of the western margin of the main carbonatite sill. The pipe weathers a distinct maroon brown, is circular in plan view, and contains both massive and breccia phases. The breccia contains 5–30% subangular to subrounded, randomly oriented xenoliths of Road River Group siltstone that range from sub-centimetre to sub-metre sizes and which are characterized by the bedding-parallel $S_1$ cleavage. The cleaved wall-rock xenoliths indicate that the diatreme pipe post-dates $D_1$ deformation that was coeval with carbonatite magmatism. Mineralogically, the pipe is characterized by a phlogopite-dominated, phlogopite–clinopyroxene–olivine macrocryst mineral assemblage hosted in a very fine-grained, hypidiomorphic dolomite–chlorite matrix. Geochemical analyses of the diatreme pipe are consistent with its classification as an aillikite (Pell 1994). A geochronological study of phlogopite separates from the matrix yielded Rb–Sr and K–Ar ages of 334 ± 7 and 323 ± 10 Ma respectively (Pell 1994). These ages are similar to the K–Ar ages reported for the lamprophyre dykes and sills.

## METHODS

Igneous units were sampled during mapping for U–Pb zircon, U–Pb titanite, and $^{40}$Ar/$^{39}$Ar phlogopite geochronological analyses at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, Vancouver, Canada. Zircon and titanite were isolated from 5–10 kg samples using standard rock crushing, grinding, and Wilfley table methods, followed by heavy liquid and magnetic separation. Zircon and titanite fractions were handpicked based on differences in crystal quality, size, magnetic susceptibility, and morphology.

Zircon was dated via laser ablation (LA) ICP–MS methods of Tafti et al. (2009) which are summarized in Appendix 1. The $^{206}$Pb/$^{238}$U age is the most precisely determined age for Phanerozoic zircon and is interpreted as the best estimate for the crystallization age of the samples. Assigned ages are based on a weighted average of overlapping, concordant $^{206}$Pb/$^{238}$U ages of individual analyses for each sample. Error ranges for all samples are quoted at the 2σ level. Titanite was dated via chemical abrasion isotope dilution thermal ionization mass spectrometry (CA–ID–TIMS) methods described in Appendix 2. Analytical data for all dated samples discussed in this report are available in Appendix 3.

Samples dated by $^{40}$Ar/$^{39}$Ar methods were prepared by handpicking phlogopite from crushed, ground mineral separates that had been reduced on a Wilfley table. Phlogopite extracts were washed in acetone, dried, wrapped in aluminum foil, and stacked in an irradiation capsule with similar-aged samples and neutron flux monitors. Extracts were then irradiated at the McMaster Nuclear Reactor in Hamilton, Ontario, for 90 MWh, with a neutron flux of approximately 3 x $10^{16}$ neutrons/cm$^2$/s. Analyses (n = 57) of 19 neutron flux monitor positions produced errors of < 0.5% in the J value. The samples were analyzed at the Noble Gas Laboratory at PCIGR. The mineral separates were step-heated at incrementally higher powers in the defocused beam of a 10 W $CO_2$ laser (New Wave Research MIR10) until fused. The gas evolved from each step was analyzed by a VG5400 mass spectrometer equipped with an ion-counting electron multiplier. All measurements were corrected for total system blank, mass spectrometer sensitivity, mass discrimination, radioactive decay during and subsequent to irradiation, as well as interfering Ar from atmospheric contamination and the irradiation of Ca, Cl and K.

## RESULTS

### Aley Carbonatite

Zircon fractions obtained from a sample of dolomite carbonatite (MA096) contained near-zero ppm concentrations of radiogenic Pb and therefore could not be used to determine a U–Pb crystallization age of the carbonatite. The sampling locality, an outcrop near the centre of the dolomite core of the intrusion, is characterized by banded to massive fersmite- and pyrite-bearing dolomite-apatite carbonatite typical of the core dolomite carbonatite phase. The zircon grains analyzed were tan-brown to beige, translucent, euhedral, stubby dipyramids and displayed significant resorption and zonation textures in cathodoluminescent light. Whole rock geochemistry of Mader (1986) showed all phases of the carbonatite to have anomalously low U content which suggests that the low Pb content of zircon is due to a lack of U in the parent magma rather than post-crystallization Pb loss.

### Skoki (Lady Laurier) Volcanic Unit

Twenty light pink, translucent, elliptical zircon grains were isolated from a sample collected from a 1 m-thick agglomeratic tuff bed, 15 m from the top of the Skoki volcanic member (sample MA062). The sampling locality lies 800 m northwest of the west margin of the carbonatite. Weakly developed growth zonation was observed in all grains under cathodolumiscence. Eighteen of the twenty $^{206}$Pb/$^{238}$U–$^{207}$Pb/$^{235}$U data points plot as a tight cluster along the concordia curve at 460 Ma with the remaining four scattered between 450 and 480 Ma (Fig. 4). A weighted average of $^{206}$Pb/$^{238}$U ages for the cluster of 18 accepted analyses is 461.1 ± 1.4 Ma (MSWD=0.37), which is interpreted as the crystallization age of the volcanic unit. This age is in close agreement with a mid-Ordovician age for the Skoki Formation as determined by paleontological investigations (Pyle and Barnes 2003) and is interpreted as the age of volcanism.

### Ospika Pipe Diatreme

Titanite grains for single-grain ID–TIMS dating were isolated from a sample of the massive diatreme phase exposed near the core of the pipe (MA045A). The sample was free of visible country rock xenoliths and contained 15% phlogopite megacrysts similar to those dated by Pell (1994). The titanite grains were translucent, pale yellow, and displayed characteris-

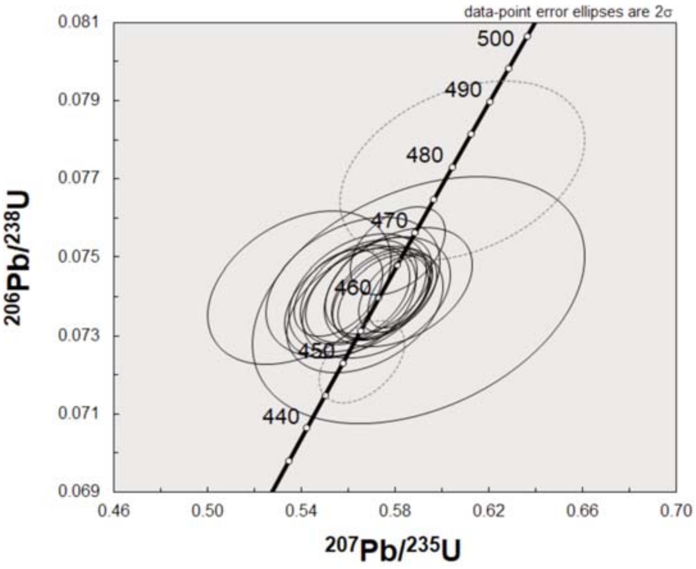


**Figure 4.** Conventional U–Pb concordia diagram for the Skoki volcanic rock (MA062). Data were used to calculate a weighted average $^{206}$Pb/$^{238}$U age of is 461.1 ± 1.4 Ma (MSWD = 0.37).

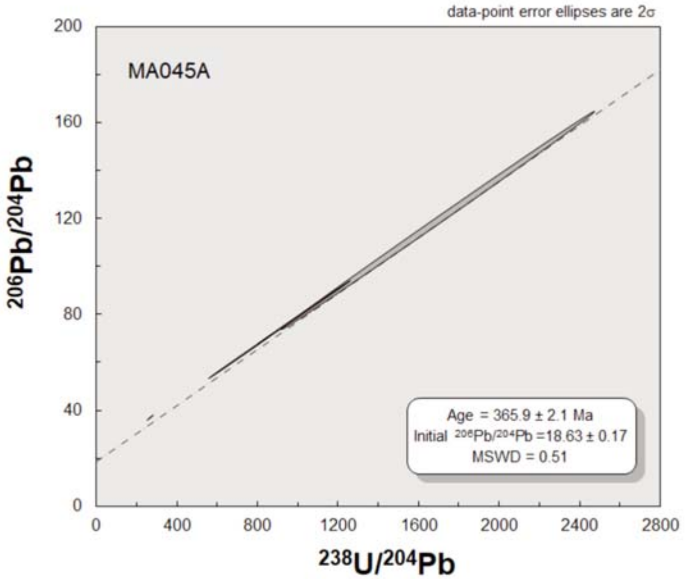


**Figure 5**. U–Pb analyses of titanite from the Ospika pipe define a four-point isochron of 365.9 ± 2.1 Ma (MSWD = 0.51).

tic wedge-shaped igneous crystal habit. In total, five grains were analyzed and four yielded usable results, which together define a $^{206}$Pb/$^{238}$U isochron age of 365.9 ± 2.1 Ma (MSWD = 0.51; Fig. 5). The titanite age is in reasonable agreement with the ca. 330 Ma K–Ar and Rb–Sr phlogopite dates of Pell (1994), provided the latter two are considered as cooling ages and the titanite age as the igneous crystallization age.

Phlogopite grains isolated from MA045A were dated with $^{40}$Ar/$^{39}$Ar step-heating techniques to further constrain the cooling history of the Ospika pipe. Two attempts were made to date two separate phlogopite grains; both yielded continuously rising age spectra. We interpret the oldest step in each attempt, 359.4 ± 3.4 Ma and 340.6 ± 3.4 Ma in first and second attempts respectively, as minimum cooling ages for phlogopite (Fig. 6).

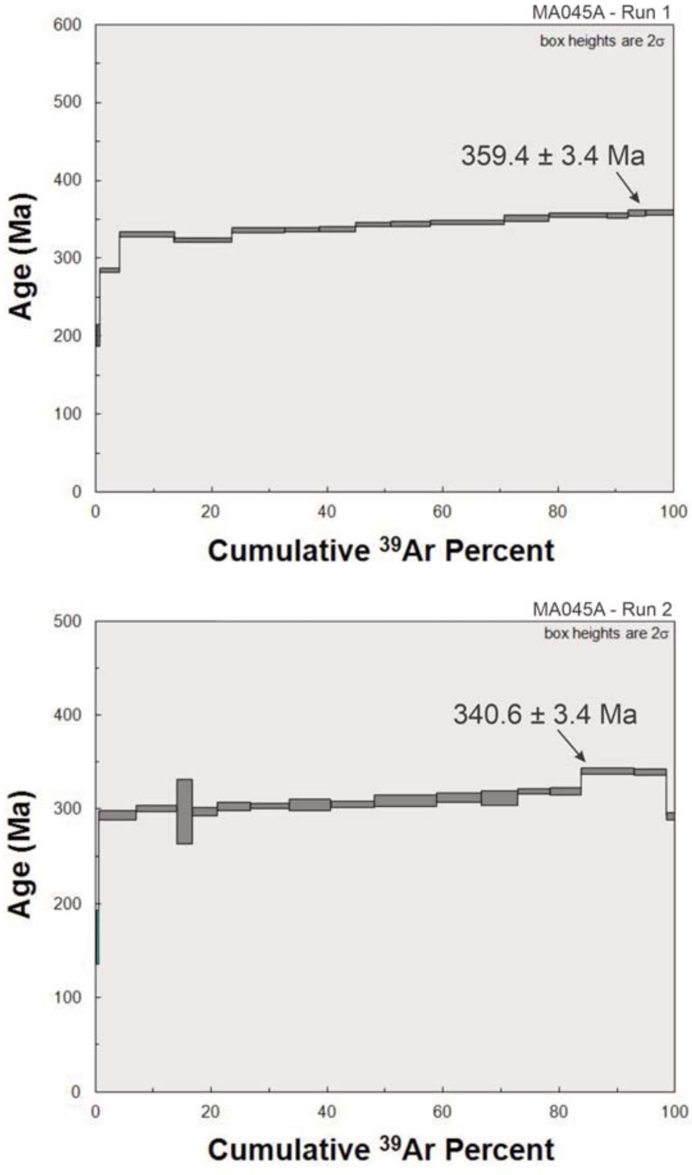


**Figure 6.** $^{40}$Ar/$^{39}$Ar step heating results for MA045A Run 1 and Run 2.

## Quartzite Clasts from the Volcano-Sedimentary Member of the Kechika Formation

Two cobble-sized quartzite clasts were cut out of two separate 25 kg loose boulder-sized talus (float) samples of fenitized conglomerate (MA076 and MA190) of the lower volcano-sedimentary member of the Kechika Formation and were processed for U–Pb detrital zircon geochronology. The quartzite clasts sampled for dating were nearly pure quartz with accessory concentrations of zircon and opaque minerals. The majority of the zircon grains isolated from the quartzite clasts were too fine-grained to be suitable for LA–ICP–MS analysis; however, 13 and 18 of the near-spherical pink zircon grains were deemed large enough and analyzed from MA076

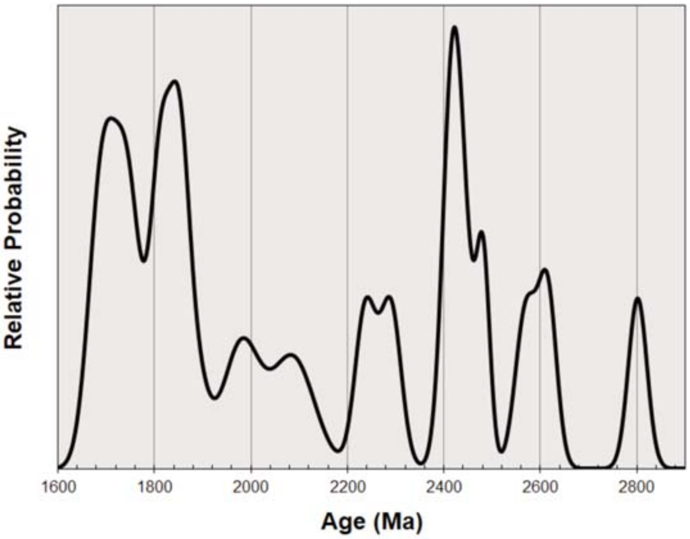


**Figure 7**. Cumulative probability density plot of $^{206}Pb/^{238}U$ zircon ages analyses (n = 19) that were < 10% discordant for detrital zircon sampled from quartzite clasts of the basal Kechika Formation.

and MA190 respectively. Nearly 40% of the zircons analyzed showed significantly large (> 10%) discordance due to Pb loss and were removed from the age determination results. No statistically significant difference was found between the age populations of the two samples; both age populations ranged from 1.7 to 2.6 Ga with major age probability peaks at 1.8 and 2.4 Ga. A zircon grain from MA076 was the only outlier from the two populations with an age of 2.8 Ga. A MA076–MA190 composite cumulative probability plot was constructed to increase the sample size (Fig. 7) and facilitate comparison with the detrital zircon signature of potential parent units (e.g. Gog Group, as postulated by Mader 1986). The extensive Pb loss displayed by many of the zircon grains is likely due to the extensive metasomatic alteration of the host conglomerate unit during intrusion of the carbonatite.

## Lamprophyres

A 0.5 m-wide lamprophyre dyke that intrudes the Skoki Formation, cutting across bedding in a dark grey, fenitized, massive argillaceous dolostone was sampled from the wall rocks of the Ospika pipe for $^{40}Ar/^{39}Ar$ phlogopite analysis. The dyke sampled is characterized by a very fine-grained calcareous, beige to orange 'rock flour' matrix hosting phlogopite megacrysts. Sample MA045D yielded coarse, dark honey brown phlogopite. Two attempts at dating separates both yielded continuously rising age spectra. The oldest step in each attempt, 353.3 ± 3.6 Ma and 352.6 ± 3.5 Ma in the first and second attempts respectively, is interpreted as the minimum age for cooling of the phlogopite (Fig. 8).

## DISCUSSION

Globally, deformed alkaline igneous rocks have been associated with and are shown to characterize suture zones of continental collisional orogens (Burke et al. 2003). In the Aley region, detailed structural mapping has shown that the western Foreland Belt of the Canadian Cordillera is characterized by a tectono-magmatic event that was contractional in nature (McLeish and Johnston 2019). Constraining the age of the Aley carbonatite thus offers an opportunity to constrain the age of mid-Paleozoic contractional deformation in the Aley region and, should the age of the Aley carbonatite be correlative with other alkaline–carbonatite complexes in the Foreland Belt, help define a margin-scale deformation event in the Canadian Cordillera.

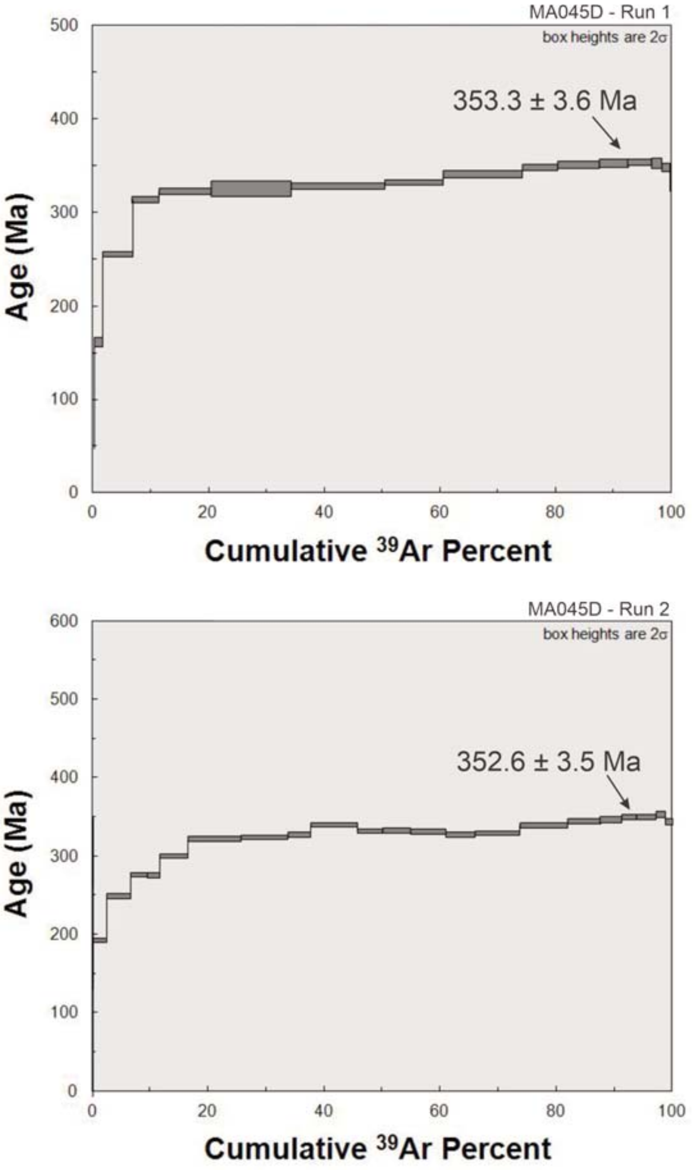


**Figure 8.** $^{40}Ar/^{39}Ar$ step heating results for MA045D Run 1 and Run 2.

The Aley carbonatite, the lamprophyre dykes and the Ospika pipe share similar 360–340 Ma K–Ar and $^{40}Ar/^{39}Ar$ cooling ages; all are therefore interpreted as having intruded and crystallized prior to 340 Ma. Because carbonatite intrusions are commonly spatially and genetically associated with coeval alkaline intrusive rocks, we argue that the carbonatite, the Ospika pipe and the lamprophyre dykes are attributable to a single magmatic event. The 366 Ma (Late Devonian) U–Pb age for magmatic titanite from the Ospika pipe yields the age of intrusion of the diatreme, and is therefore the minimum possible age of the Aley carbonatite and the $D_1$ nappe- and cleavage-forming tectonic event. The maximum possible age of the Aley carbonatite is constrained by the Early Devonian age of the Road River Group, the youngest strata intruded by carbonatite dykes and involved in the syn-magmatic $D_1$ nappe-forming event. Hence carbonatite magmatism, and the coeval $D_1$ event, is constrained to have occurred between about 400 Ma, the age of the youngest Road River Group intruded by carbonatite dykes, and 366 Ma, the emplacement age of the Ospika pipe, an interval of just over 30 million years. The $D_1$ tectonic event is therefore constrained to have occurred in the Late Devonian close to, but prior to, 366 Ma.

The 460 Ma U–Pb zircon crystallization age of the Lady Laurier volcanic member of the Skoki Formation is consistent with the Upper Ordovician fossil ages for the Skoki dolostone members. The Lady Laurier volcanic member of the Skoki Formation, despite being characterized by alkaline magmatism (Goodfellow et al. 1995), pre-dated intrusion of the Aley carbonatite by 90 million years and constituted a distinct magmatic event unrelated to the Aley carbonatite. The tectonic controls and implications of this volcanism, which locally significantly disrupted Middle Ordovician passive margin sedimentation, remain poorly understood.

Detrital zircon data from quartzite clasts of the Kechika Formation volcano-sedimentary member indicate that the quartzite has a maximum age of 1680 Ma (late Paleoproterozoic). The age-spectra are similar to those derived from samples of sandstone and quartzite of the Cambrian Atan Group, the northernmost British Columbia Foreland Belt equivalent of the Hamill–Gog Groups (Gehrels and Ross 1998). They differ from those from quartzite of the Ordovician Monkman Formation, which crops out to the immediate south of Aley, in that they do not contain Grenvillian-aged (1.0–1.1 Ga) zircon (Gehrels and Ross 1998).

Paleozoic alkaline volcanic centres and alkaline–carbonatite intrusive complexes are known along the length of the Cordilleran Foreland Belt (Fig. 9). However, whether these alkaline igneous suites and complexes, including the Aley, constitute coeval components of a margin-wide, syn-tectonic alkaline magmatic province has remained unclear due to a paucity of age constraints. Geochronological data exists for only one other carbonatite complex, the Ice River of the southern Rocky Mountains of British Columbia (Fig. 9). Parrish et al. (1987) obtained U–Pb ages of 363.1 ± 2.2 Ma on zircon and 368.8 ± 7.0 Ma on titanite from the Ice River Complex. More recently Tappe and Simonetti (2012) obtained a 361.7 ± 1.0 Ma U–Pb age on perovskite from the Ice River Complex. Available geochronological data are, therefore, consistent with interpretation of the Aley and Ice River complexes having intruded during, and being correlative components of, a major carbonatitic magmatic event that affected the western Foreland Belt. Field relationships constrain the undated alkaline–carbonatite complexes to emplacement in the Late Devonian to Early Mississippian (Pell 1994). Available geological and geochronological constraints are therefore consistent with coeval carbonatite magmatism in the Upper Devonian along the length of the western Foreland Belt of the Canadian Cordillera.

Similarities exist in the stratigraphy that is host to the six alkaline–carbonatite complexes. All intruded deep water shelf–slope carbonate and clastic rocks proximal to and west of the carbonate–shale facies boundary that separates and distinguishes the eastern and western subprovinces of the Foreland Belt. Detailed structural data and mapping at Aley has established that carbonatite magmatism was syn-kinematic with a major collisional tectonic event that gave rise to crustal scale nappes and a related bedding-parallel cleavage. Currie (1975) demonstrated that the Ice River Complex has, like Aley, undergone complex polyphase deformation and that its wall rocks are similarly characterized by an $S_1$ bedding-parallel cleavage. The fabrics and folds at Ice River have commonly been interpreted as products of Cretaceous Rocky Mountain deformation (Currie 1975) despite an absence of age constraints. Our findings suggest that the bedding-parallel cleavage that characterizes the wall rocks of the Ice River Complex and other carbonatite complexes of the western Foreland Belt, may have resulted from Late Devonian deformation. Demonstrating syn-magmatic tectonism during emplacement of the other foreland carbonatite complexes constitutes a test of our interpretation of the foreland carbonatite complexes as comprising a syn-tectonic alkaline magmatic province.

Structural and stratigraphic data from along the length of the Cordilleran orogen are consistent with a continental scale Late Devonian collisional orogenic event. This event was originally recognized as the Antler Orogen in north-central Nevada (Roberts Mountain area) where large-scale Late Devonian to Early Mississippian folding, nappe formation and thrust sheet emplacement produced a major angular unconformity (Roberts et al. 1958). Johnson (1971) proposed that the Antler orogeny affected the entire North American Cordillera based in part on the recognition by Gabrielse (1963, 1967) of similar contractional structures and unconformities in the Cariboo and Cassiar districts of British Columbia and Yukon. Although there are different models of the Antler orogeny (e.g. Burchfiel and Davis 1972, 1975; Wright and Wyld 2006; Nelson et al. 2006; Colpron and Nelson 2009), the main constraints come from the western US where Antler orogenesis has been attributed to arc–continent collision involving west-dipping subduction of oceanic lithosphere lying west of and continuous with North American continental lithosphere, leading to partial subduction of continental crust beneath a far-traveled arc (Schweickert and Snyder 1981). Obduction of the arc formed the Roberts Mountain allochthon along the Roberts Mountain thrust (Johnson and Pendergast 1981; Speed and Sleep 1982; Dickinson 2004). In Canada, the Antler Orogeny is manifest by mid-Devonian contractional deformation in the Purcell and southern Rocky Mountains (Root 2001); Late Devonian to Early Mississippian erosional unconformities in the Cariboo Mountains and Kootenay Arc (Klepacki 1985; Struik 1986); volcanism and alkaline magmatism along the length of the western Foreland Belt (Goodfellow et al. 1995); and Devono-Mississippian coarse clastic sedimentation in northern British Columbia and Yukon (e.g. Earn Group, Gordey et al. 1987). Paleocurrent indicators suggest that the Earn Group was derived from an uplifted landmass that lay to

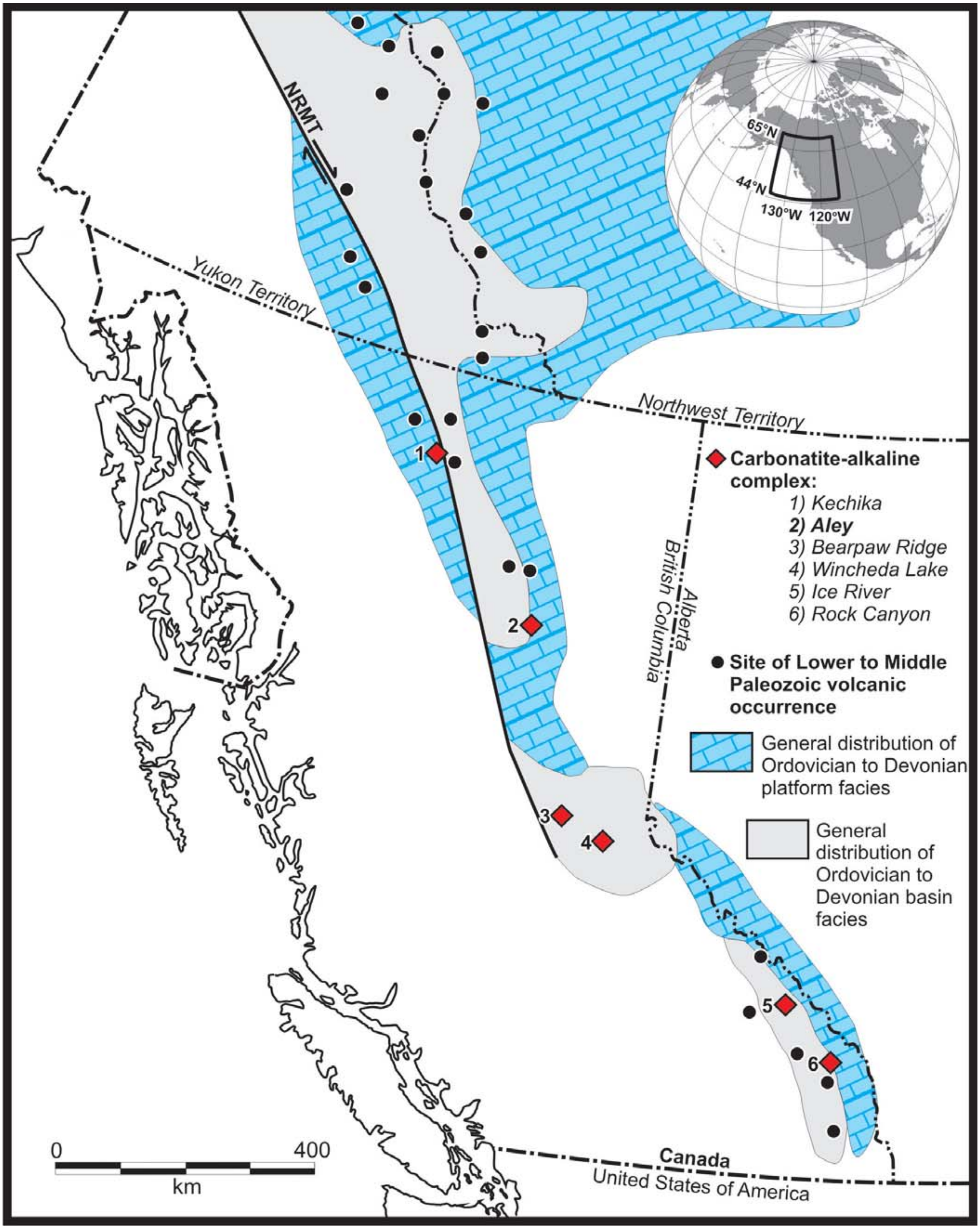


**Figure 9.** Distribution of early and mid-Paleozoic alkaline volcanic and carbonatite occurrences in the Canadian Cordillera, revised after Goodfellow et al. (1995) with additional data from Hunt (2002).

the west and shed clastic sediment to the east (Gabrielse 1977; Beranek et al. 2016). However, Gordey et al. (1987) suggested that the Earn Group was sourced from uplifted chert and other continental margin rocks to the west, and did not necessarily require an accreting landmass. Beranek et al. (2010) interpreted detrital zircon separated from a sample of the Earn Group as being consistent with such an 'autochthonous' model. However, more recently, Beranak et al. (2016) concluded, based on detrital zircon and Hf isotopic data, that correlative strata in eastern Idaho were derived from a more westerly source, within or west of the intermontane terranes. Finally, Hauck et al. (2017), based on the study of Upper Devonian strata (Sassenach Formation) in the vicinity of Jasper concluded that the accretion of terranes of Caledonian, Baltican or Siberian origin along the Cordilleran and Arctic margins of Laurentia coeval with the Antler orogeny were the source of detrital zircon in the Sassenach Formation.

With respect to the tectonic setting, Gordey et al. (1987) and other workers suggested that extension, not contraction explains Earn Group sedimentation, noting that deposition was concurrent with the eruption of rift-related volcanic rocks, extensional faulting, and the development of exhalative barite and SEDEX and VMS deposits. However, Smith et al. (1993) proposed that Devonian–Mississippian orogenesis characterized the entire Cordilleran margin, that it resulted from continent–arc collision, and that the resulting orogenic welt shed clastic detritus eastward into a foreland basin as exemplified by the westerly-derived Earn Group. In their model, extensional features were explained as products of a migrating orogenic forebulge (Smith et al. 1993). In the Kechika Trough near the Aley area, mid-Devonian syn-sedimentary extensional faulting, formation of exhalative deposits, and rift-related magmatism (Paradis et al. 1998; Piercey et al. 2004) indicate tensile deformation preceded Antler-age contractile deformation and may indicate extension in response to the onset of westward subduction of the continental margin (Schweickert and Snyder 1981). The model by Smith et al. (1993) is consistent with the suggestion by Root (2001) that the basinal western Foreland Belt strata of eastern British Columbia constituted a foreland basin generated by an Antler arc–continent collision in the Middle to Late Devonian (Miall 2019).

The syn-magmatic deformation at Aley Creek appears to have been synchronous with the ca. 370 Ma (Oldow et al. 1989) Antler Orogeny. Observations from the stratigraphic, structural, and magmatic record in our study area indicate that the $D_1$ event affecting the Aley area is consistent with Antler-style orogenesis: (1) quartzite observed in the Ordovician–Devonian Road River Group is similar to coarse clastic sediment of the Antler-linked Earn Group exposed to the north of the Aley Creek area (Fig. 2); and (2) the syn-magmatic $D_1$ deformation, including tight folding and nappe formation, is similar to Antler deformation observed in the Kootenay and Cariboo Mountains of southern and central British Columbia.

## CONCLUSIONS

Our geochronological data demonstrate that the Aley carbonatite and associated alkaline intrusive units were emplaced at ca. 365 Ma, coeval with the ca. 362 Ma Ice River Complex, and support the interpretation of the carbonatite intrusions of the western Foreland Belt as genetically linked components of an alkaline–carbonatitic magmatic province. Syn-magmatic contractional deformation at Aley suggests that the Foreland Belt carbonatite intrusions are magmatic manifestations of a Late Devonian orogenic event of continental scope. Structural, stratigraphic, and geochronological data from the Aley area indicate that deformation was similar in style to and coeval with structures attributable to the Antler orogeny, supporting the interpretation of the Antler orogen having extended the length of the Cordilleran margin from the southern United States to Alaska. Further structural, stratigraphic, and geochronological investigations of the other five alkaline–carbonatite complexes in the western Foreland Belt of the Canadian Cordillera are required to further test this hypothesis.

## ACKNOWLEDGEMENTS

This research was made possible by support and funding from the BC Geological Survey, and by a Geoscience BC Student Research Grant to D. McLeish and an NSERC Discovery Grant to S. Johnston. T. Ambrose and M. Mihalynuk are thanked for their invaluable assistance offered during field mapping and geochronological sample collection. T. Ambrose also provided skillful assistance with sample preparation. Craig Hart and an anonymous reviewer are thanked for their insightful reviews of an earlier version of the manuscript. The final version of the manuscript benefited from a careful and constructive review by Editor B. Murphy.

## REFERENCES

Aitken, J.D., 1971, Control of lower Paleozoic sedimentary facies by the Kicking Horse Rim, southern Rocky Mountains, Canada: Bulletin of Canadian Petroleum Geology, v. 19, p. 557–569, https://doi.org/10.35767/gscpgbull.19.3.557.

Beranek, L.P., Mortensen, J.K., Lane, L.S., Allen, T.L., Fraser, T.A., Hadlari, T., and Zantvoort, W.G., 2010, Detrital zircon geochronology of the western Ellesmerian clastic wedge, northwestern Canada: Insights on Arctic tectonics and the evolution of the northern Cordilleran miogeocline: Geological Society of America Bulletin, v. 122, p. 1899–1911, https://doi.org/10.1130/B30120.1.

Beranek, L.P., Link, P.K. and Fanning, C.M., 2016, Detrital zircon record of mid-Paleozoic convergent margin activity in the northern U.S. Rocky Mountains: Implications for the Antler orogeny and early evolution of the North American Cordillera: Lithosphere, v. 8, p. 533–550, https://doi.org/10.1130/L557.1.

Burchfiel, B.C., and Davis, G.A., 1972, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States: American Journal of Science, v. 272, p. 97–118, https://doi: 10.2475/ajs.272.2.97.

Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis: American Journal of Science, v. 275-A, p. 363–396.

Campbell, R.W., Beranek, L.P., Piercey, S.J., and Friedman, R., 2019, Early Paleozoic post-breakup magmatism along the Cordilleran margin of western North America: New zircon U–Pb age and whole-rock Nd-and Hf-isotope and lithogeochemical results from the Kechika group, Yukon, Canada: Geosphere, v. 15, p. 1262–1290, https://doi.org/10.1130/GES02044.1.

Cecile, M.P., and Norford, B.S., 1979, Basin to platform transition, Lower Paleozoic strata of Ware and Trutch map areas, northeastern British Columbia: Current Research, part A, Geological Survey of Canada Paper 79-1A, p. 219–226, https://doi.org/10.4095/104850.

Chakhmouradian, A.R., Reguir, E.P., Kressall, R.D., Crozier, J., Pisiak, L.K., Sidhu, R., and Yang, P., 2015, Carbonatite-hosted niobium deposit at Aley, northern British Columbia (Canada): Mineralogy, geochemistry and petrogenesis: Ore Geology Reviews, v. 64, p. 642–666, https://doi.org/10.1016/j.oregeorev.2014.04.020.

Chung, C.J., and Crozier, J., 2008, Assessment report on diamond drilling performed on the Aley Carbonatite Property: British Columbia Ministry of Energy, Mines, and Petroleum Resources, Assessment Report 30113, 194 p.

Colpron, M., and Nelson, J.L., 2009, A Palaeozoic Northwest Passage: Incursion of Caledonian, Baltican and Siberian terranes into eastern Panthalassa, and the early evolution of the North American Cordillera, *in* Cawood, P.A., and Kröner, A., *eds*., Earth Accretionary Systems in Space and Time: Geological Society

London, Special Publications, v. 318, p. 273–307, https://doi.org/10.1144/SP318.10.

Currie, K.L., 1975, The geology and petrology of the Ice River alkaline complex, British Columbia: Geological Survey of Canada, Bulletin 245, 68 p., https://doi.org/10.4095/103978.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 32, p. 13–45, https://doi.org/10.1146/annurev.earth.32.101802.120257.

Gabrielse, H., 1963, McDame map area, Cassiar District, British Columbia: Geological Survey of Canada, Memoir 319, 138 p., https://doi.org/10.4095/100546.

Gabrielse, H., 1967, Tectonic evolution of the northern Canadian Cordillera: Canadian Journal of Earth Sciences, v. 4, p. 271–298, https://doi.org/10.1139/e67-013.

Gabrielse, H., 1985, Major dextral transcurrent displacements along the Northern Rocky Mountain Trench and related lineaments in north-central British Columbia: Geological Society of America Bulletin, v. 96, p. 1–14, https://doi.org/10.1130/0016-7606(1985)96<1:MDTDAT>2.0.CO;2.

Gabrielse, H., Dodds, C.J., and Mansy, J.L., 1977, Operation Finlay, British Columbia: Geological Survey of Canada, Report of Activities, Paper 77-1A, p. 243–246.

Gehrels, G.E., and Ross, G.M., 1998, Detrital zircon geochronology of Neoproterozoic to Permian miogeoclinal strata in British Columbia and Alberta: Canadian Journal of Earth Sciences, v. 35, p. 1380 – 1401, https://doi.org/10.1139/e98-071.

Goodfellow, W.D., Cecile, M.P., and Leybourne, M.I., 1995, Geochemistry, petrogenesis, and tectonic setting of lower Paleozoic alkalic and potassic volcanic rocks, northern Canadian Cordilleran miogeocline: Canadian Journal of Earth Sciences, v. 32, p. 1236–1254, https://doi.org/10.1139/e95-101.

Gordey, S.P., Abbott, J.G., Tempelman-Kluit, D.J., and Gabrielse, H., 1987, "Antler" clastics in the Canadian Cordillera: Geology, v. 15, p. 103–107, https://doi.org/10.1130/0091-7613(1987)15<103:AEITCC>2.0.CO;2.

Hauck, T.E., Pană, D., and DuFrane, S.A., 2017, Northern Laurentian provenance for Famennian clastics of the Jasper basin (Alberta, Canada): a Sm–Nd and U–Pb detrital zircon study: Geosphere, v. 13, p. 1149–1172, https://doi.org/10.1130/GES01453.1.

Hunt, J.A., 2002, Volcanic-associated massive sulphide (VMS) mineralization in the Yukon-Tanana Terrane and coeval strata of the North American miogeocline in the Yukon and adjacent areas: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, Bulletin 12, 107 p.

Johnson, J.G., 1971, Timing and coordination of orogenic, epeirogenic, and eustatic events: Geological Society of America Bulletin, v. 82, p. 3263–3298, https://doi.org/10.1130/0016-7606(1971)82[3263:TACOOE]2.0.CO;2.

Johnson, J.G., and Pendergast, A., 1981, Timing and mode of emplacement of the Roberts Mountains allochthon, Antler orogeny: Geological Society of America Bulletin, v. 92, p. 648–659, https://doi.org/10.1130/0016-7606(1981)92<648:TAMOEO>2.0.CO;2.

Klepacki, D.W., 1985, Stratigraphy and structural geology of the Goat Range area, southeastern British Columbia: Unpublished PhD thesis, Massachusetts Institute of Technology, Cambridge, MA, 268 p.

Kressall, R., Chakhmouradian, A.R., McLeish, D.F., and Crozier, J., 2010, The Aley carbonatite complex -Part II: Petrogenesis of a Cordilleran niobium deposit: Geology of Rare Metals International Workshop, British Columbia Geological Survey Open File 2010-10, p. 25–26.

Linde, G.M., Trexler Jr., J.H., Cashman, P.H., Gehrels, G., and Dickinson, W.R., 2017, Three-dimensional evolution of the Early Paleozoic western Laurentian margin: New insights from detrital zircon U–Pb geochronology and Hf isotope geochemistry of the Harmony Formation of Nevada: Tectonics, v. 36, p. 2347–2369, https://doi.org/10.1002/2017TC004520.

MacIntyre, D.G., 1998, Geology, geochemistry and mineral deposits of the Akie River Area, northeast British Columbia: British Columbia Ministry of Energy and Mines Bulletin 103, 91 p.

Mader, U.K., 1986, The Aley carbonatite complex: Unpublished MSc thesis, University of British Columbia, Vancouver, BC, 176 p.

McLeish, D.F., 2013, Structure, stratigraphy and U–Pb zircon–titanite geochronology of the Aley carbonatite complex, northeast British Columbia: Evidence for Antler-aged orogenesis in the Foreland Belt of the Canadian Cordillera: Unplubished MSc thesis, University of Victoria, BC, 142 p.

McLeish, D.F., and Johnston, S.T., 2019, The Upper Devonian Aley carbonatite, NE British Columbia: a product of Antler orogenesis in the western Foreland Belt of the Canadian Cordillera: Journal of the Geological Society, v. 176, p. 620–628, https://doi.org/10.1144/jgs2018-180.

McLeish, D.F., Kressall, R., Chakhmouradian, A.R., Crozier, J., Johnston, S.T., and Mortensen, J.K., 2010, The Aley carbonatite complex -Part I: Structural evolution of a Cordilleran niobium deposit: Geology of Rare Metals International Workshop, British Columbia Geological Survey Open File 2010-10, p. 21–23.

Miall, A.D., 2019, The Paleozoic Western craton margin, *in* Miall A.D., *ed.,* The Sedimentary Basins of the United States and Canada, v. 5, p. 181–209, https://doi.org/10.1016/S1874-5997(08)00005-1.

Nelson, J.L., Colpron, M., Piercey, S.J., Dusel-Bacon C., Murphy, D., and Roots, C., 2006, Paleozoic tectonic and metallogenic evolution of pericratonic terranes in Yukon, northern British Columbia and eastern Alaska, *in* Colpron M., and Nelson, J.L., *eds*., Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America, Canadian and Alaskan Cordillera: Geological Association of Canada Special Paper 45, p. 323–360.

Norford, B.S., 1979, Lower Devonian graptolites in the Road River Formation, northern British Columbia: Geological Survey of Canada, Current Research Part A, Paper 79-1A, p. 383–384, https://doi.org/10.4095/104870.

Oldow, J.S., Bally, A.W., Avé Lallement, H.G., and Leeman, W.P., 1989, Phanerozoic evolution of the North American Cordillera, United States and Canada, *in* Bally, A.W., and Palmer, A.R., *eds*., The Geology of North America – An Overview: Geological Society of America, v. A, p. 139–232, https://doi.org/10.1130/DNAG-GNA-A.139.

Paradis, S., Nelson, J.L., and Irwin, S.E.B., 1998, Age constraints on the Devonian shale-hosted Zn-Pb-Ba deposits, Gataga District, northeastern British Columbia, Canada: Economic Geology, v. 93, p. 184–200, https://doi.org/10.2113/gsecongeo.93.2.184.

Parrish, R.R., Heinrich, S., and Archibald, D., 1987, Age of the Ice River complex, southeastern British Columbia: Geological Survey of Canada Paper 87-2, p. 33–37, https://doi.org/10.4095/122744.

Pell, J., 1994, Carbonatites, nepheline syenites, kimberlites and related rocks in British Columbia: British Columbia Ministry of Energy, Mines and Petroleum Resources Bulletin 88, 136 p.

Piercey, S.J., Murphy, D.C., Mortensen, J.K., and Creaser, R.A., 2004, Mid-Paleozoic initiation of the northern Cordilleran marginal backarc basin: Geologic, geochemical, and neodymium isotope evidence from the oldest mafic magmatic rocks in the Yukon-Tanana terrane, Finlayson Lake district, southeast Yukon, Canada: Geological Society of America Bulletin, v. 116, p. 1087–1106, https://doi.org/10.1130/B25162.1.

Pride, K.R., 1983, Geological Survey on the Aley Claims, Omineca Mining Divison, British Columbia: British Columbia Ministry of Energy, Mines and Petroleum Resources Assessment Report 12018.

Pride, K.R., 1987a, 1986 year end report on the Aley property: British Columbia Ministry of Energy, Mines, and Petroleum Resources, Assessment Report 15721, 69 p.

Pride, K.R., 1987b, 1986 Diamond drilling assessment report: British Columbia Ministry of Energy, Mines, and Petroleum Resources, Assessment Report 16484, 59 p.

Pride, K.R., LeCouteur, P.C., and Mawer, A.B, 1986, Geology and mineralogy of the Aley carbonatite, Ospika River Area, British Columbia (Abstract): Canadian Institute of Mining and Metallurgy, Bulletin, v. 79, 10th District 6 Meeting, Victoria, BC, p. 32.

Pyle, L.J., and Barnes, C.R., 2001, Conodonts from the Kechika Formation and Road River Group (Lower to Upper Ordovician) of the Cassiar Terrane, northern British Columbia: Canadian Journal of Earth Sciences, v. 38, p. 1387–1401, https://doi.org/10.1139/e01-033.

Pyle, L.J., and Barnes, C.R., 2003, Conodonts from a platform-to-basin transect, lower Ordovician to lower Silurian, northeastern British Columbia, Canada: Journal of Paleontology, v. 77, p. 146–171, https://doi.org/10.1017/S0022336000043493.

Roberts, R.J., 1951, Geology of the Antler Peak quadrangle, Nevada: U.S. Geological Survey, Map with accompanying text. Available: https://ngmdb.usgs.gov/Prodesc/proddesc_544.htm.

Roberts, R.J, Hotz, P.E., Gilluly, J., and Ferguson, H.G., 1958, Paleozoic rocks of north-central Nevada: American Association of Petroleum Geologists Bulletin, v. 42, p. 2813–2857.

Root, K.G., 2001, Devonian Antler fold and thrust belt and foreland basin development in the southern Canadian Cordillera: implications for the Western Canada Sedimentary Basin: Bulletin of Canadian Petroleum Geology, v. 49, p. 7–36, https://doi.org/10.2113/49.1.7.

Schweickert, R.A., and Snyder, W.S., 1981, Paleozoic plate tectonics of the Sierra Nevada and adjacent regions, *in* Ernst, W.G., *ed*., The Geotectonic Development of California: Prentice Hall, Englewood Cliffs, NJ, p. 183–201.

Smith, M.T., Dickinson, W.R., and Gehrels, G.E., 1993, Contractional nature of Devonian–Mississippian Antler tectonism along the North American continental margin: Geology, v. 21, p. 21–24, https://doi.org/10.1130/0091-7613(1993)021<0021:CNODMA>2.3.CO;2.

Speed, R.C, and Sleep, N.H., 1982, Antler orogeny and foreland basin: A model: Geological Society of America Bulletin, v. 93, p. 815–828, https://doi.org/10.1130/0016-7606(1982)93<815:AOAFBA>2.0.CO;2.

Struik, L.C., 1986, Imbricated terranes of the Cariboo gold belt with correlations and implications for tectonics in southeastern British Columbia: Canadian Journal of Earth Sciences, v. 23, p. 1047–1061, https://doi.org/10.1139/e86-105.

Tafti, R., Mortensen, J.K., Lang, J.R., Rebagliati, M., and Oliver, J.L., 2009, Jurassic U–Pb and Re–Os ages for the newly discovered Xietongmen Cu-Au porphyry district, Tibet, PRC: Implications for metallogenic epochs in the southern Gangdese belt: Economic Geology, v. 104, p. 127–136, https://doi.org/10.2113/gsecongeo.104.1.127.

Tappe, S., and Simonetti, A., 2012, Combined U–Pb geochronology and Sr-Nd isotope analysis of the Ice River perovskite standard, with implications for kimberlite and alkaline rock petrogenesis: Chemical Geology, v. 304–305, p. 10–17, https://doi.org/10.1016/j.chemgeo.2012.01.030.

Taylor, G.C., 1979, Trutch (94G) and Ware east half (94F, E1/2) map-areas, northeastern British Columbia: Geological Survey of Canada Open File Report 606, scale 1:250,000, 1 sheet.

Taylor, G.C., and Stott, D.F., 1973, Tuchodi Lakes map-area, British Columbia (94K): Geological Survey of Canada Memoir 373, 37 p., 1 sheet, https://doi.org/10.4095/102437.

Taylor, G.C., Cecile, M.P., Jefferson, C.W., and Norford, B.S., 1979, Stratigraphy of Ware (east half) map area, northeastern British Columbia: Geological Survey of Canada Paper 79-1A, Current Research, part A, p. 227–231.

Thompson, R.I., 1989, Stratigraphy, tectonic evolution and structural analysis of the Halfway River map area (94B), northern Rocky Mountains, British Columbia: Geological Survey of Canada Memoir 425, 119 p., https://doi.org/10.4095/127002.

Trexler Jr., J.H., Cashman, P.H., Snyder, W.S., and Davydov, V.I., 2004, Late Paleozoic tectonism in Nevada: Timing, kinematics, and tectonic significance: Geological Society of America Bulletin, v. 116, p. 525–538, https://doi.org/10.1130/B25295.1.

Wheeler, J.O., and McFeely, P., 1991, Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America: Geological Survey of Canada, "A Series Map 1712A, scale 1:2,000,000, 2 sheets, https://doi.org/10.4095/133549.

Wright, J.E., and Wyld, S.J., 2006, Gondwanan, Iapetan, Cordilleran interactions: A geodynamic model for the Paleozoic tectonic evolution of the North American Cordillera, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., *eds.*, Paleogeography of the North American Cordillera: Evidence For and Against Large-Scale Displacements: Geological Association of Canada Special Paper 46, p. 377–408.

**Received June 2020**
**Accepted as revised October 2020**

For access to the McLeish et al. (2020) Supplementary Material: *Appendix 1: LA-ICP-MS Methods, Appendix 2: CA-ID-TIMS Methods,* and *Appendix 3: Supporting Analytical data*, please visit the GAC's open source GC Data Repository for the Andrew Hynes Series: Tectonic Processes at: https://gac.ca/gc-data-repository/.

# SERIES

## Igneous Rock Associations 27. Chalcophile and Platinum Group Elements in the Columbia River Basalt Group: A Model for Flood Basalt Lavas

**Stephen P. Reidel[1] and D. Brent Barnett[2*]**

[1] *School of the Environment, Washington State University*
*Tri-Cities, Richland, Washington, 99354, USA*
*E-mail: sreidel@wsu.edu*

[2] *Pacific Northwest National Laboratory*
*902 Battelle Boulevard, Richland, Washington, 99352, USA*
** Deceased*

### SUMMARY

The Columbia River Basalt Group is the youngest and best preserved continental Large Igneous Province on Earth. The 210,000 $km^3$ of basaltic lavas were erupted between 16.6 and 5 Ma in the Pacific Northwest, USA. The peak of the eruptions occurred over a 700,000-year period when nearly 99% of the basalts consisting of the Steens, Imnaha, Picture Gorge, Grande Ronde and Wanapum Basalts were emplaced. In this study we examined the Platinum Group Elements (PGEs) Pt and Pd, and the chalcophile elements Cu and Zn in the Columbia River Basalt Group. The presence of Pt, Pd and Cu in the compositionally primitive Lower Steens, Imnaha and Picture Gorge Basalts suggests that the Columbia River Basalt Group magma was a fertile source for these elements. The PGEs are contained mainly in sulphides in the earliest formations based on their correlation with immiscible sulphides, sulphide minerals and chalcophile elements. Grande Ronde, Wanapum and Saddle Mountains Basalts are depleted in PGEs and chalcophile elements compared to earlier formations. Sulphur was saturated in many flows and much of it probably came from assimilation of cratonic rock from a thinned lithosphere. We propose a model where the presence or absence of PGEs and chalcophile elements results primarily from the interaction between an advancing plume head and the crust/lithosphere that it encountered. The early lavas erupted from a plume that had little interaction with the crust/lithosphere and were fertile. However, as the plume head advanced northward, it assimilated crustal/lithospheric material and PGE and chalcophile elements were depleted from the magma. What little PGE and chalcophile elements remained in the compositionally evolved and depleted Grande Ronde Basalt flows mainly were controlled by substitution in basalt minerals and not available for inclusion in sulphides.

### RÉSUMÉ

Le groupe basaltique du Columbia est une grande province ignée continentale. Il s'agit de la plus jeune et la mieux préservée au monde. Les 210 000 $km^3$ de laves basaltiques ont été émis entre 16,6 et 5 Ma dans le Nord-Ouest Pacifique, aux États-Unis. Le pic des éruptions s'est produit sur une période de 700 000 ans lorsque près de 99% des basaltes comprenant les basaltes de Steens, Imnaha, Picture Gorge, Grande Ronde et Wanapum ont été mis en place. Dans cette étude, nous avons examiné les éléments du groupe platine (EGP) Pt et Pd, et les éléments chalcophiles Cu et Zn dans le groupe basaltique du Columbia. La présence de Pt, Pd et Cu dans les basaltes de Lower Steens, Imnaha et Picture Gorge, de composition primitive, suggère que le magma du groupe basaltique du Columbia était une source fertile pour ces éléments. Les EGP sont principalement contenus dans les sulfures des formations les plus anciennes en fonction de leur corrélation avec les sulfures non miscibles, les minéraux sulfurés et les éléments chalcophiles. Les basaltes de Grande Ronde, de Wanapum et de Saddle Mountains sont appauvris en EGP et en éléments chalcophiles par rapport aux formations antérieures. Le soufre était saturé dans de nombreux écoulements et une grande partie provenait probablement de l'assimilation des roches cratoniques d'une lithosphère amincie. Nous proposons un modèle où la présence ou l'absence d'EGP et d'éléments chalcophiles

*Geoscience Canada,* v. 47, https://doi.org/10.12789/geocanj.2020.47.166 pages 187–214 © 2020 GAC/AGC®

résulte principalement de l'interaction entre une tête de panache en progression et la croûte / lithosphère rencontrée. Les premières laves ont été émises à partir d'un panache qui avait peu d'interaction avec la croûte / lithosphère et étaient fertiles. Cependant, à mesure que la tête du panache avançait vers le nord, elle a assimilé du matériel crustal / lithosphérique, et le magma a été appauvri en EGP et en éléments chalcophiles. Le peu d'EGP et d'éléments chalcophiles restant dans les écoulements de basalte de composition évoluée et appauvrie de Grande Ronde ont été principalement contrôlés par la substitution dans les minéraux du basalte et n'étaient pas disponibles pour l'inclusion dans les sulfures.

*Traduit par la Traductrice*

## INTRODUCTION

Large Igneous Provinces (LIPs) are the major source for Platinum Group Elements (PGEs) and are typically associated with sulphide deposits (Cawthorn 2005; Ernst and Jowitt 2013; among others) but they represent a difficult exploration target (Mungall 2005, and papers therein). PGE deposits in LIPs typically occur in deep seated layered intrusions that only become exposed after many millions of years of uplift and erosion. Most authors recognize that these layered intrusions fed surface lavas such as the Noril'sk-Talnakh deposits (Ryabov et al. 2014; Pavlov et al. 2019) but in many cases it is difficult to relate these intrusions to surface lavas (e.g. Naldrett et al. 1992, 2011, 2012; Pavlov et al. 2019). Typically, this is due to the lack of preservation of the lavas, but more often preserved lavas lack any economical deposit and thus there is little incentive to characterize them for PGEs and chalcophile elements.

Research on flood-basalt provinces has shown that detailed characterization is important for unraveling the history of these LIPs and to understand the petrogenetic processes that resulted in their complex compositions (e.g. Macdougall 1988; Mahoney and Coffin 1997; Hooper et al. 2007; papers in Reidel et al. 2013a; Ernst 2014). Thus, to fully understand the role of PGE and chalcophile deposits in LIPs, an understanding of the lavas is an essential requirement.

The Columbia River Flood-Basalt Province of the Pacific Northwest is one of the best characterized LIPs in the world (Fig. 1) and, thus, is an excellent target for examining the role of PGEs and chalcophile elements in LIP lava flows. The accessibility, excellent surface exposures, numerous deep boreholes, and many thousands of published ICP-MS and XRF major, minor, trace-element, and isotope analyses, have led to a good understanding of the stratigraphy, the volume and extent of the lavas, and the petrogenesis of the basalt (e.g. Reidel et al. 2013a and papers therein). Because basalt flows are the surface expression of deeper magma chamber processes and are extruded over time, the study of PGEs and chalcophile elements in well characterized flood basalts like the Columbia River Flood-Basalt Province can give new insights into how they may become distributed over time and concentrated to form deposits. One part of the story, however, is lacking in the Columbia River Basalt Group, that of the occurrence of PGEs and chalcophile elements, and their role in the petrogenesis of the basalts. Thus, the Columbia River Basalt Group provides an excellent laboratory to study the occurrence and controls on these elements and could lead to a better understanding of them in LIPs and better models for targets.

## GEOLOGICAL SETTING

The Columbia River Flood-Basalt Province, Pacific Northwest, USA, is composed of the Columbia River Basalt Group (Fig. 2) which is a series of generally tholeiitic basalts to basaltic andesites and andesites with sparse alkali-olivine basalts that erupted between ~16.7–5.5 Ma (Jarboe et al. 2008; Barry et al. 2010, 2013; Kasbahm and Schoen 2018). The basalts cover more than 210,000 km$^2$ of Washington, Oregon, Idaho and Nevada with an estimated volume of 210,000 km$^3$ (Reidel et al. 2013b), and form part of a larger volcanic region that includes the Chilcotin Plateau Basalts of British Columbia, the contemporaneous silicic centres in northern Nevada, the basaltic and time-transgressive rhyolitic volcanic fields of the Snake River Plain and Yellowstone Plateau, and the High Lava Plains of central Oregon. Although the province is the smallest LIP on Earth, its location in the easily accessible Pacific Northwest, USA, has allowed the geology to be refined by over 50 years of study. Thus, the Columbia River Basalt Group has become a model for the study of similar provinces worldwide.

The Columbia River Basalt Group erupted in a back-arc setting between the Cascade volcanic arc and the Rocky Mountains along the western edge of the North American craton (Fig. 1). The flood-basalt lavas cover basement rocks that record a long and complex geological history of western North America beginning in the Proterozoic with the breakup of the supercontinent Rodina, followed by the suturing of Mesozoic accreted terranes, and deposition and deformation of Paleogene and Neogene sediments and volcanic rocks. These basement structures became the template for geological structures now superimposed on the basalt province (Reidel et al. 2013c, 2020; Reidel 2015).

Columbia River Basalt Group volcanism initially began in the Oregon Plateau and quickly spread north to the Columbia Basin through a linear fissure system (Figs. 1 and 3; Camp and Ross 2004). In the Oregon Plateau (Figs. 1 and 3), flood basalt eruptions were contemporaneous with rhyolitic volcanism at the western end of the Snake River Plain hotspot track and with a major period of crustal extension in northern Nevada that began at ca. 17–16 Ma (Camp et al. 2003). In the Columbia Basin, rapid subsidence along with folding and faulting of the basalt accompanied volcanism (Reidel et al. 1989b, 2013c). The Chilcotin Plateau Basalts of British Columbia complete the northward progression of basaltic volcanism in the Pacific Northwest from Miocene to Pliocene (Bevier 1983; Mathews 1989).

### Columbia River Basalt Group

The main eruptive phase of the Columbia River Basalt Group (Fig. 2) includes the Steens, Imnaha, Picture Gorge, Grande Ronde Basalts and early part of the Wanapum Basalt when 99% of the basalt erupted in ~700,000 years (Kasbohm and Shoene 2018). The peak of the eruptions occurred during

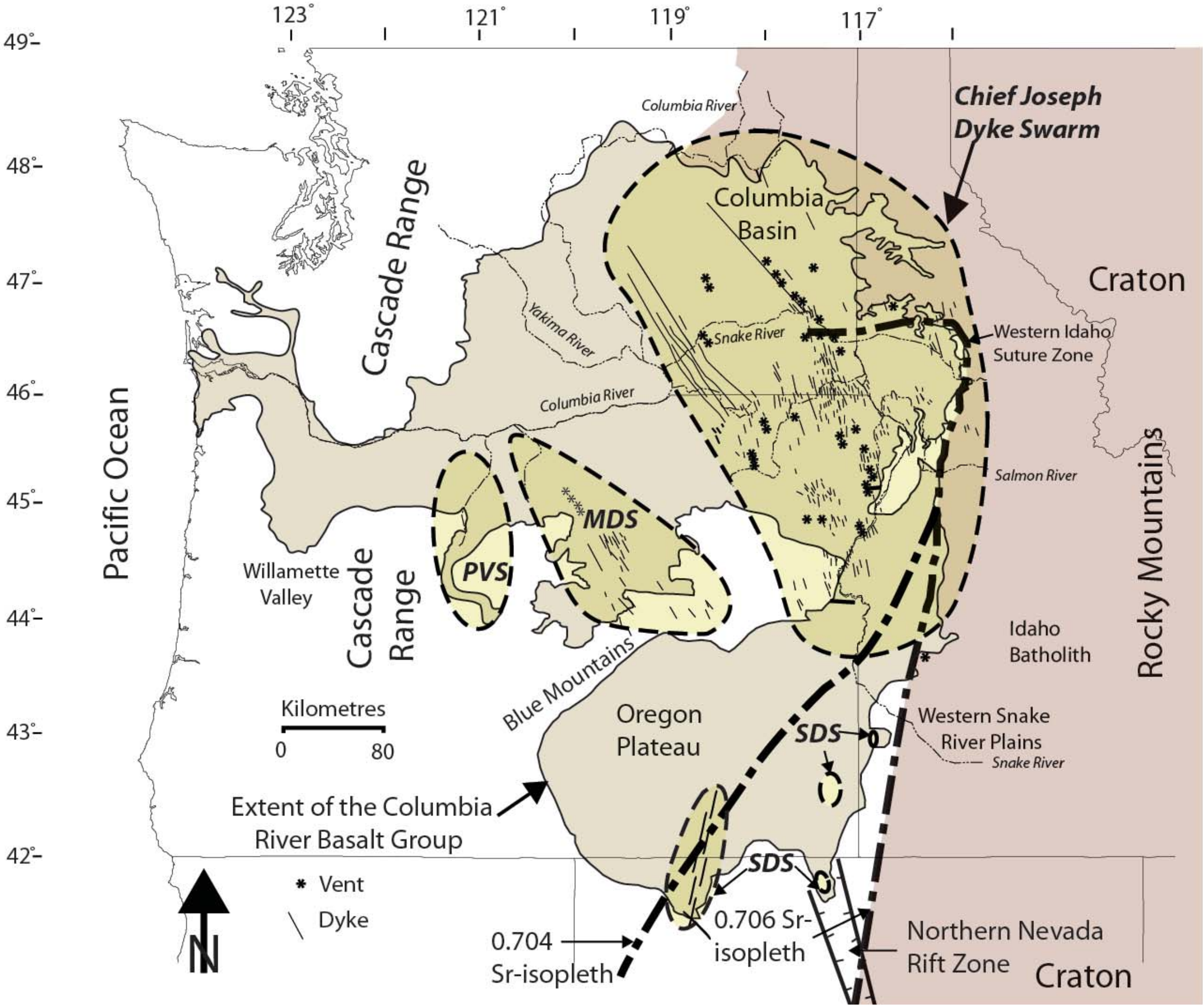


**Figure 1.** Location map of the Columbia River flood basalt province. This figure shows the extent of the Columbia River Basalt Group and dykes. The Columbia Basin forms the northern portion of the province and the Oregon Plateau forms the southern portion of the province south of the Blue Mountains. Geographic features include: Chief Joseph dyke swarm, Steens Basalt dyke swarms (SDS,) Monument (Picture Gorge) dyke swarm (MDS) and Prineville Basalt source area (PVS). The initial mainly granitic $^{87}$Sr/$^{86}$Sr 0.704 and 0.706 isopleths are from Pierce and Morgan (2009) and Armstrong et al. (1977). The Precambrian craton lies east of the 0.706 isopleth, oceanic accreted terranes lie west of the 0.704 isopleth, and transitional crust with cratonic affinities lies between the two. Basement rocks include the Precambrian craton of North America east of the 0.706 line, transitional crust with cratonic affinity between the 0.706 and 0.704 lines, and Paleozoic to Mesozoic oceanic accreted terranes west of the 0.704 line.

Grande Ronde time, when ~74% of the flood-basalt volume was generated. The Picture Gorge Basalt was erupted coeval with the Grande Ronde Basalt and comingled with it (Bailey 1989; Fig. 2), although a recent study suggests that the Picture Gorge Basalt may be among the oldest of the Columbia River Basalt Group (CRBG) formations (Cahoon et al. 2020). The waning phase includes the later part of the Wanapum Basalt and Saddle Mountains Basalt that erupted over ~10-million-years but account for only a few percent of the basalt. Many of the basalt flows were of extraordinary size, commonly exceeding 1000 km$^3$ in volume and traveling many hundreds of kilometres from their vent systems (Tolan et al. 1989; Reidel et al. 1989b; Reidel 1998, 2005, 2015; Reidel and Tolan 2013). Although radiating dyke swarms typically are often associated with plumes, e.g. Ernst and Buchan (2001), CRBG dykes (Fig. 1) are probably more influenced by the northward progression of the plume and eruptions through pre-existing structures (Reidel et al. 2013c).

## Lithology

For 16-million-year-old lava flows, the Columbia River Basalt Group is remarkably fresh with little alteration. Glass in thin sections typically is used as an important discriminator to determine alteration in the flows but the Mafic Index also can

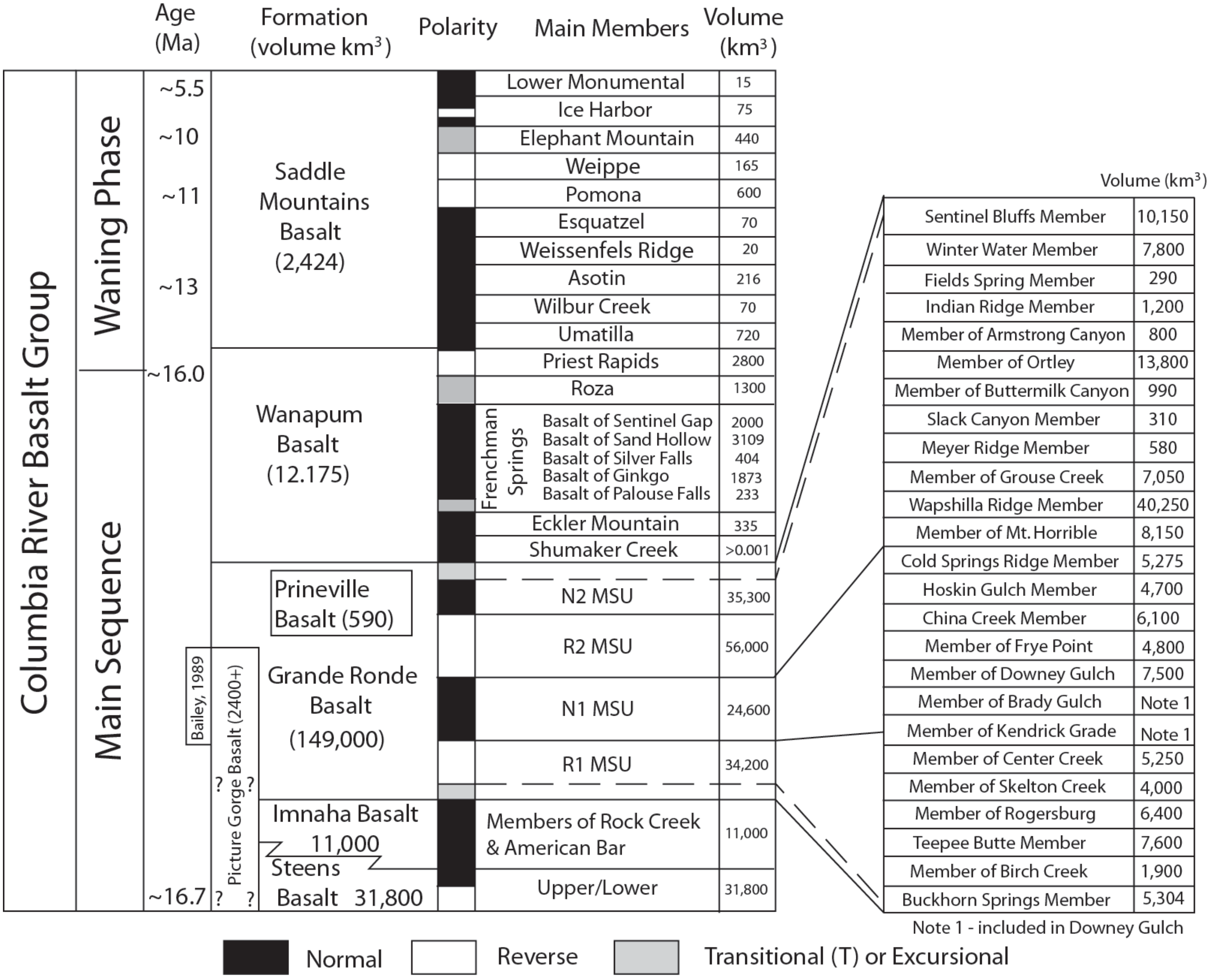


**Figure 2.** Generalized stratigraphy of the Columbia River Basalt Group showing the main stratigraphic units discussed in the text. Boxes around Prineville Basalt and Picture Gorge Basalt represent interfingering with the Grande Ronde Basalt. Stratigraphy, volumes, and polarities are from Reidel et al. (2013a), Reidel and Tolan (2013), Camp et al. (2013), and Reidel (2015). Picture Gorge Basalt extension is from Cahoon et al. (2020). Age dates are from Barry et al. (2010), Barry et al. (2013) and Kasbohm and Schoene (2018). N1-Normal 1; R1-Reversed 1; N2-Normal 2; R2- Reversed 2. T-Polarity transitions or excursions.

be used with the composition to evaluate the presence or absence of alteration (Baker et al. 2019). The basalt compositions used in this study are from unaltered, fresh samples. Typically, Columbia River Basalt Group flows are composed of plagioclase, clinopyroxene and glass with lesser amounts of olivine and minor amounts of orthopyroxene, ilmenite, magnetite, titanomagnetite and fluorapatite. Generally, the flows have equal amounts of clinopyroxene and plagioclase. Clinopyroxene is mainly augite-aegirine often with overgrowths of pigeonite and occasionally cores of orthopyroxene (Reidel 1983). Plagioclase typically ranges from $An_{30}$ to $An_{60}$. Olivine, although minor, ranges from $Fo_{20}$ to $Fo_{65}$. One of the most significant lithologic aspects of a flow is the presence or absence of plagioclase phenocrysts and olivine microphenocrysts (e.g. Swanson et al. 1979; Beeson et al. 1985; Bailey 1989; Reidel et al. 1989a; Hooper 2000). Most flows are commonly aphyric to rarely phyric, with the exception including the highly plagioclase-phyric flows of Steens, Imnaha and Picture Gorge Basalts, along with several Wanapum Basalt and Saddle Mountains Basalt flows. Although the Grande Ronde Basalt is often mischaracterized as strictly aphyric, many of these flows can be recognized by the presence of plagioclase phenocrysts and microphenocrysts (Reidel et al. 1989a; Reidel and Tolan 2013).

## Composition

The Columbia River Basalt Group is a series of generally tholeiitic basalts to basaltic andesites and andesites with sparse

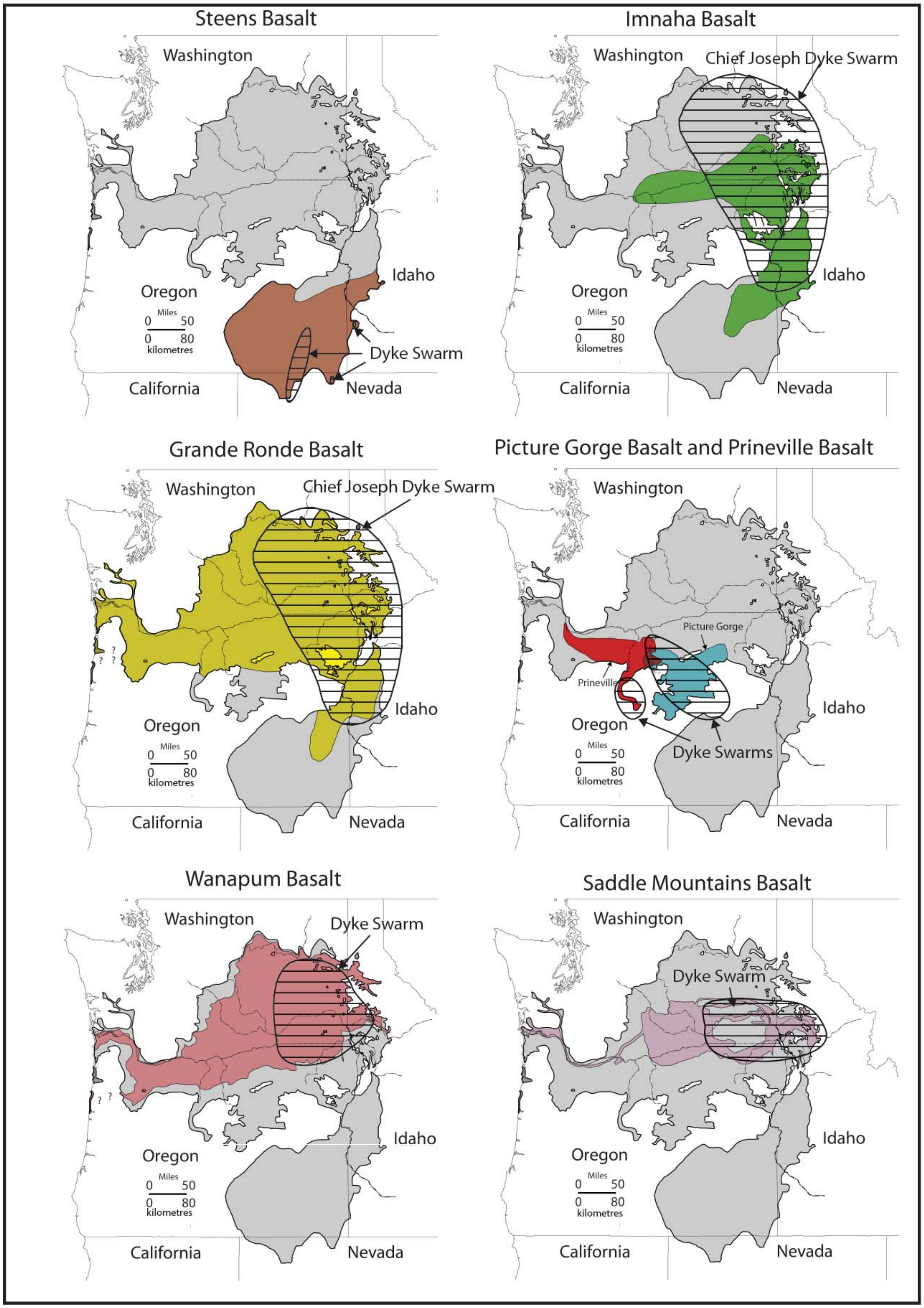


**Figure 3.** Extent of the seven formations of the Columbia River Basalt Group. The dyke swarms for each formation are shown as areas with horizontal lines. The Chief Joseph dyke swarm is the main swarm area for the Imnaha, Grande Ronde, Wanapum and Saddle Mountains Basalts. The Steens dyke swarm fed the Steens Basalt and the Monument dyke swarm fed the Picture Gorge Basalt. The Grande Ronde Basalt dykes cover the entire Chief Joseph dyke swarm but the Imnaha Basalt dyke swarm is confined to the southern part. The Wanapum and Saddle Mountains dyke swarms are broken out to show their limited extent. Extent of formations from Reidel et al. (2013b).

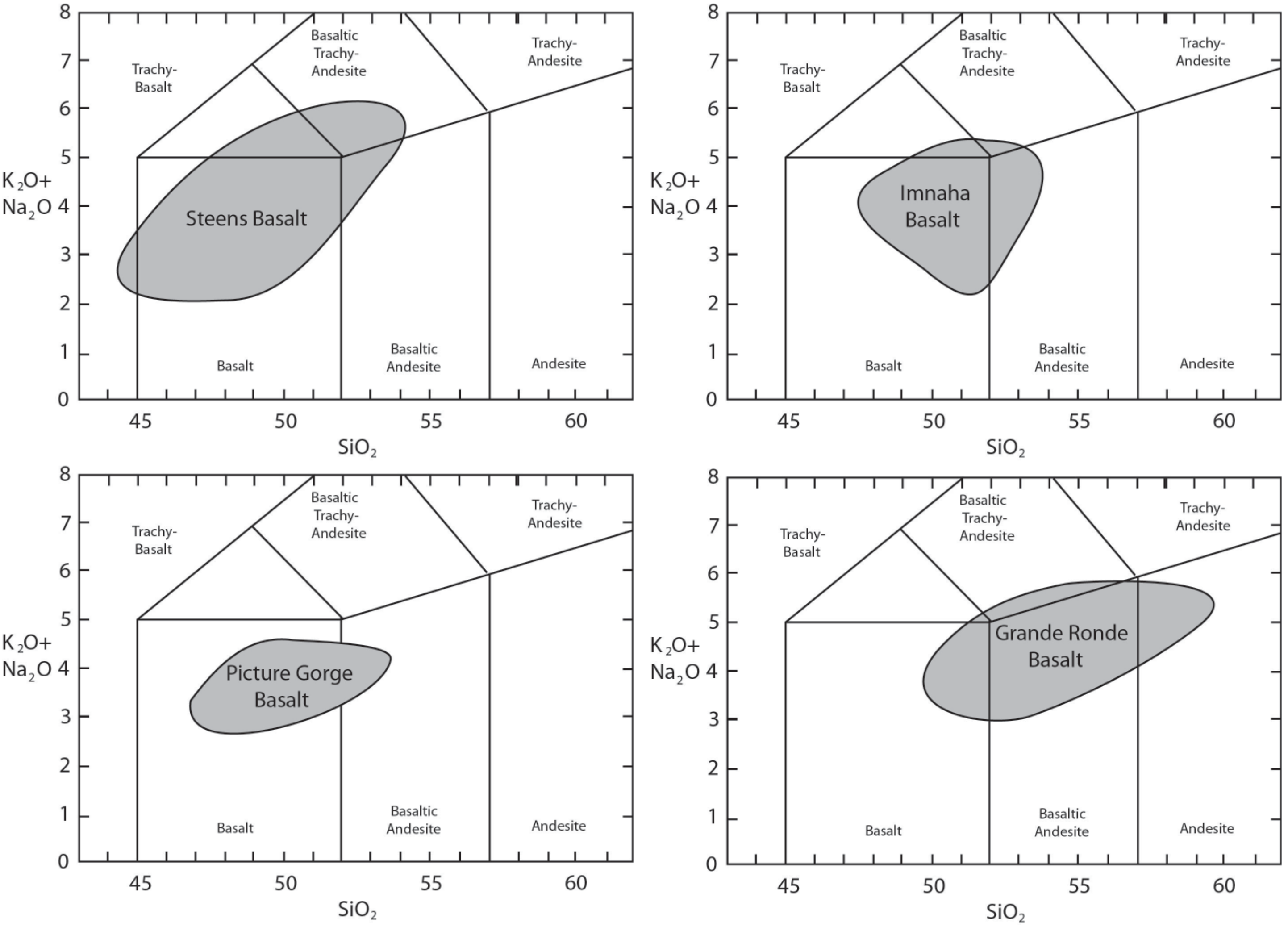


**Figure 4.** $K_2O+Na_2O$ versus $SiO_2$ plot for the Steens, Imnaha, Grande Ronde and Picture Gorge Basalts. The diagram shows the range of established formations and is based on La Bas et al. (1986). Data from Bailey (1989), Schuster (1993), Hooper (2000), Camp et al. (2003, 2013), Wolff et al. (2008 Appendix), Reidel and Tolan (2013) and S. Reidel unpublished data.

alkali-olivine basalts (Fig. 4). By far, the composition of the lavas has proven to be one of the most important tools for recognizing and correlating flows, as well as understanding the origin of these flows (e.g. Wright et al. 1973, 1989; Hooper 1974, 1997, 2000; Swanson et al. 1979; Reidel 1983, 1998, 2005; Beeson et al. 1985; Mangan et al. 1986; Reidel et al. 1989a, b; Hooper and Hawkesworth 1993; Ramos et al. 2005, 2013; Hooper et al. 2007; Camp and Hanan 2008; Camp 2013; Rodriguez and Sen 2013). Over the last 50+ years the Columbia River Basalt Group has been extensively analyzed for major and minor oxides, trace elements and isotopes. Many lava flows have a remarkable ‘bulk’ compositional homogeneity despite their huge volumes and distances traveled. However, with more detailed work, the recognition of compositional heterogeneities within Columbia River Basalt Group flows now must be taken into consideration (e.g. Reidel and Fecht 1987; Reidel and Tolan 1992; Reidel 1998, 2005; Martin et al. 2013; Reidel and Tolan 2013).

## Origin

The origin of the Columbia River Basalt Group has been an area of considerable debate for many years. The two main proposed sources for the basalts are: back-arc spreading and mantle plume (e.g. Hooper and Hawkesworth 1993; Camp and Hanan 2008; Camp 2013). The majority of workers now support the mantle plume hypothesis (e.g. Duncan 1982; Brandon and Goles 1988, 1995; Draper 1991; Hooper and Hawkesworth 1993; Geist and Richards 1993; Camp 1995, 2013; Dodson et al. 1997; Mege and Ernst 2001; Ernst and Buchan 2001; Hooper et al. 2002, 2007; Camp et al. 2003; Camp and Ross 2004; Caprarelli and Reidel 2004; Ramos et al. 2005; Camp and Hanan 2008; Wolff et al. 2008; Humphreys and Schmandt 2011). However, unresolved arguments on the nature and extent of the mantle plume, and the petrogenetic processes within the magma are still debated (e.g. Ivanov 2007; Smith 2007). The nearly coeval, back-arc setting of the Miocene to Pliocene Chilcotin Plateau Basalts (Bevier 1983;

Mathews 1989) that occur just north of the CRBG also have been proposed to have a mantle plume origin (Ernst and Buchan 2010) further suggesting that the CRBG mantle plume concept may be more complex than originally thought. Most petrogenetic models have concentrated on the Steens, Imnaha, and Grande Ronde Basalts. The waning phase, Wanapum Basalt and Saddle Mountains Basalt, has been attributed to increasing crustal contamination of the residual melts from a subcontinental lithospheric mantle enriched at ~2000 Ma (e.g. Hooper and Hawkesworth 1993; Hooper et al. 2007; Camp and Hanan 2008).

Nearly all researchers agree that the CRBG cannot be the result of a simple model of decompression partial melting of a mantle plume source (e.g. Carlson et al. 1981; Hooper et al. 2007). Most agree that the Imnaha Basalt is the most primitive endmember corresponding to Carlson's (1984) C2 component. The Imnaha component is interpreted to be upwelling depleted mantle (EM) II Type Ocean-Island basalt with perhaps a small component of cratonic crust and forms the endmember for the Steens, Picture Gorge and Grande Ronde Basalt formations (e.g. Hooper and Hawkesworth 1993; Hooper et al. 2007; Camp and Hanan 2008; Wolff and Ramos 2013). Hooper and Hawkesworth (1993), Camp et al. (2003, 2013), Wolff et al. (2008) and Ramos et al. (2013) suggest that the eruption of the oldest CRBG, Steens Basalt, consists of the Imnaha component and Pacific MORB with minor subduction or assimilated accreted terrane rocks. Hooper et al. (2002) and Camp (2013) divided the Steens Basalt into a Lower and Upper series; the Lower being the more primitive and the Upper being evolved. Moore et al. (2020) propose a three-stage evolution for the Steens Basalt involving contributions from a depleted mantle and an enriched mantle. The earliest Steens, the Lower A series, is equally supplied by both. The most voluminous, the Lower Steens B, has a larger contribution from the depleted mantle and the Upper Steens has an equal contribution from both but considerable assimilation of the middle and upper crust. Fractionation is minor in the Lower Steens but may exceed recharge in the Upper Steens Basalt.

The next eruptions, Imnaha Basalt, are more primitive than the Steens Basalt (Hooper and Hawkesworth 1993; Wolff et al. 2008, 2013; Camp 2013; Ramos et al. 2013) and form an important endmember in the CRBG. This lead Camp and Hanan (2008) to propose that the plume initially impinged under the Juan de Fuca plate and mixed with it to produce the Steens Basalt. The Imnaha Basalt, however, broke through the Juan de Fuca plate encountering the oceanic crust producing the more primitive and enriched melts.

The Grande Ronde Basalt is the most voluminous of the formations and probably the most contaminated by crustal material. The Grande Ronde Basalt is distinct from the Imnaha Basalt and has led most researchers to consider them to have distinct histories or, as Camp and Hanan (2008) propose, a step-function chemical change between the two. Wolf and Ramos (2013), however, suggest the Grande Ronde Basalt is simply Imnaha Basalt with crustal contamination. The Grande Ronde Basalt has a distinct major-element pyroxene signature that has led many to argue for a peridotite-pyroxenite or ecologite partial melt (Wright et al. 1973, 1989; Reidel 1983; Takahahshi et al. 1998; Camp and Hanan 2008). The available evidence suggests that there are two equally viable alternatives to generate the Grande Ronde chemical trends: (1) through the modification of peridotite partial melts by large-scale fractional crystallization and assimilation, or (2) through direct melting of a mafic crustal source.

The role of fractional crystallization and assimilation in the Grande Ronde Basalt (GRB) is well recognized but the amount of each has been an area of debate. Most models consider fractional crystallization to be minor but crustal contamination significant. The GRB was erupted in less than 400,000 years which creates problems for strict crustal assimilation. Camp and Hanan (2008), however, solve this problem by allowing assimilation of delaminated cratonic rock, thus providing more surface area for assimilation.

The Picture Gorge Basalt is interfingered with the GRB but erupted from dykes farther west that passed through oceanic accreted terrane. Hooper and Hawkesworth (1993) suggest that the lavas were derived from a lithospheric source without significant contribution from an asthenosphere source. Wolff and Ramos (2013), however, suggest that the Picture Gorge Basalt has the Imnaha component plus depleted mantle with a subduction related fluid-fluxed arc source.

## METHOD OF STUDY

We are aware of only one complete set of published PGE and chalcophile analyses from Columbia River Basalt Group flows (Table 1) and that is the USGS standard BCR-1 (Flanagan 1976) which is from the Wapshilla Ridge Member (Fig. 2) of the Grande Ronde Basalt. BCR-1 shows that at least one of the voluminous Columbia River Basalt Group flows had minor but measurable PGEs and, therefore others might also have measurable PGEs as well. The only other PGE analyses were by Chesley and Ruiz (1998), Vye et al. (2013) and Moore et al. (2020) who measured Os along with Re and Re/Os isotopic ratios for several flows. However, Oregon Sunstones that are Steens Basalt plagioclase phenocrysts that contain native copper (Wierman 2018), and immiscible sulphides in the Imnaha Basalt (Korzendorfer 1979) and Grande Ronde Basalt (Reidel 1978) demonstrate the presence of chalcophile elements in CRBG lavas. In order to get a more representative set of analyses for PGEs and chalcophile elements in the Columbia River Basalt Group, we collected a suit of 46 samples for PGEs and compiled a database of Cu and Zn from published and our unpublished analyses (e.g. Reidel 1983, 2005; Hooper and Hawkesworth 1993; Hooper et al. 1995, 2002, 2007; Hooper 2000; Camp et al. 2003; Camp and Ross 2004; Camp and Hanan 2008; Wolff et al. 2008 Appendix; Reidel and Tolan 2013). All our chalcophile element analyses were from samples analyzed at the GeoAnalytical Laboratory at Washington State University under the direction of Peter Hooper and Rick Conrey with additional analyses from Camp and Ross (2004), Bailey (1989) and the appendix in Wolff et al. (2008). We selected Pt and Pd as our representative target PGEs and had the samples analyzed at Act Labs using their Fire-Assay-ICP-MS technique. The first 21 samples (Table 2) were analyzed with a

**Table 1.** Published Platinum Group and Chalcophile Elements Analyses for the Columbia River Basalt Group.

| Sample | Formation+ | Member | Re ppb | Ru ppb | Rh ppb | Pd ppb | Os ppb | Ir ppb | Pt ppb |
|---|---|---|---|---|---|---|---|---|---|
| Standard BCR-1 | GRB | Wapshilla Ridge | 0.8 | 1 | 0.2 | < 0.5 – 12* | 0.1000 | 0.004 | 2.32 |
| JTC-DB | IB | American Bar | 0.558 | | | | 0.0292 | | |
| JTC-BUK | IB | American Bar | 0.659 | | | | 0.0991 | | |
| JTC RC-1d | IB | Rock Creek | 0.051 | | | | 0.3932 | | |
| JTC RC-2-1 | IB | Rock Creek | 0.402 | | | | 0.1700 | | |
| JTC RC-2-2 | IB | Rock Creek | 1.099 | | | | 0.0137 | | |
| JTC RC-2-3 | IB | Rock Creek | 2.568 | | | | 0.1623 | | |
| JTC RC-2-4 | IB | Rock Creek | 0.524 | | | | 0.3272 | | |
| JTC RC-2-5 | IB | Rock Creek | 2.221 | | | | 0.1981 | | |
| JTC-PHGR-1 | GRB | Buckhorn Springs | 1.13 | | | | 0.0155 | | |
| JTC-PHGR-2 | GRB | Buckhorn Springs | 0.529 | | | | 0.0032 | | |
| TTC-PH8-90-Tg | GRB | | 1.091 | | | | 0.001 | | |
| JTC-LW-2 | GRB | | 1.382 | | | | 0.0021 | | |
| JTC-ROZA-14-1 | WB | Roza | 0.00015 | | | | ND | | |
| JTC-ROZA-14-2 | WB | Roza | 2.126 | | | | 0.5708 | | |
| JTC-ROZA-17-1 | WB | Roza | 0.835 | | | | 0.0010 | | |
| JTC-ROZA-17-2 | WB | Roza | 2.735 | | | | 0.0042 | | |
| JTC-ROZA1-1 | WB | Roza | 0.97 | | | | 0.0020 | | |
| JTC-ROZA1-2 | WB | Roza | 1.365 | | | | 0.0287 | | |
| JTC-ROZA3-1 | WB | Roza | 1.601 | | | | 0.0039 | | |
| JTC-ROZA3-2 | WB | Roza | 3.565 | | | | 0.0095 | | |
| JTC-HS1-51 | SMB | Wilbur Creek | 1.97 | | | | 0.0077 | | |

+GRB-Grande Ronde Basalt, IB-Imnaha Basalt, SMB-Saddle Mountains Basalt, WB- Wanapum Basalt; ND-Not Detected
JTC = Chesley and Ruiz (1998) * Two analyses for Pd in BCR-1

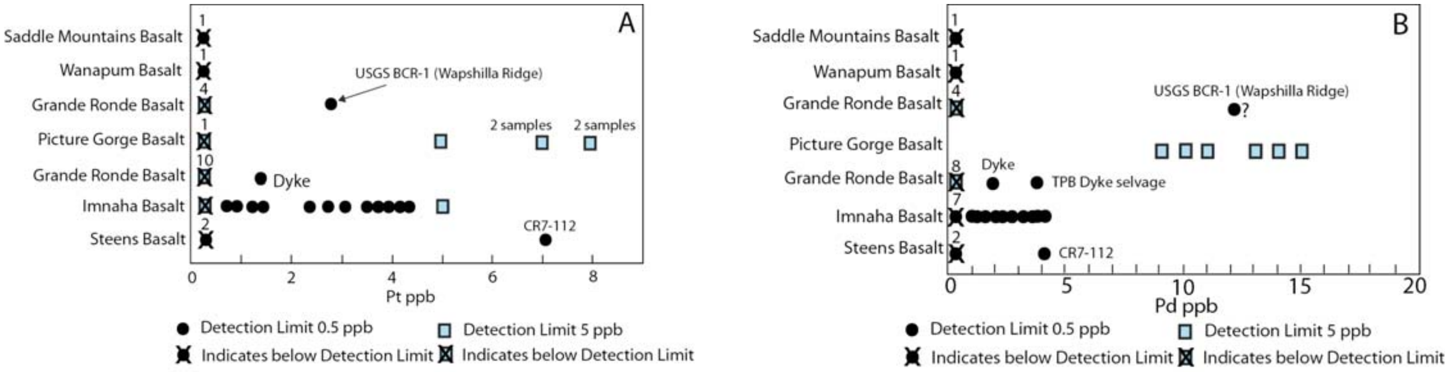


**Figure 5.** Pt and Pd abundances in the main formations of the Columbia River Basalt Group. A) is Pt in ppb, and B) is Pd in ppb.

detection limit of 5 ppb Pt and 4 ppb Pd as a reconnaissance for PGEs in the basalts. When this suite of samples showed that some samples contained PGEs above the detection limit, we then analyzed an additional 25 samples with a detection limit of 0.5 ppb Pt and 0.5 ppb Pd (Table 2). Our samples were from the Steens, Imnaha, Picture Gorge, and Grande Ronde Basalts. The Prineville, Wanapum and Saddle Mountains Basalts are minor by volume (Fig. 2) and represent the waning phases of the Columbia River Basalt Group. They contain low chalcophile element concentrations as shown later so we did not think a series of samples from these formations would be as useful as samples from the main phase. Our samples came from field exposures and continuous drilled core.

## Results

Figure 5a and 5b summarize the Pt and Pd results for the formations we targeted and Figure 6 shows Cu and Zn from all CRBG formations. Two formations stand out for their abundance of PGEs: the Imnaha Basalt and the Picture Gorge Basalt; the few samples we have for the Steens Basalt does not allow us to say the same, but we suspect that the Lower Steens probably is rich in PGEs. The most voluminous formation, the Grande Ronde Basalt from which USGS Standard BRC-1 was obtained appears to have low PGEs concentrations as well as that of Cu and Zn. Each formation will be discussed separately from oldest to youngest.

**Table 2.** Columbia River Basalt Group Platinum Group Element Analyses for this Study.

| Sample | Formation | Member | Pt DL | Pd DL | Pt ppb | Pd ppb |
|---|---|---|---|---|---|---|
| VCR7-112 | Steens Basalt | Lower | 0.5 | 0.5 | 7.1 | 4.1 |
| VCR8-203 | Steens Basalt | Lower | 0.5 | 0.5 | < 0.5 | < 0.5 |
| VCR7-122 | Steens Basalt | Upper | 0.5 | 0.5 | < 0.5 | < 0.5 |
| VCR-270 | Imnaha Basalt | Upper Pole Creek | 0.5 | 0.5 | 2.4 | 1 |
| VCR7-11 | Imnaha Basalt | Upper Pole Creek | 0.5 | 0.5 | < 0.5 | < 0.5 |
| VCR-90 | Imnaha Basalt | Upper Pole Creek | 0.5 | 0.5 | 2.8 | 1.2 |
| DBIB-9 | Imnaha Basalt | American Bar | 0.5 | 0.5 | 0.9 | < 0.5 |
| DBIB-11 | Imnaha Basalt | American Bar | 0.5 | 0.5 | 0.5 | < 0.5 |
| DBIB-12 | Imnaha Basalt | American Bar | 0.5 | 0.5 | 0.5 | < 0.5 |
| DBIB-14 | Imnaha Basalt | American Bar | 0.5 | 0.5 | 1.2 | 0.6 |
| DBIB-15 | Imnaha Basalt | American Bar | 0.5 | 0.5 | 0.6 | < 0.5 |
| DBIB-16 | Imnaha Basalt | American Bar | 0.5 | 0.5 | 0.7 | < 0.5 |
| SRIBdyke-1 | Imnaha Basalt | American Bar Dyke | 0.5 | 0.5 | 1.4 | 1.9 |
| DBIB-4 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 4.3 | 2.9 |
| DBIB-5 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 3.9 | 3.1 |
| DBIB-6 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 4.1 | 3 |
| DBIB-18 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 2.3 | 1.9 |
| DBIB-3 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 4.6 | 3.4 |
| DBIB-10 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 2.1 | 1.6 |
| DBIB-2 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 4.1 | 2.6 |
| DBIB-7 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 3.5 | 2.4 |
| DBIB-1 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 3.1 | 1.6 |
| DBIB-13 | Imnaha Basalt | Rock Creek Flow | 0.5 | 0.5 | 1.4 | < 0.5 |
| SRIM02-1 | Imnaha Basalt | Log Creek | 5 | 4 | 5 | 4 |
| SRBS-1 | Grande Ronde Basalt | Buckhorn Springs Member | 5 | 4 | < 5 | < 4 |
| SRTPB-S-1 | Grande Ronde Basalt | Teepee Butte selvage | 5 | 4 | < 5 | 4 |
| SRTPB-D-1 | Grande Ronde Basalt | Teepee Butte dyke | 5 | 4 | < 5 | < 4 |
| SRTPB-D-2 | Grande Ronde Basalt | Teepee Butte dyke | 5 | 4 | < 5 | < 4 |
| SRTPB-D-3 | Grande Ronde Basalt | Teepee Butte dyke | 5 | 4 | < 5 | < 4 |
| SRTPB-D-4 | Grande Ronde Basalt | Teepee Butte dyke | 5 | 4 | < 5 | < 4 |
| SRTPB-D-5 | Grande Ronde Basalt | Teepee Butte dyke | 5 | 4 | < 5 | < 4 |
| SRTPB-D-6 | Grande Ronde Basalt | Teepee Butte dyke | 5 | 4 | < 5 | < 4 |
| SRTPB-D-7 | Grande Ronde Basalt | Teepee Butte dyke | 5 | 4 | < 5 | < 4 |
| SEPG02-11 | Grande Ronde Basalt | Sentinel BM at Patrick Grade | 5 | 4 | < 5 | < 4 |
| IMD-1 | Grande Ronde Basalt | Dyke at JC and road | 0.5 | 0.5 | 1.4 | 1.9 |
| SRMH-1 | Grande Ronde Basalt | Mt Horrible Member | 5 | 4 | < 5 | < 4 |
| SRMT-1r | Grande Ronde Basalt | Mt Horrible repeat | 5 | 4 | < 5 | < 4 |
| SRLGD02-1 | Grande Ronde Basalt | Sentinel Bluffs Member | 5 | 4 | < 5 | < 4 |
| SRSB-1 | Grande Ronde Basalt | Sentinel Bluffs-Museum | 5 | 4 | < 5 | < 4 |
| SRSB-2 | Grande Ronde Basalt | Sentinel Bluffs-Museum | 5 | 4 | < 5 | < 4 |
| SRPGB-1 | Picture Gorge Basalt | Franklin Mountain | 5 | 4 | < 5 | 13 |
| SRPGB-2 | Picture Gorge Basalt | Donney Basin | 5 | 4 | 7 | 11 |
| SRPGB-3 | Picture Gorge Basalt | Donney Basin | 5 | 4 | 5 | 9 |
| SRPGB-4 | Picture Gorge Basalt | Donney Basin | 5 | 4 | 8 | 10 |
| SRPGB-5 | Picture Gorge Basalt | Camas Creek | 5 | 4 | 7 | 15 |
| SRPGB-6 | Picture Gorge Basalt | Holmes Creek | 5 | 4 | 8 | 14 |
| WB-82-1 | Wanapum Basalt | Roza Member | 0.5 | 0.5 | < 0.5 | < 0.4 |
| SMBHH-1 | Saddle Mountains Basalt | Umatilla | 0.5 | 0.5 | < 0.5 | < 0.4 |
| BCR-1 | | | | | | |

DL-Detection Limit in ppb < Less Than

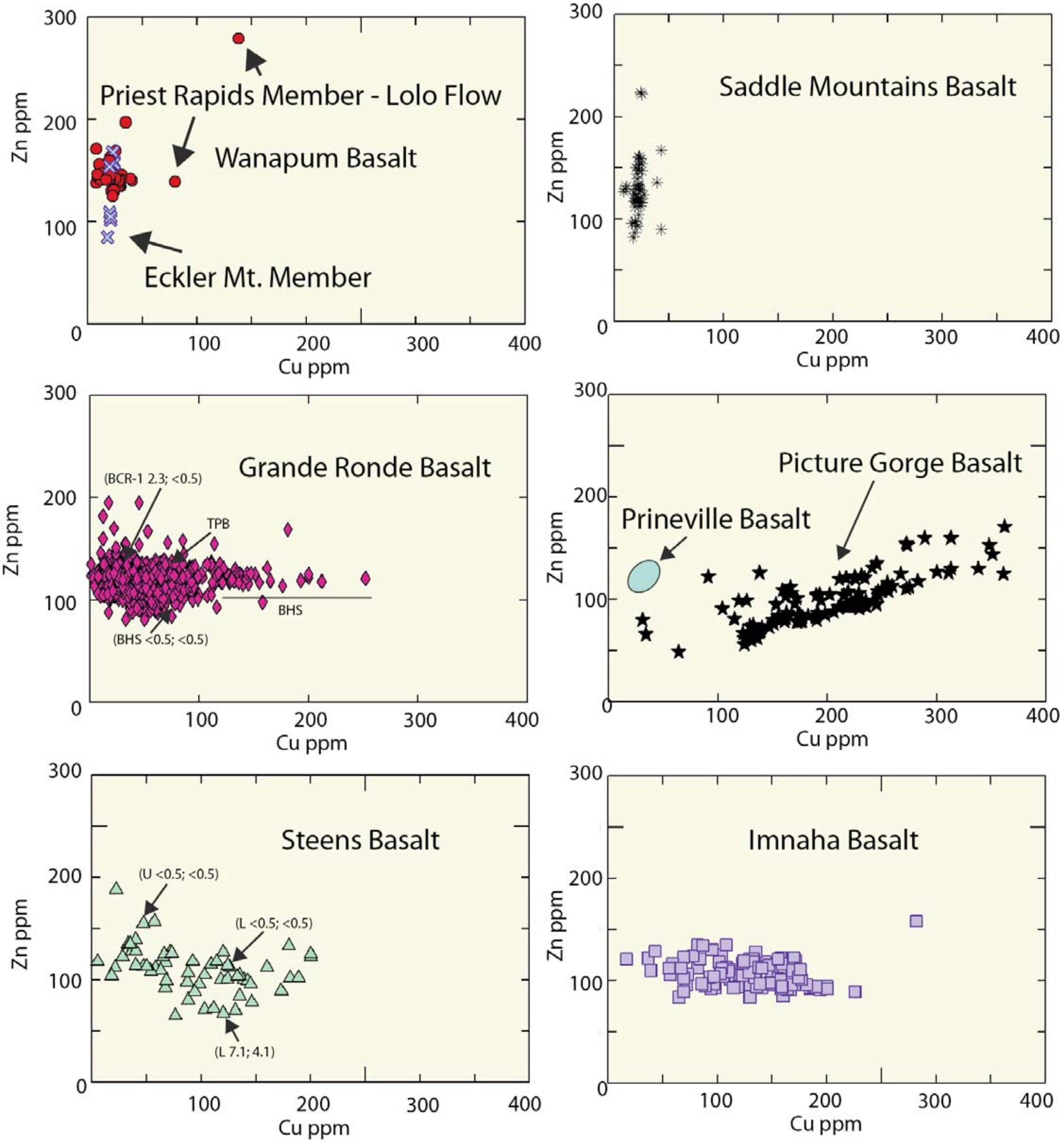


**Figure 6**. Variation diagram of Cu and Zn for the formations of the Columbia River Basalt Group. Data from Bailey (1989), Schuster (1993), Hooper (2000), Camp et al. (2003, 2013), Wolff et al. (2008 Appendix), Reidel and Tolan (2013) and S. Reidel unpublished data. In Steens Basalt plot, U-Upper Steens; L-Lower Steens Basalt. In Grande Ronde Basalt plot, BCR-1 is USGS standard BCR-1; BHS- Buckhorn Springs Member (see Fig. 2); TPB-Teepee Butte Member (see Fig. 2).

### *Steens Basalt*

Three Steens Basalt samples were analyzed for PGEs; one is from the most primitive Lower B series Steens; one is from the most evolved, the Upper Steens; and one is from a flow intermediate to both although classified by Camp et al. (2013) as Lower Steens. Of those samples only the most primitive

Lower Steens Basalt has Pt and Pd above detection limits (Fig. 5). The Upper Steens and intermediate composition Lower Steens both have Pt and Pd below detection limits. The Upper Steens lavas include more evolved trachy-andesites and basaltic andesites (Fig. 4; Camp et al. 2003, 2013; Moore et al. 2020); the intermediate composition Lower Steens is transitional between the compositions of the Lower and Upper Steens Basalt. The various models for the Steens Basalt (e.g. Camp et al. 2013) conclude that the Lower Steens Basalt formed from more-primitive mantle with minor lithospheric contamination whereas the Upper Steens has undergone extensive contamination and fractionation. The intermediate composition Lower Steens may represent the initial stage of that contamination.

Immiscible sulphides and native Cu in Oregon Sunstones are present in Lower Steens Basalt but not Upper Steens Basalt (Wierman 2018). The Moore et al. (2020) model requires extensive sulphide precipitation in the Lower Steens Basalt but not in the Upper Steens Basalt to account for their high Os isotopic values.

There appears to be no correlation between Cu and Zn (Fig. 6). Zn is relatively constrained having a range of about ~100 ppm with a few outliers. Cu ranges between 5 and 200 ppm, however, Wierman (2018) reports Cu as high as 400 ppm. We plotted PGEs for our three Steens samples on Figure 6. The Lower Steens flows have more Cu than the Upper Steens, but with our limited data there appears to be no relationship between Cu, Zn and PGEs. We also plotted Cu vs. MgO and Zn vs. $TiO_2$ (Fig. 7), and Cu vs. Ni (Fig. 8). These plots examine the possible correlation between Cu and Zn and the basalt mineralogy. Zn is positively correlated with $TiO_2$ and FeO but not MgO; Cu shows no correlation with any oxide or element, a conclusion also reached by Wierman (2018). Ni, expectedly is correlated with Cr (Fig. 9).

### Imnaha Basalt

The Imnaha Basalt is mainly tholeiitic basalt to basaltic andesite (Fig. 4). Hooper (1974) and Hooper et al. (1984) defined two major compositional types in the Imnaha Basalt, the Rock Creek type and the American Bar type (Fig. 2), and several minor ones. We analyzed 19 samples for PGEs with the intent to collect the major compositional types and as many minor ones as possible. Our sampling design was twofold: 1) we collected 12 samples from various field locations of the Imnaha Basalt, and 2) 7 samples through a 150-m-thick Rock Creek flow to determine how Pt and Pd were distributed within an individual flow. Segregation zones and pegmoidal patches recognized by Holden and Hooper (1976) were avoided. All Imnaha Basalt samples except one contained either some Pt or Pd or both (Fig. 5; Table 2).

Cu and Zn are plotted for the Imnaha Basalt in Figure 6. Like the Steens Basalt, Zn has a limited range but Cu ranges from nearly 0 to 250 ppm. Overall, there appears to be no correlation between Cu and Zn, and Cu and MgO. However, there is a strong correlation between Zn and $TiO_2$ (Fig. 7); and Zn and FeO. Zn and MgO (not shown) has a negative correlation but Zn is not correlated with CaO. Like the Steens Basalt, Ni and Cr show a positive correlation (Fig. 9).

### Distributed samples

Eight samples are from outcrops of the Rock Creek chemical type and the American Bar chemical type; one sample is from the Log Creek flow (Rock Creek chemical type); three are from the upper Pole Creek (Imnaha Basalt, Oregon Plateau) of Hooper et al. (2002) and Camp et al. (2003) and one is an American Bar dyke sample. Two of the three upper Pole Creek samples contained Pt above detection limits (< 0.5 ppb) but not all contained Pd. Pt and Pd were more abundant in the Rock Creek samples than in the American Bar samples. The Rock Creek samples typically contain Pd but Pd in the American Bar samples was below detection limits. The Log Creek sample (uppermost Imnaha Basalt in Joseph Creek) is below the contact with the Grande Ronde Basalt and contains the highest Pt and Pd recorded for the Imnaha Basalt. The American Bar samples came from below the Rock Creek and Log Creek samples suggesting that the Pt and Pd contents increased with time during the eruption of the Imnaha Basalt. In general, the older American Bar samples have higher $SiO_2$ and lower MgO and have had significantly more plagioclase and pyroxene fractionation (Hooper et al. 1984; Hooper 1988; Hooper and Hawkesworth 1993).

### Rock Creek flow

Seven samples were collected from the 150-m-thick Rock Creek flow previously studied by Holden and Hooper (1976) and Korzendorfer (1979). Korzendorfer examined three stratigraphic sections, two of which were studied previously by Holden and Hooper (1976). We sampled Korzendorfer's (1979) Section A that is 75 m east of Holden and Hooper's (1976) main western section. Korzendorfer (1979) collected 36 samples from this section to study the opaque mineralogy. Our samples were from the massive part of the Rock Creek flow at Korzendorfer's section; we avoided the zeolitized scoria flow top and segregation zones and pegmatoid like Korzendorfer had done. Holden and Hooper (1976) analyzed 6 samples from the massive part of the Rock Creek flow for major and minor elements. We reanalyzed their samples on a newer and more precise XRF machine for major, minor and trace elements. We omitted Holden and Hooper's (1976) upper most samples (16a, 16b, and 16c) as they were from the zeolitized scoria and were altered by groundwater and weathering.

Korzendorfer (1979) recognized ilmenite, titanomagnetite, disseminated sulphide minerals and immiscible sulphide droplets in the Rock Creek flow (Fig. 10) which are only visible by microscope. Chromite was not present and has not been recognized in any Columbia River Basalt Group flow. Immiscible sulphide droplets have been recognized in other Columbia River Basalt Group flows (e.g. Reidel 1978, 1983; Wierman 2018). Korzendorfer (1979) recognized two main occurrences of sulphides: 1) round, often complex, polymineralic immiscible sulphides, and 2) monomineralic sulphide grains or simple mineral combinations that he believes crystallized directly from the melt. He identified chalcopyrite and pyrrhotite as the main sulphides and lesser amounts of cubanite, pyrite, bornite, covellite and a dull, purplish gray mineral with a reflectivity of 10–15% which he was unable to identify. He did not recognize any PGE minerals.

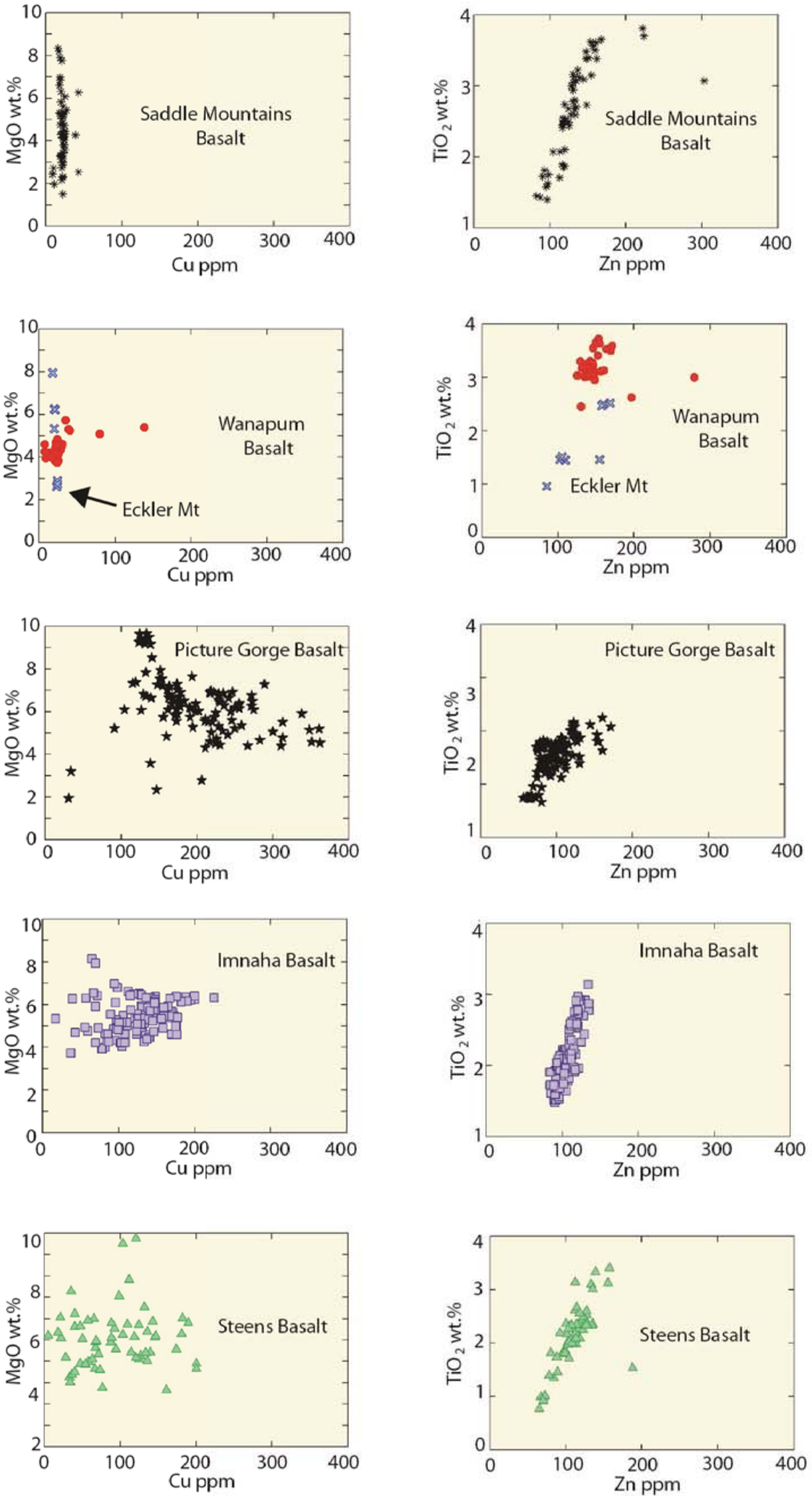


**Figure 7.** Variation diagrams for MgO and Cu, and $TiO_2$ and Zn for the Steens, Imnaha, Picture Gorge, Wanapum and Saddle Mountains Basalts. Data from Bailey (1989), Schuster (1993), Hooper (2000), Camp et al. (2003, 2013), Wolff et al. (2008 Appendix), Reidel and Tolan (2013), and S. Reidel unpublished data.

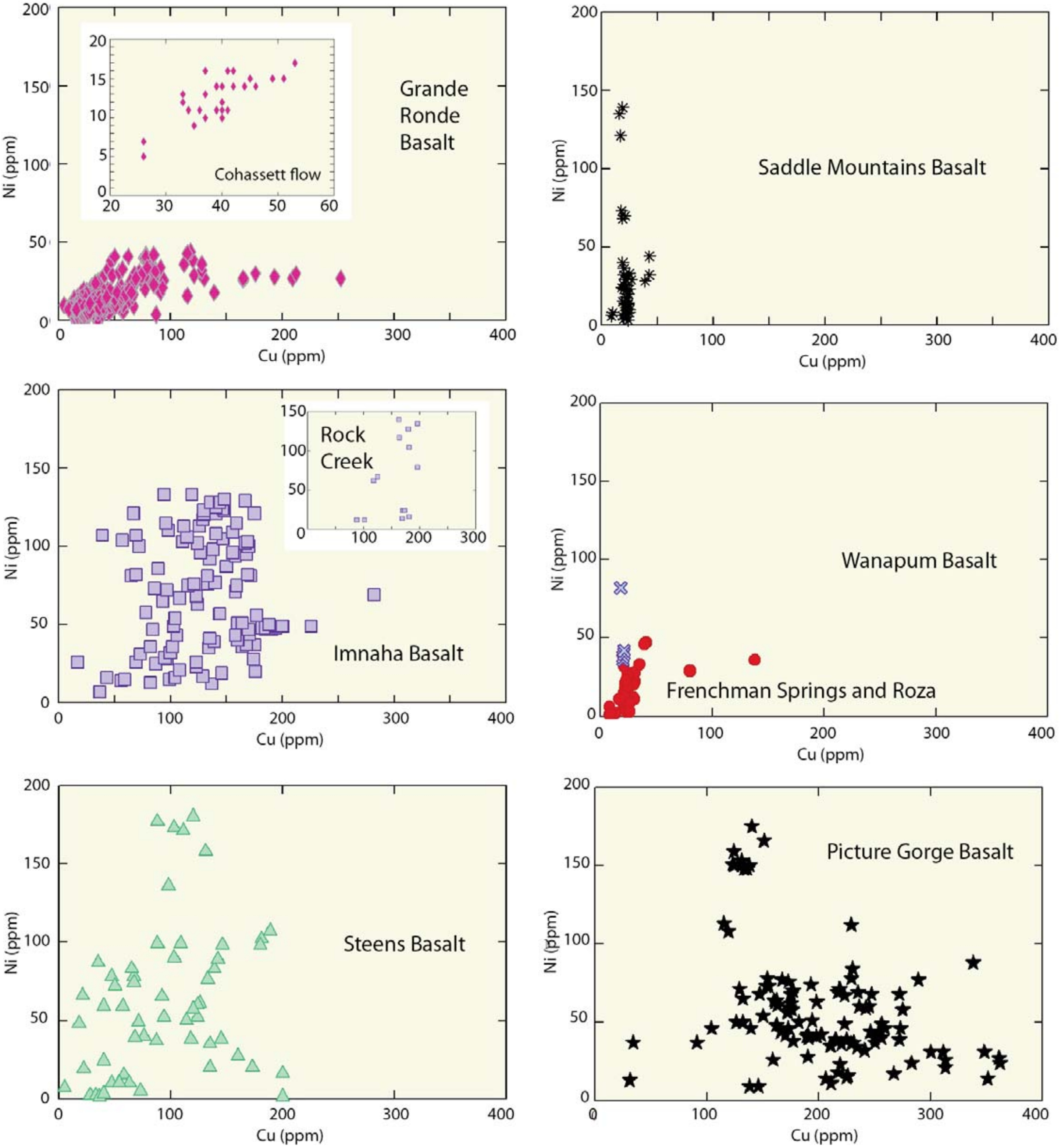


**Figure 8.** Variation diagram for Cu and Ni in the Columbia River Basalt Group. Data from Bailey (1989), Schuster (1993), Hooper (2000), Camp et al. (2003, 2013), Wolff et al. (2008 Appendix), Reidel and Tolan (2013), and S. Reidel unpublished data. For Wanapum Basalt, circle is Frenchman Springs Member and 'x' is Lolo flow, Priest Rapids Member (see Fig. 2).

Our Pt and Pd analyses and our reanalyzed Holden and Hooper (1976) samples for Cu, Zn and $TiO_2$ are shown in Figure 10a along with Korzendorfer's (1979) sulphide, ilmenite and, titanomagnetite and our Pt, Pd, Cu, Zn and $TiO_2$ occurrences. Figure 10b shows Korzendorfer's (1979) ilmenite, titanomagnetite and sulphides, and our Pt and Pd analyses with

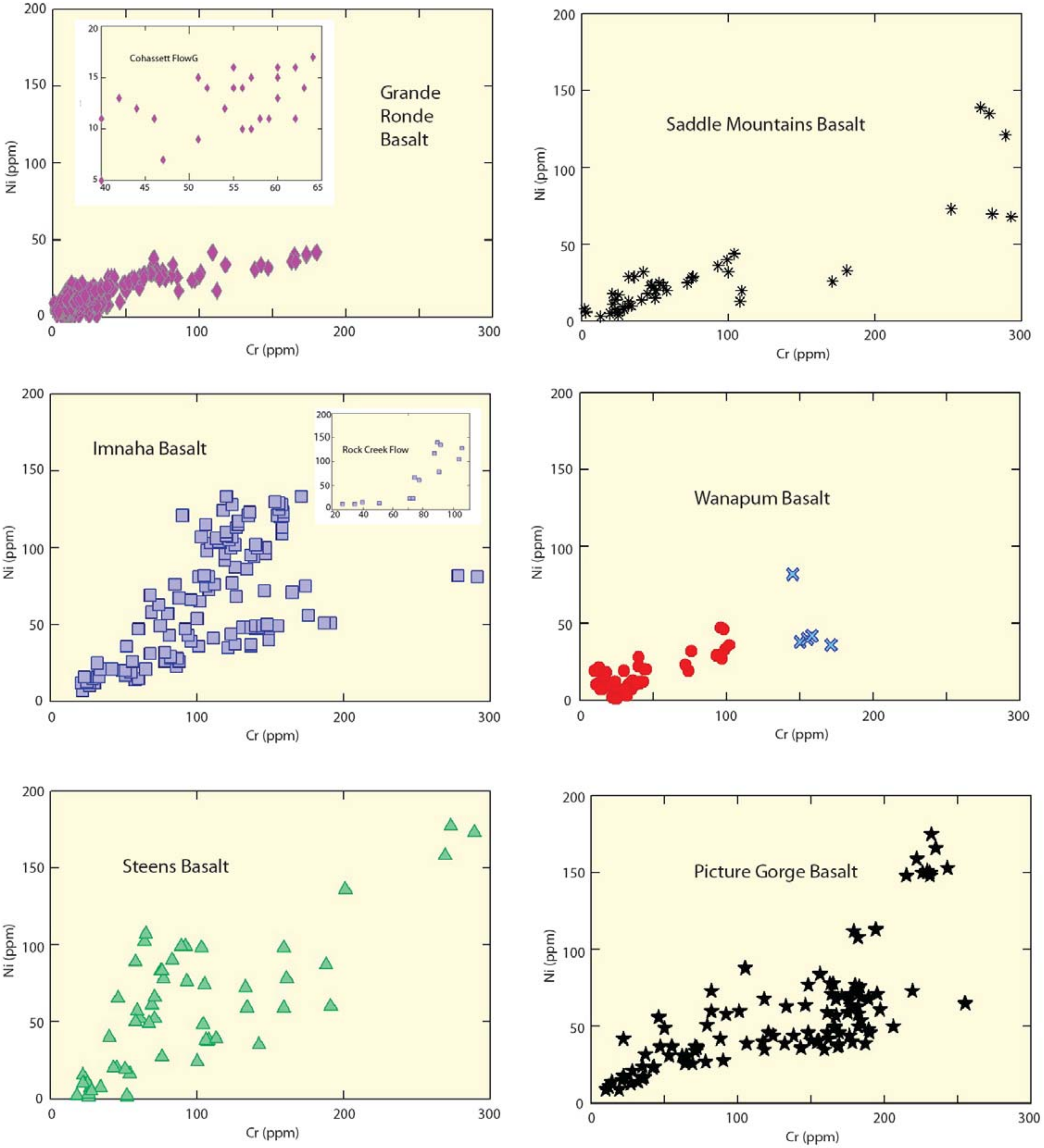


**Figure 9.** Variation diagram for Ni and Cr in the Columbia River Basalt Group. Data from Bailey (1989), Schuster (1993), Hooper (2000), Camp et al. (2003, 2013), Wolff et al. (2008 Appendix), Reidel and Tolan (2013), and S. Reidel unpublished data.

our reanalyzed Holden and Hooper (1976) samples for Ni, Cr, MgO, $FeO_{total}$, along with modal olivine and pyroxene from Holden and Hooper (1976). MgO, $FeO_{total}$, and Ni to a lesser degree, correlate with modal olivine and pyroxene as expected

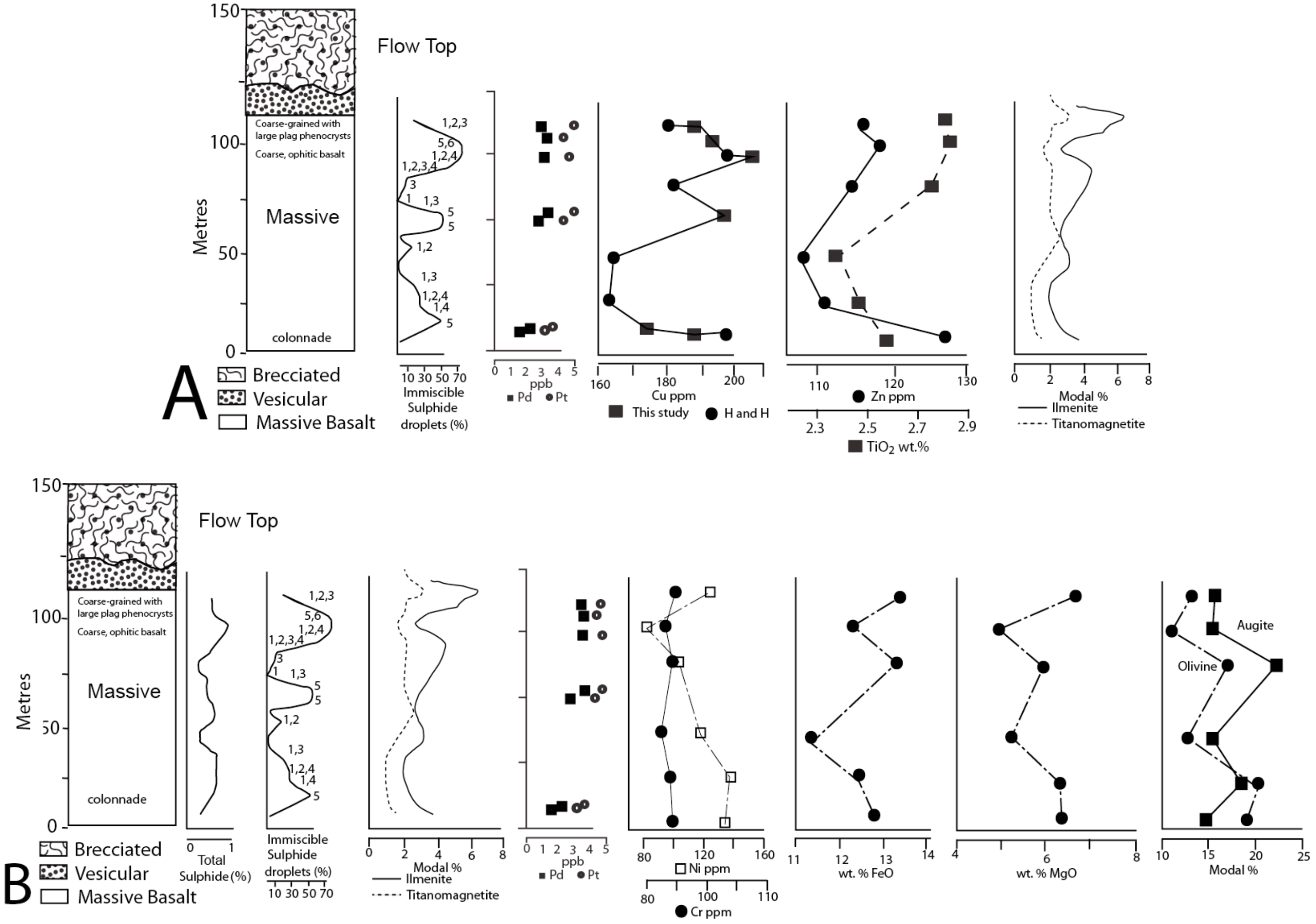


**Figure 10.** Compositional and mineralogical concentrations in the Rock Creek flow, Imnaha Basalt. A) Pt, Pd, Cu, Zn, Ilmenite, titanomagnetite, sulphides; B) Pt and Pd, Ni, Cr, MgO, $Fe_{Total}$ as FeO, and modal olivine and pyroxene, ilmenite, titanomagnetite and sulphides. Pt and Pd from this study, immiscible sulphide, total sulphides, and Ilmenite and titanomagnetite abundances from Korzendorfer (1979) and Ni, Cr, MgO, $Fe_{Total}$, and modal olivine and pyroxene from Holden and Hooper (1976) with samples reanalyzed by this study. For Immiscible Sulphide Droplets, 1 = mainly pyrrhotite with some chalcopyrite; 2 = equal amounts of pyrrhotite and chalcopyrite; 3 = mainly chalcopyrite; 4= chalcopyrite and exsolved (?) cubanite; 5 = mainly goethite with chalcopyrite and small amount of unknown mineral; 6 = mainly bornite with chalcopyrite and minor titanomagnetite from Korzendorfer (1979).

whereas Pt and Pd appear to be independent of them but increase with height. This may reflect increasing S saturation to form PGE-scavenging sulphides or rising Cl- and S-rich volatiles that carried the PGE upward. The importance of volatiles is shown by segregation zones and pegmoidal patches in the upper part of the flow. In addition, the upper 25 m of the Rock Creek flow is a vesicular flow top atypical of the CRBG. However, in Figure 10a, Cu appears to correlate with sulphide occurrences but we did not collect samples for Pt and Pd from the low-sulphide areas so we cannot be certain that there is a perfect correlation. Nevertheless, we interpret this to suggest that Pt and Pd are probably concentrated in the sulphides with Cu whereas Ni and probably Cr are concentrated in olivine. Modal ilmenite and titanomagnetite also appear to correlate with FeO and $TiO_2$ but they are accessory minerals. Zn, however, correlates with $TiO_2$ indicating that Zn substitutes for $Fe^{++}$ in mainly pyroxene and olivine but also for $Fe^{++}$ in ilmenite and titanomagnetite.

### Grande Ronde Basalt

We collected 14 samples for Pt and Pd from the Grande Ronde Basalt in addition to USGS Standard BCR-1. Little time had passed between the Imnaha and Grande Ronde Basalt eruptions, but the flows are different both compositionally and physically. Ten samples are from the Grande Ronde Basalt below Bailey's (1989) Picture Gorge Basalt (PGB) interval (Fig. 2) and four come from above Bailey's (1989) Picture Gorge Basalt. It is clear from Figure 5 that in most samples, Pt and Pd are below detection limits (5 ppb Pt and 4 ppb Pd). The samples using a lower detection limit (0.5 Pt; 0.5 Pd ppb) did contain PGEs but significantly less than the Imnaha Basalt and Picture Gorge Basalt (Table 2). In the samples below the PGB interval, no sample had Pt above the detection limit and only one had Pd. One sample from the oldest Grande Ronde Basalt member, the Buckhorn Springs, was collected directly above our Imnaha Basalt sample in Joseph Creek and it contained no Pt or Pd above our detection limit but did contain more Cu and Zn than later flows. Because of our higher detection limits for most Grande Ronde Basalt samples, we assume that the samples that did detect Pt at the lower detection limit are typical but Pd is surprising. Standard BCR-1 contains a recommended content of 12 ppb Pd (Flanagan 1976) and is well above the 4 ppb detection limit yet none of our samples were near that value. For BCR-1 there were only two analyses, one 12 ppb and the other < 0.5 ppb. It is probable that the lower value may be the more accurate one. We interpret this to indicate that Pd and Pt are minor.

We have a large database of chalcophile elements from the Grande Ronde Basalt. Like earlier flows, Zn has a restricted range relative to Cu (Fig. 6) with a few higher content Cu samples. In order to get a better understanding of where the higher Cu occurs, we plotted Cu content for each member (Fig. 11). This figure shows that the highest Cu content occurs in the oldest members, the Buckhorn Springs Member through the Rogersburg, (Fig. 2) and Cu content decreases up section. We then examined our GRB database and realized that the highest Cu content for the Buckhorn Springs Member occurs in down-flow samples, i.e. in the earliest part of the eruption that is distal (250 km) to the feeder dyke. Our Pt–Pd sample was from the earliest Buckhorn Springs Member flow but from the very last part of the eruption near the dyke. This suggests that the PGEs may have been in the initial eruption but were quickly depleted like Cu.

The Teepee Butte Member followed shortly after the Buckhorn Springs Member; this member has been described in detail by Reidel and Tolan (1992). Eight samples were collected from the dyke of the Joseph Creek flow of the Teepee Butte Member (Fig. 12). Platinum is below detection limits (5 ppb) for all dyke samples except one of the two selvage zones contains measurable Pd (Table 2). We did not sample the other selvage zone. The Pd in the dyke occurs in the sample with the highest Cu and Zn content (Fig. 12b) whereas Ni and Cr (Fig. 12a) follow the opposite pattern suggesting they are probably incorporated in olivine and pyroxene. In addition to the Teepee Butte dyke, we sampled another dyke that fed a stratigraphically slightly higher flow which occurs below Bailey's (1989) Picture Gorge Basalt interval. This sample (IMD-1) contained 1.4 ppb Pt and 1.9 ppb Pd which is below BCR-1 Pt and Pd content suggesting minimal Pt and Pd contents.

Of the five samples from the Grande Ronde Basalt above the Picture Gorge Basalt interval, only one sample contained detectable PGEs and that was the USGS Standard BCR-1. Our samples had a higher detection limit than BCR-1 which is more compositionally evolved than the more MgO- and CaO-rich samples of Grande Ronde Basalt like the Teepee Butte Member.

In Figure 13 we plotted 25 samples for Cu, Zn, MgO and $TiO_2$ through the Cohasset flow of the Sentinel Bluffs Member, the youngest member of the Grande Ronde Basalt (Fig. 2). We analyzed four samples for PGEs at the higher detection limit and found none exceeded it. Despite the relatively small range of Zn in the GRB, it is clear that Cu and Zn are inversely correlated (Fig. 13). Cu is positively correlated with MgO, CaO and Ni (Fig. 8) but negatively correlated with Rb (not shown). Zn is positively correlated with $TiO_2$, FeO, $P_2O_5$ and Zr but negatively correlated with $Al_2O_3$, MgO, CaO, and Y (Fig. 14). This suggests that both Cu and Zn are controlled not by sulphides in the Grande Ronde Basalt but are incorporated in the silica melt and other minerals in the basalt. This will be discussed later.

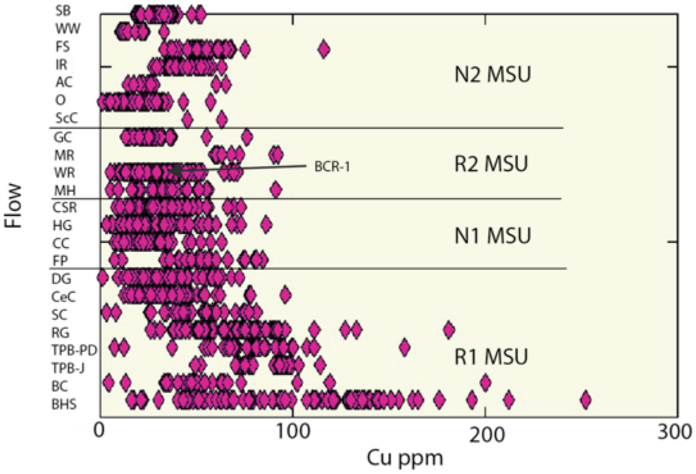


**Figure. 11.** Concentration of Cu in members of the Grande Ronde Basalt. Oldest is on the bottom and youngest on top. Smaller volume flows have been omitted. From oldest to youngest: BHS – Buckhorn Springs; BC – Birch Creek; TPB-J – Teepee Butte, Joseph Creek flow; TPB-PD – Teepee Butte, Pruitt Draw flow; RG – Rodgersburg; SC – Skelton Creek; CeC – Center Creek; DG – Downey Gulch; FP – Frye Point; CC – China Creek; HG – Hoskin Gulch; CSR – Cold Springs Ridge; MH – Mt. Horrible; WR – Wapshilla Ridge; MR – Meyer Ridge; GC – Grouce Creek; ScC – Slack Canyon; O – Ortley; AC – Armstrong Canyon; IR – Indian Ridge; FS – Fields Spring; WW – Winter Water; SB – Sentinel Bluffs. Data from Schuster (1993), Hooper and Hawkesworth (1993), Hooper (2000), Wolff et al. (2008 Appendix), Reidel et al. (2013b), Reidel and Tolan (2013), and S. Reidel unpublished data.

### *Picture Gorge Basalt*

The Picture Gorge Basalt (PGB) was erupted during Grande Ronde Basalt time but from the Monument dyke swarm west of the Chief Joseph dyke swarm (Fig. 3). The PGB is mainly basalt with some basaltic andesites (Bailey 1989; Fig. 4). The Mt. Horrible Member of the Grande Ronde Basalt (Fig. 2) directly overlies the PGB indicating that the PGB eruptions ended before the voluminous Wapshilla Ridge Member of BCR-1.

We collected six Picture Gorge Basalt samples mainly from the lower part of Bailey's (1989) section, the Twickenham and Monument Mountain Members (Fig. 15). The Twickenham Member is the oldest member and plagioclase- and olivine-phyric. Later members are more aphyric. We collected three samples from the Basalt of Donnely Basin, a plagioclase-phyric flow like the Imnaha Basalt and the oldest flow recognized by Bailey (1989). Except for Pt in the Basalt of Franklin Mountain, the PGB suggests an increase in Pt and Pd with decreasing age (Fig. 15). We sampled the Mt. Horrible Member of the Grande Ronde Basalt directly above the PGB and found no Pt or Pd above the limit of detection. The Mt. Horrible Member was erupted from a dyke 100 km east of the Picture Gorge area.

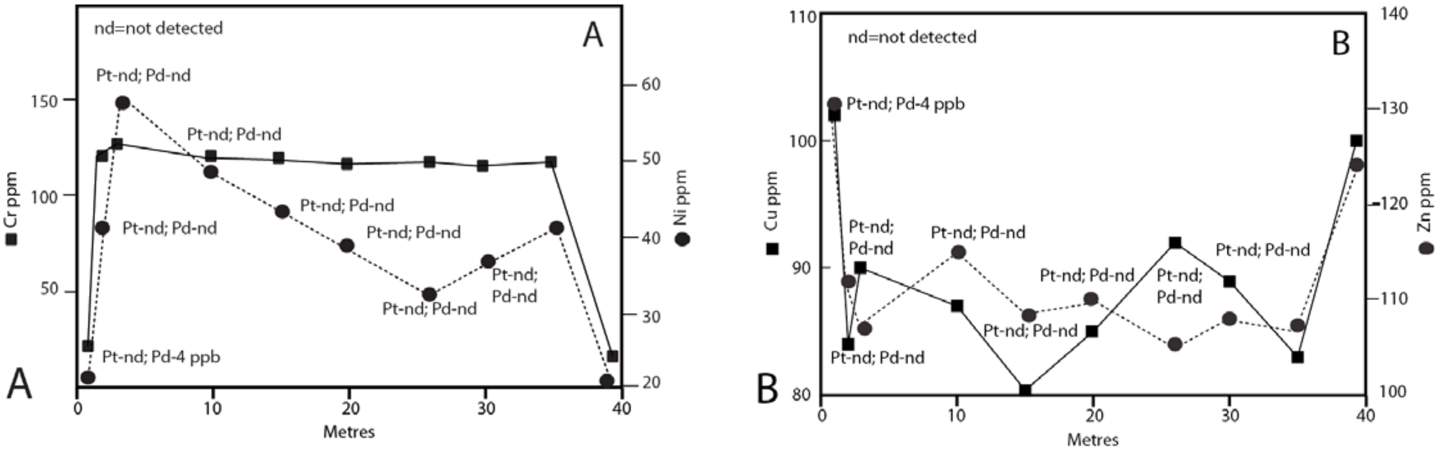


**Figure 12.** Selected trace element concentrations in the Joseph Creek dyke, Teepee Butte Member, Grande Ronde Basalt. Pt and Pd from this study, Cu, Zn, Ni and Cr from Reidel and Tolan (1992). A) Pt, Pd, Ni and Cr. B) Pt, Pd, Cu and Zn.

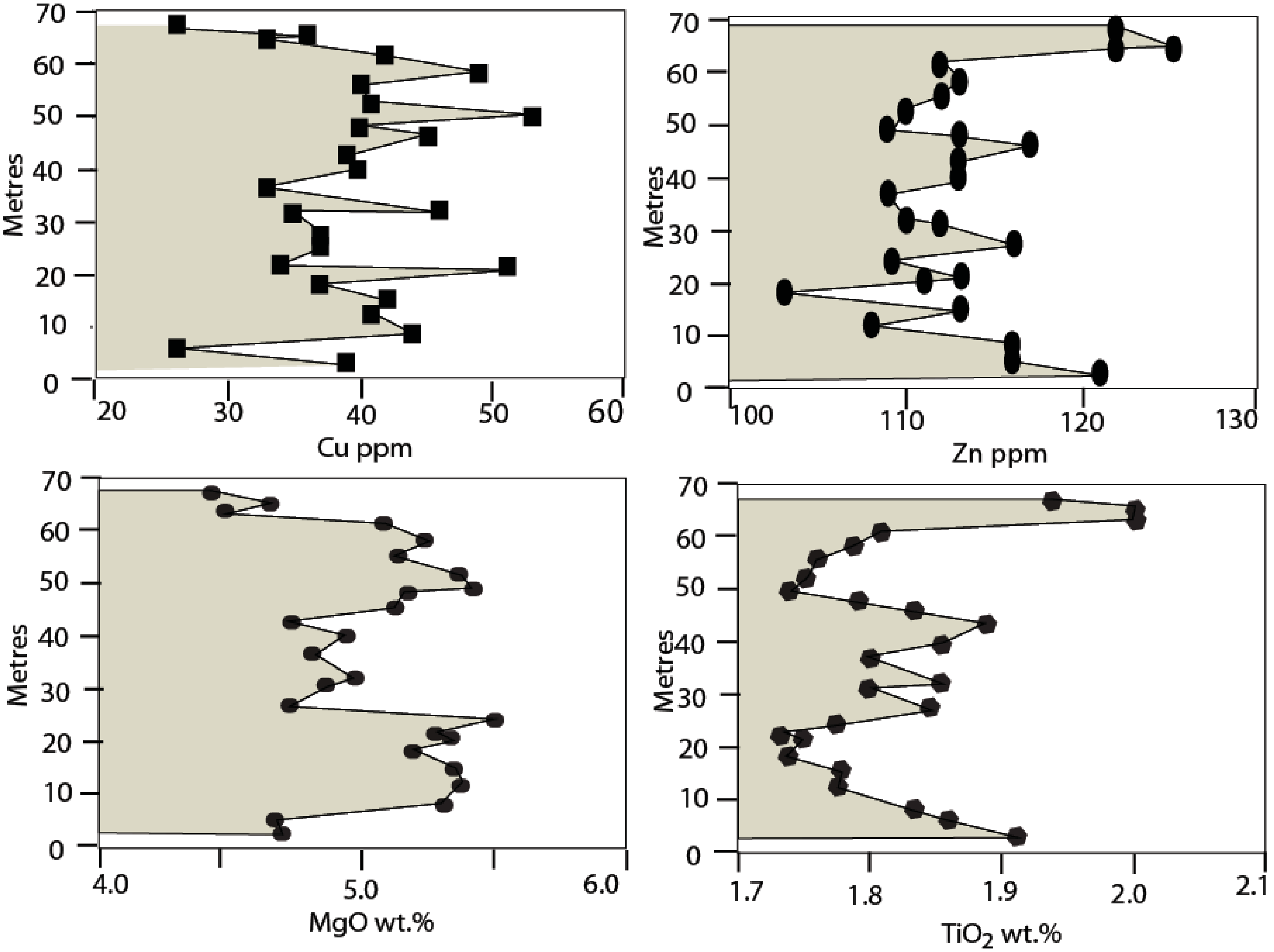


**Figure 13.** Concentration of Cu, Zn, MgO and $TiO_2$ with height from base of the Cohasset flow, Sentinel Bluffs Member, Grande Ronde Basalt. Data from Reidel (2005).

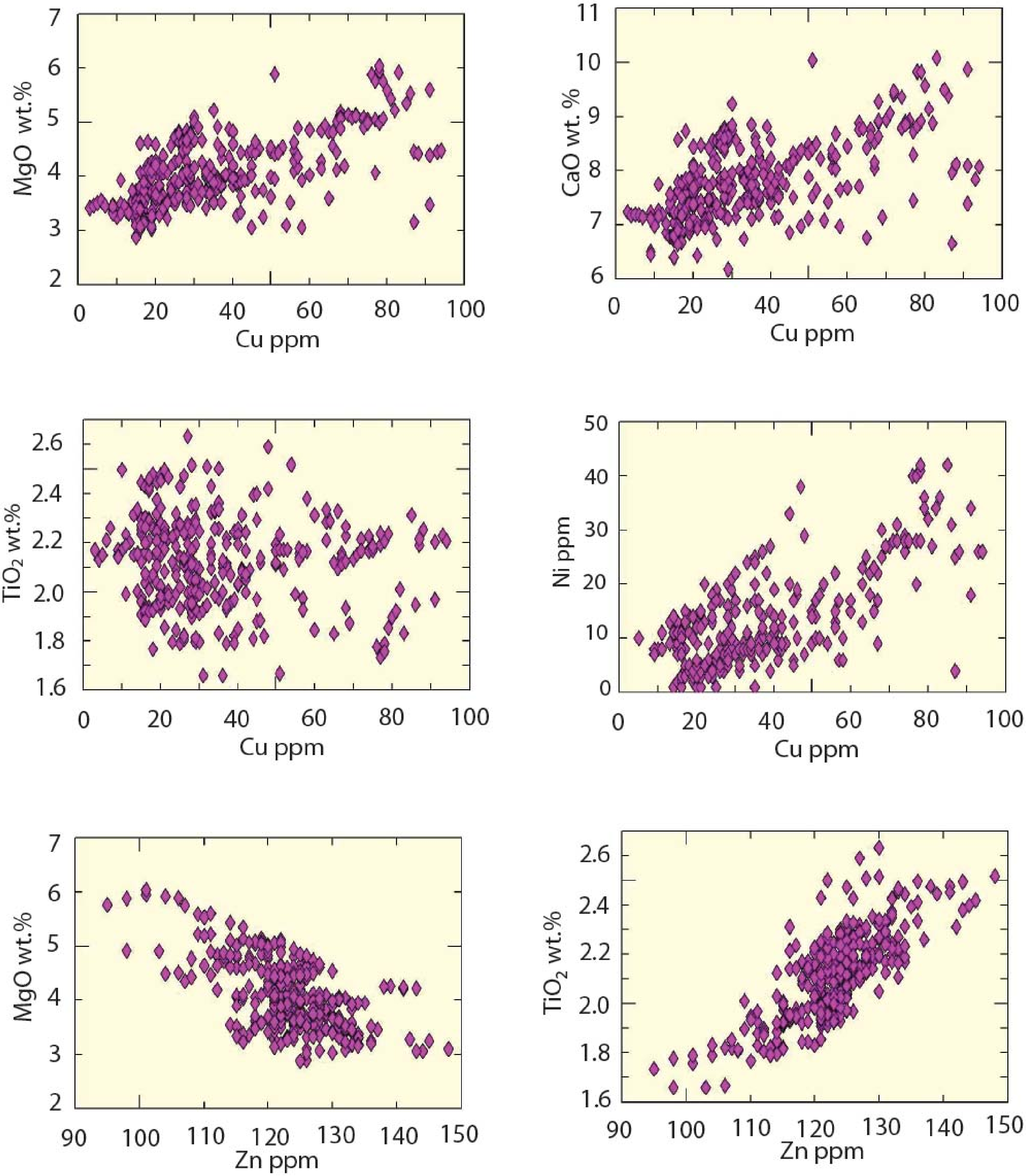


**Figure 14.** Variation diagrams for Cu vs. MgO, $TiO_2$, CaO and Ni, and Zn vs. MgO and $TiO_2$ for the Grande Ronde Basalt. Data from Reidel and Tolan (1992, 2013), Schuster (1993), Hooper and Hawkesworth (1993), Hooper (2000), Reidel (2005) and S. Reidel unpublished data.

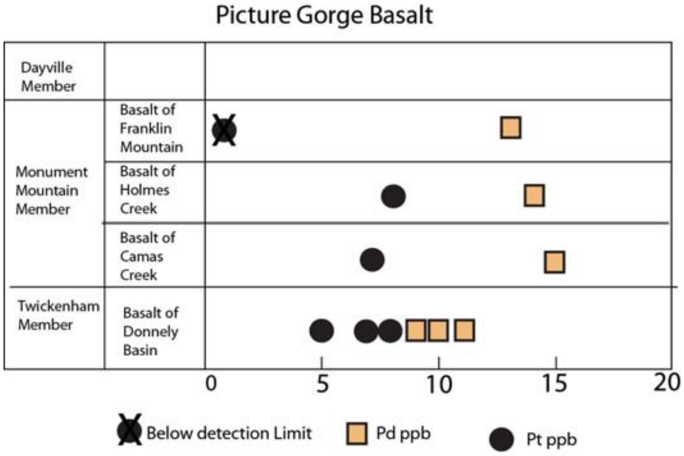


**Figure 15.** Pt and Pd abundance in Picture Gorge Basalt. Stratigraphic nomenclature based on Bailey (1989). Data from this study (Table 2).

Although Zn has a restricted range compared to Cu, there is a positive correlation between the two (Fig. 6). Furthermore, Zn content, although somewhat scattered, and Cu show no trend with younger flows (Fig. 16). Cu and Zn have a poor inverse correlation with MgO and CaO (not shown) while Zn also is positively correlated with $TiO_2$ (Fig. 7) and FeO. In the Picture Gorge Basalt Cu and Ni (Fig. 8) are not correlated whereas Ni and Cr are positively correlated (Fig. 9).

### *Wanapum Basalt and Saddle Mountains Basalt*

We collected one sample each from the upper two formations but Pt and Pd were below detection limits. These formations contain low chalcophile element concentrations compared to the other formations (Fig. 6). We did not concentrate on these two formations because they are not part of the main phase and represent the declining magma. The Wanapum Basalt represents only 5.8% of the Columbia River Basalt Group and the Saddle Mountains Basalt only ~1%.

For both the Wanapum and Saddle Mountains Basalts, Cu and Zn have very restricted ranges (Fig. 6) except for the youngest flow of the Wanapum Basalt, the Basalt of Lolo. Cu shows no correlation with any other oxide or element but when considering only the Frenchman Springs and Roza Members, Cu and Ni (Figs. 8 and 17) are positively correlated.

For the Wanapum Basalt, Zn is correlated with $TiO_2$ FeO (Fig. 7) $P_2O_5$, Zr and Y and negatively correlated with $Al_2O_5$, MgO, CaO and Cr. The Saddle Mountains Basalt Cu is not correlated with any oxide or element except for the Umatilla Member which has a negative correlation with Ba and a positive correlation with both V and Zr. The Umatilla Member is the most contaminated basalt of all the CRBG (Reidel 1998). Ni and Cr are positively correlated (Fig. 9) in both the Wanapum Basalt and Saddle Mountains Basalt whereas in the Wanapum Basalt Cu and Ni (Fig. 8) are positively correlated yet not in the Saddle Mountains Basalt.

## DISCUSSION

Naldrett (2011, 2012) described seven steps deemed necessary to form a magmatic sulphide deposit. These included: 1) Birth of the source, i.e. the generation of a mafic magma due to mantle melting; 2) Development of the source by assent of the magma through the mantle and into the crust; 3) Fertilization of the source by contamination of the magma with the crust and development of immiscible sulphides; 4) Delivery by farther ascent into crust; 5) Growth or concentration of the sulphides; 6) Nourishment or enrichment due to additional interaction with a continuing supply of magma; and 7) Full maturity. Furthermore, understanding the effect of composition, temperature, and pressure on sulphide solubility in a silicate melt, partial melting and partitioning of the chalcophile and PGEs between magma, silicates and liquid sulphides and the phase equilibria are equally important.

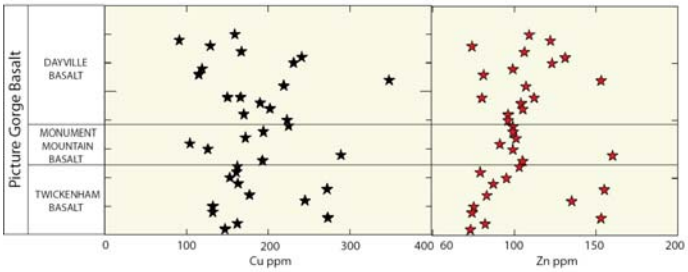


**Figure 16.** Cu and Zn in the Picture Gorge Basalt. Stratigraphic nomenclature and data based on Bailey (1989), Hooper and Hawkesworth (1993) and Wolff et al. (2008 Appendix).

The Columbia River Basalt Group qualifies in the first four stages. It is a LIP that produced large volume lava flows in a short period of time. A general agreement is that the main phase of magmatism (Steens, Imnaha, Grande Ronde, and Picture Gorge Basalts) is derived from a mantle plume that underwent some degree of fractionation and crustal contamination (e.g. Reidel 1983; Hooper and Hawkesworth 1993; Camp and Hanan 2008; Hooper et al. 2007; Camp 2013). Crustal contamination has been suggested to be minor in the Lower Steens, Imnaha and Picture Gorge Basalts but could reach 20% or greater in the Upper Steens Basalt and Grande Ronde Basalt (e.g. Hooper and Hawkesworth 1993; Camp and Hanan 2008). Thus, the Columbia River Basalt Group should be an excellent candidate to contain PGEs.

Our study shows that the Columbia River Basalt Group contains measurable PGEs. The oldest members, the Lower Steens, Imnaha and Picture Gorge Basalts, all contain Pt and Pd in abundances similar to that of the mantle (6.6 Pt, 3.27 Pd, Palme and O'Neill 2005; 7.1 Pt, 3.9 Pd, McDonough and Sun 1995). The two principal collectors of PGEs in a basaltic magma are sulphides and chromite (Mungall 2005). Chromite has not been recognized in any Columbia River Basalt Group flow but Cr, Ni and MgO (Fig. 9) are positively correlated in all the CRBG formations suggesting that Cr and Ni are compatible with olivine and pyroxene. However, immiscible sulphides and sulphide minerals have been recognized in the Steens Basalt, Imnaha Basalt and the oldest Grande Ronde Basalt flows (e.g. Reidel 1978; Korzendorfer 1979; Wierman 2018).

The Cu abundance decreases with younger CRBG flows. Cu is most abundant in the earliest part of the main phase (Steens, Imnaha, Picture Gorge and oldest Grande Ronde

Basalts) thus correlating with PGE abundance in the flows. Except for the small volume Eckler Mountain Member, Wanapum Basalt (Fig. 6), Cu decreases through the Wanapum Basalt and Saddle Mountains Basalt. Thus, higher Cu concentrations also suggest that some PGEs are controlled by sulphides and Cu contents maybe an excellent prospecting tool in the Columbia River Basalt Group.

## Fertility, Crustal Contamination and Sulphur Saturation

The two major factors to consider in determining the Cu–PGE prospectively of a set of igneous rocks are: fertility and S saturation of the host (Jowitt and Ernst 2013; Jowitt et al. 2014). Fertility is depletion or enrichment of PGEs and chalcophile elements. Because Cu will act as an incompatible element in S-undersaturated silicate melts, a ratio of Cu and a similar incompatible element as is Zr, can reflect the effects of silicate fractionation or accumulation in the magma. Thus, following Jowitt and Ernst (2013), we plot the abundance of chalcophile elements in the CRBG relative to MgO (Fig. 17). The Cu/Zr ratio, relative to the primitive mantle (PM), reflects the sulphide budget of the magma; that is, sulphide accumulation or segregation. In general, all formations are greatly depleted in Cu except for the Lower Steens Basalt and Picture Gorge Basalt. The most depleted are the Grande Ronde, Wanapum and Saddle Mountains Basalts, the last formations to be emplaced. This suggests that chalcophile elements and PGEs have been depleted from the magma prior to their eruptions.

A thinned and metasomatized craton edge has been suggested as a necessary requirement for PGE deposits because magmas cannot melt a thick lithosphere (Kerrich et al. 2005; Begg et al. 2010; Ernst 2014). Melting of the craton and transport of magma through it can be an important source of sulphur, sulphide concentration and segregation of PGEs (Naldrett 1997; Ernst 2014). Geophysical studies indicate the lithosphere is only about 40–50 km thick under the Columbia River flood basalt province (e.g. Catchings and Mooney 1988). The Columbia River Basalt Group magma ponded along the craton-accreted terrane boundary (Fig. 1; 0.704 and 0.706 Sr-isopleth lines; Armstrong et al. 1977; Camp et al. 2003; Camp and Ross 2004; Pierce and Morgan 2009; Camp 2013) and thus, many of the dykes for Columbia River Basalt Group flows passed through craton and oceanic accreted terrane rocks. The Picture Gorge Basalt and Prineville Basalt, however, erupted only in oceanic accreted terrane rocks west of the craton-accreted terrane boundary.

Tectonic studies support an interaction between the plume and crust; studies have shown that the Columbia Basin was subsiding at the same rate that the basalts were erupting (Reidel et al. 1989b, 2013c). The greatest rate of subsidence occurred during the main phase of the CRBG and declined as the rate and volume of eruptions declined. Furthermore, a series of grabens (e.g. Lewiston Basin) developed along the craton-accreted terrane boundary and their rate of development also matched the rate of basalt eruptions suggesting crustal magma storage. Delamination and subsiding of the crust into the plume, as suggested by Camp and Hanan (2008), provides a viable mechanism for the magma to assimilate crust and acquire sulphur.

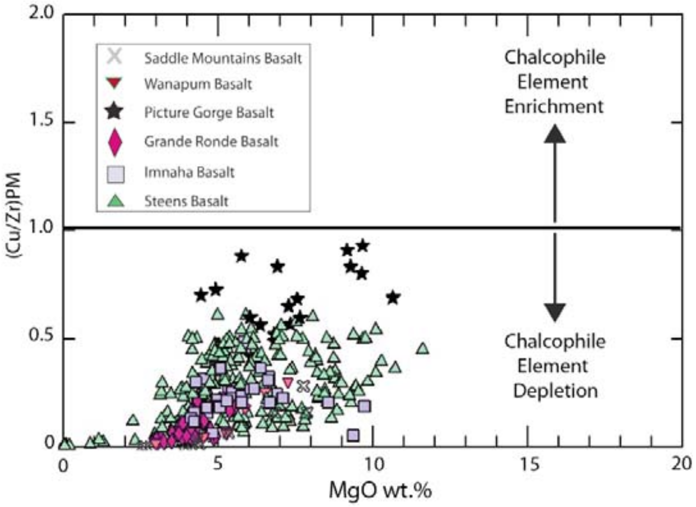


**Figure 17.** Diagram showing (Cu/Zr)PM and MgO. The ratios are normalized to primitive mantle values (PM) of McDonough and Sun (1995) and Jowitt et al. (2014). This figure shows the abundance of chalcophile elements in the CRBG. The Cu/Zr(PM) reflects the sulphide budget of the magma and suggests that all formations are greatly depleted in Cu with the Steens Basalt and Picture Gorge Basalt being the least depleted. The most depleted are the Grande Ronde Basalt, Wanapum Basalt and Saddle Mountains Basalt, the last formations to be emplaced.

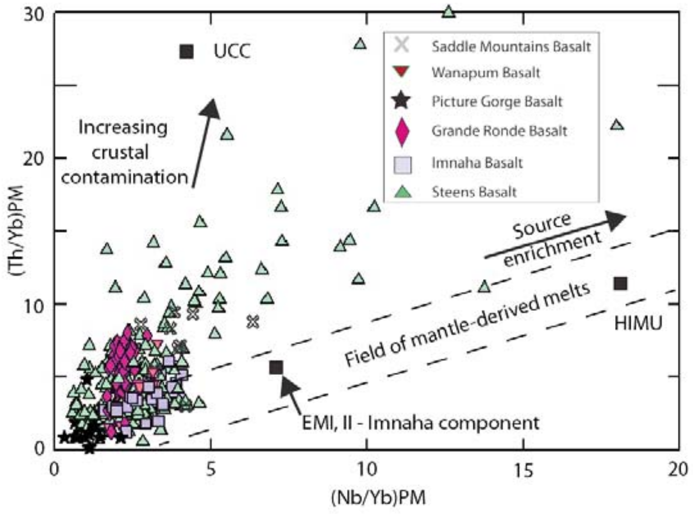


**Figure 18.** Diagram showing variation in (Nb/Yb)PM and (Th/Yb)PM. The ratios are normalized to primitive mantle values (PM) of McDonough and Sun (1995) following Jowitt and Ernst (2013) and Jowitt et al. (2014). N-MORB is from Hofmann (1988); Upper Continental Crust (UCC) composition is from Taylor and McLennan (1985) and Enriched Mantle (EMI, EMII –the Imnaha component of Hooper and Hawkesworth 1993) and HIMU values concentrations from Condie (2001). This diagram assesses the probability of the Columbia River Basalt Group magmas assimilating significant amounts of crustal material prior to emplacement. Note that the Grande Ronde, Upper Steens, Wanapum and Saddle Mountains Basalts show evidence of crustal contamination. Picture Gorge, Imnaha, and Lower Steens Basalts indicate little crustal contamination as has been shown by Hooper and Hawkesworth (1993), and Camp and Hanan (2008).

Lithospheric contamination can account for as much as ~20% of the Grande Ronde Basalt (e.g. Hooper and Hawkesworth 1993; Camp and Hanan 2008). Figure 18 shows variations in (Nb/Yb)PM and (Th/Yb)PM for the CRBG following Pearce (2008), Jowitt and Ernst (2013) and Jowitt et al. (2014). The effects of crustal contamination and variations in mantle source regions on the basalts are shown. The Lower Steens, Imnaha and Picture Gorge Basalts plot close to, or within the field of mantle derived melts (EMII, Imnaha component) supporting previous work (e.g. Hooper and Hawkesworth 1993; Camp and Hanan 2008). The Upper Steens, Wanapum, Saddle Mountains and most of the Grande Ronde Basalt show evidence of increasing contamination, again supporting previous work.

The difference in abundance between PGEs and chalcophile elements in the Lower Steens to Upper Steens, and from Imnaha Basalt to near absence in the Grande Ronde Basalt may be due to sulphur availability. The Upper Steens Basalt and Grande Ronde Basalt assimilated a substantial amount of cratonic material while the Lower Steens Basalt and Imnaha Basalt did not. This may have allowed the depletion of PGEs and chalcophile elements as they encountered sulphur from the cratonic crust. The inclusion of PGEs in the co-erupting Picture Gorge Basalt may be due to the lack of sulphur in the oceanic accreted-terrane rocks that basalt passed through. Thus, assimilation of cratonic material may have been an important factor in depleting PGEs and chalcophile elements from the basalt.

In order to evaluate whether the CRBG magma assimilated significant amounts of crustal material prior to eruption, we employed the Jowitt and Ernst (2013) and Jowitt et al. (2014) (Nb/Th)PM ratio vs. (Th/Tb)PM diagram (Fig. 19). These ratios correlate with the amount of crustal material assimilated. Low (Nb/Th)PM values and high (Th/Yb)PM values are consistent with assimilation of crustal material (Jowitt and Ernst 2013). High (Nb/Th)PM and low (Th/Yb)PM are more consistent with mantle compositions (Lightfoot and Hawkesworth 1988; Lightfoot et al. 1990; Jowitt and Ernst 2013; Jowitt et al. 2014). CRBG samples trend between an average mantle composition (N-MORB, Hofmann 1988) with high (Nb/Th)PM and low (Th/Yb)PM ratios and typical crustal contamination with low (Nb/Th)PM and high (Th/Yb)PM (Jowitt et al. 2014; Jowitt and Ernst 2013 and references therein). The Steens Basalt shows a consistent mixing line. The Lower Steens samples lie closer to primitive mantle and the Upper Steens show crustal contamination suggesting that the Steens Basalt became progressively contaminated with time as suggested by Camp and Hanan (2008) and Moore et al. (2020). The Imnaha Basalt corresponds more closely with N-MORB or OIB as Hooper and Hawkesworth (1993) have concluded. The Grande Ronde Basalt, Wanapum Basalt and Saddle Mountains Basalt all show varying degrees of crustal contamination.

Mavrogenes and O'Neill (1999) suggest that most basaltic magmas will never achieve S-saturation under near-surface conditions unless they have undergone at least 60% fractional crystallization. However, Jowitt and Ernst (2013) have suggested that for mantle partial melting, if, for example, the mantle originally contained 250 ppm sulphur, partial melting of 25% of the mantle will result in immiscible sulphide melts being assimilated by the basaltic magmas, and the basaltic magmas can assimilate up to 1000 ppm of sulphides (Mavrogenes and O'Neill 1999; Jowitt and Ernst 2013). Once the sulphides have been assimilated, where the chalcophile elements ends up depends only on their partitioning. As these elements, especially PGEs, are either incompatible or highly incompatible in S-undersaturated magmas (Keays 1995), rather than remaining in the depleted mantle, the chalcophile elements would preferentially partition into a S-undersaturated partial melt, thus producing fertile magmas. Magmas produced by less than 25% partial melting may, depending on the conditions of melting, leave residual sulphide and therefore chalcophile elements in the mantle.

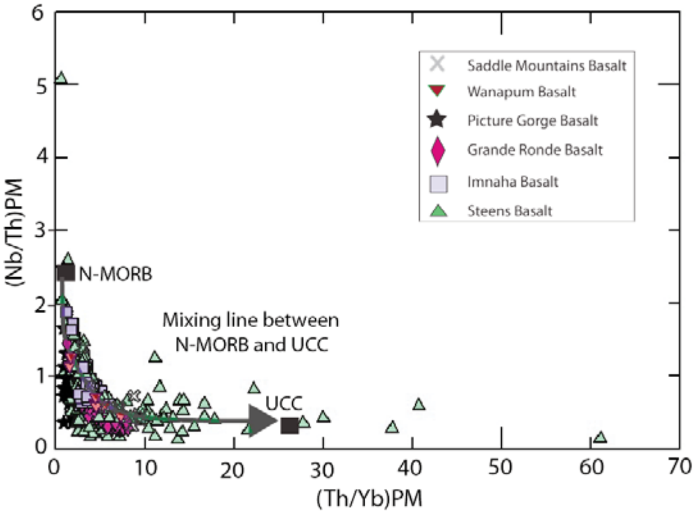


**Figure 19.** Diagram showing variations in (Nb/Th)PM and (Th/YB)PM ratios after Jowitt and Ernst (2013) and Jowitt et al. (2014). The ratios are normalized to primitive mantle values of McDonough and Sun (1995). This trend corresponds with mixing between primitive mantle (PM) compositions (N-MORB, Hofmann 1988) with high (Nb/Th)PM and low (Th/Yb)PM ratios and typical crustal contamination (UCC; Taylor and McLennan 1985) with low (Nb/Th)PM and high (Th/Yb)PM. The Steens Basalt shows a consistent mixing line. The Lower Steens samples lie close to primitive mantle and the Upper Steens show crustal contamination suggesting that the Steens Basalt became progressively contaminated with time as suggested by Camp and Hanan (2008). The Imnaha Basalt corresponds more closely with N-MORB or OIB as Hooper and Hawkesworth (1993) have concluded.

The role of sulphur saturation in the CRBG is difficult to access but several studies have measured sulphur in the CRBG lavas. Knowing the extent of partial melting is an important consideration. The CRBG has undergone various degrees of partial melting (e.g. Hooper and Hawkesworth 1993) but because of the highly evolved nature of the lavas, the amount of partial melting is difficult to determine. Blake et al. (2010) developed a numerical model for determining S-saturation in basalts and S release based on only total iron ($FeO_{total}$), assuming initial sulphide saturation of basaltic magmas. Davis et al. (2017) determined that some Wapshilla Ridge Member phenocrysts contained Fe-saturated-sulphide melt (pyrrhotite) on quenching. Figure 20 shows the S wt.% that could be contained in the main CRBG based on the model of Blake et al. (2010) and, again assuming that all magmas were S-saturated. On this we have plotted the measured S content for the Wapshilla Ridge and Meyer Ridge Members of the Grande Ronde Basalt from Davis et al. (2017) and for the Roza Member (Thordarson and Self 1996), the Ginkgo (Ho and Cashman

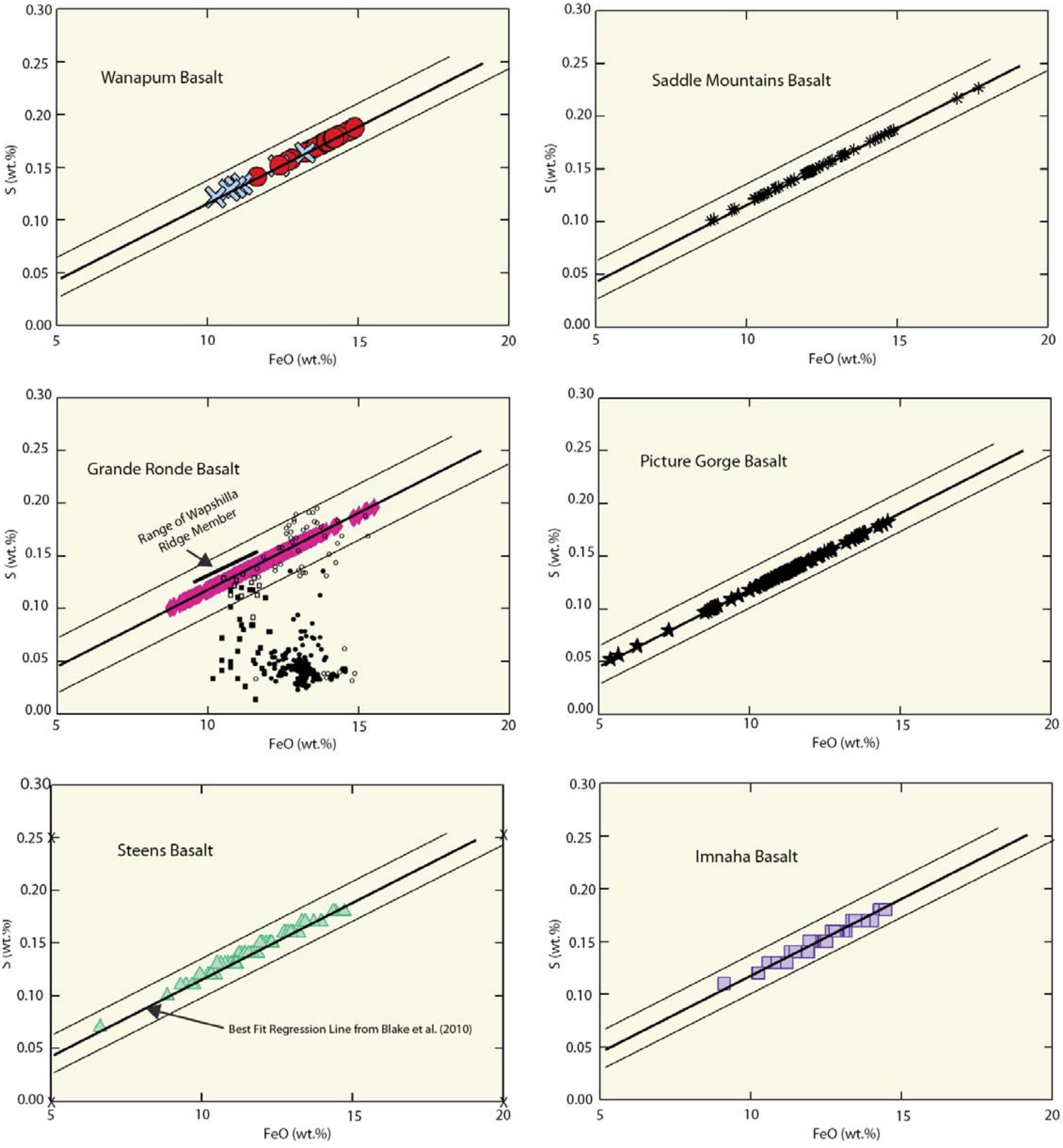


**Figure 20.** Diagram showing the potential sulphur saturation of the Columbia River Basalt Group (CRBG). Diagram is based on the Blake et al. (2010) numerical model for determining S-saturation in basalts and S release based on only total iron ($FeO_{total}$), assuming initial sulphide saturation of basaltic magmas. This diagram shows the Sulphur wt.% that could be contained in the main CRBG based on that model assuming that all magmas were S-saturated. Also plotted are the measured S content for the Wapshilla Ridge and Meyer Ridge Members of the Grande Ronde Basalt (Davis et al. 2017), the Roza Member (Thordarson and Self 1996), the Ginkgo (Ho and Kashman 1997), Sand Hollow and Sentinel Gap flows, Frenchman Springs Member, Wanapum Basalt (Blake et al. 2010; Martin et al. 2013). The lines are the best-fit regression line and error lines of +1 sigma.

1997), Sand Hollow and Sentinel Gap flows (Blake et al. 2010) of the Wanapum Basalt. These data suggest that at least some of the Grande Ronde Basalt and the Wanapum Basalt were S-saturated. The presence of immiscible sulphides in the Lower Steens suggest that they were S-saturated. Unfortunately, we do not have data for the other formations so we cannot assess their S-saturation.

PGEs partition more readily into sulphides than do Cu and Ni (Peach et al. 1990); this suggests that any PGEs present in the S-saturated Grande Ronde Basalt and Wanapum Basalt flows should be in sulphides. The main sulphide in the Wapshilla Ridge and Meyer Ridge flows is pyrrhotite (Davis et al. 2017) although chalcopyrite is present in the oldest GRB flows. Pt in standard BCR-1 probably resides in sulphur melt inclusions that were identified by Davis et al. (2017).

## A Model for PGEs and Chalcophile Elements in the CRBG

Nearly all world-wide PGE-chalcophile deposits occur in intrusives and not in surface lavas (e.g. Mungall 2005). Most North America PGE localities occur in basaltic dykes and intrusives of Precambrian age (Ernst and Hubbart 2003) but there are localities where PGE and chalcophile elements occur in lava flows. For example, the East Greenland Igneous Province (Momme et al. 2002), the Kerguelen Plateau (Chazey and Neal 2005) and the Deccan (Andreasen et al. 2002). Unfortunately, these studies do not provide good models for PGEs in lava flows. They do, however, share similarities with the CRBG lavas. For example, the PGEs occur mainly in more primitive high-MgO lavas and, like the CRBG, are sparce to absent in low-MgO flows like those observed in the CRBG.

The Keweenaw basalts near Lake Superior are famous for native Cu deposits in the flow-top breccias of lavas, but they also contain Cu sulphide deposits. Steens Basalt plagioclase phenocrysts also contains native Cu (Oregon Sunstones) whereas the Keweenaw deposits are not derived from a magmatic plume but are probably either due to metamorphism or meteoric waters (Brown 2006). Pavlov et al. (2019) concluded that, like the CRBG, the Siberian Traps were emplaced rapidly and Latyshev et al. (2020) showed that all main ore-bearing intrusions of the Noril'sk Complex, as well as weakly mineralized and barren intrusions, are coeval with the Morongovsky–Mokulaevsky level of the volcanic sequence. However, models for the Noril'sk deposits range from magmas that fed the deposits also feeding lava flows (e.g. Naldrett 1997; Naldrett et al. 1992) to those not being related to the lava flows (Czamanske et al. 1994, 1995; Latypov 2002). Our study conclusively shows that the PGEs in the CRBG are magmatic and their abundance in the lavas are directly controlled by petrogenetic processes.

The volcanic, tectonic, and petrologic history of the CRBG form the basis for understanding the occurrence of PGEs and chalcophile elements in the flows. We use that knowledge here to provide a model of how the PGEs and chalcophile elements fit into the evolution of the CRBG LIP.

The Lower Steens Basalt marks the beginning of the Columbia River Basalt volcanic episode with the initial eruptions occurring as the plume encountered the lithosphere. The Lower Steens Basalt contains PGEs and Cu and Zn but the younger Upper Steens Basalt does not. Sulphides have been recognized in the Steens Basalt (Wierman 2018) suggesting S-saturation. There is no correlation between Cu and/or any other oxide or trace element suggesting that Cu, like the PGEs, probably occurs in microscopic sulphides or as immiscible sulphides. Wierman (2018) found that magnetite followed by pyroxene and olivine contain the most Cu other than that in sulphides and Oregon Sunstones. Zn is positively correlated with $TiO_2$ and FeO but not with MgO or CaO suggesting that Zn appears to occur predominantly in ilmenite and titanomagnetite. Ni and Cr are positively correlated with MgO but not Cu or Zn suggesting only minor amounts of Cu and Zn are in pyroxenes and olivine as Wierman (2018) found. The contaminated Upper Steens Basalt appears depleted in PGEs and Cu. This suggests that the first Steens Basalt eruptions were fertile with PGEs and chalcophile elements but as the eruptions continued the plume began to assimilate crustal material containing sulphur depleting PGEs and chalcophile elements from the magma prior to eruption.

The Imnaha Basalt episode marks the beginning of the northward spread of the plume head. Camp (2013) argued that previously the plume had encountered the subducting Juan de Fuca Plate but by Imnaha Basalt time, the plume broke through the subducting plate and had little interaction with the crust. As the plume head progressed northward, the magma was recharged and replenished with PGEs and chalcophile elements. The presence of sulphides in the Imnaha Basalt suggests that at least some of the Imnaha Basalt flows were S-saturated upon eruption and its magma was fertile with PGEs and chalcophile elements. Sulphides are distributed throughout the Rock Creek flow suggesting that S-saturation had been achieved. Because PGEs are more readily partitioned into sulphides than Cu and Zn (Peach et al. 1990), these sulphides probably contain the PGEs we detected. Zn, however, correlates with FeO and $TiO_2$ and, thus, $Zn^{+2}$ is probably substituting for $Fe^{+2}$ mainly in titanomagnetite and ilmenite. Ni, while a common element in many Ni–Cu-sulphide deposits in layered igneous intrusions, is a minor component in Columbia River Basalt Group sulphides. Korzendorfer (1979) measured only 0–1.3% Ni in chalcopyrite in the Imnaha Basalt. Ni and Cr are correlated with MgO suggesting they were incorporated in olivine and pyroxene.

Following the Imnaha Basalt eruptions, the plume continued to be recharged and replenished with PGEs and chalcophile elements as the plume head advanced northward and the most voluminous Grande Ronde Basalt began erupting. The lavas were largely depleted in PGEs and chalcophile elements relative to the earliest formations, yet the many flows reached S-saturation precipitating pyrrhotite rather than Cu sulphides. Depletion probably occurred as the magma assimilated crustal and lithospheric material progressively contaminating it. Camp and Hanan (2008) propose delamination and assimilation as a viable scenario for this process.

Chalcophile elements are more abundant at the distal end of the earliest GRB flows but became depleted in the proximal near dyke/vent end. In addition, some of the youngest flows contain the highest concentration of Cr and Ni but they occur in olivine and pyroxene. The early GRB Teepee Butte Member dyke contains Pd but only in the evolved selvage zone which is the first erupted basalt. However, in the main part of the dyke, PGEs are below our detection limits and Cu and Zn are depleted compared to the selvage zones. USGS Standard BCR-1 did contain some PGEs but was generally depleted in chalcophile elements as is the majority of the Grande Ronde Basalt. This suggests that the magma chamber became a repository for PGEs and chalcophile elements.

The low Cu and Zn concentrations in the voluminous Grande Ronde Basalt appear to be controlled mainly by silicate and oxide mineral phases (e.g. pyroxene, ilmenite) or mesostasis. The correlation of Cu and Ni with MgO and CaO (Fig. 12) suggests what little Cu present may be incorporated in pyroxene and olivine. Wager and Brown (1967, p. 180, fig. 122) recognized Cu in pyroxene and olivine from the Skaergaard intrusion as did Wierman (2018) in the Lower Steens Basalt. Zn correlates with FeO and $TiO_2$ in Grande Ronde Basalt (Fig. 7) which is probably due to $Zn^{+2}$ substituting for $Fe^{+2}$ mainly in titanomagnetite and ilmenite. In the Grande Ronde Basalt, Zn inversely correlates with MgO and CaO suggesting that there may be some substitution for Fe in pyroxenes or olivine but is mainly in ilmenite and titanomagnetite.

The Picture Gorge Basalt erupted through Mesozoic accreted terranes west of the Chief Joseph dyke swarm and Cahoon et al. (2020) suggested it may encompass the entire CRBG episode up to nearly the end of the Grande Ronde Basalt (Fig. 2). Camp and Ross (2004) suggested that the Picture Gorge Basalt is a separate lobe of the main plume head. The Picture Gorge Basalt has PGEs like that of the Imnaha Basalt and significantly greater than the coeval Grande Ronde Basalt. However, some flows are more enriched in chalcophile elements (Fig. 17) than either the Steens Basalt or Imnaha Basalt. In the Picture Gorge Basalt, Cu correlates with Zn (Fig. 6) but with no other oxide or element. This could imply that Cu and PGEs may be in sulphides; however, the most detailed study of the Picture Gorge Basalt by Bailey (1989) did not report any sulphides. Zn correlates with the high-field strength elements $TiO_2$, FeO, $P_2O_5$, V and Y but has no correlation with any other oxide or element. We suggest that Zn, like in other CRBG formations is mainly incorporated in ilmenite and titanomagnetite and possibly pyroxene. We suspect that the Picture Gorge Basalt may not have been S-saturated because the Picture Gorge Basalt, unlike the Imnaha Basalt and Steens Basalt did not get emplaced in the a cratonic crust but in accreted oceanic crust and has not undergone significant crustal contamination (Fig. 18). It probably lacked sufficient S to allow saturation and thus, the PGEs and chalcophile elements were partitioned to the silicate melt.

The eruption of the PGB in the Monument dyke swarm west of the Chief Joseph dyke swarm probably represents a separate lobe of the advancing plume as Camp and Ross (2004) have suggested. While the Chief Joseph dyke swarm was erupting Grande Ronde Basalt lavas depleted in PGEs and chalcophile elements, the Picture Gorge Basalt was erupting undepleted flows at the same time. As Camp and Ross (2004) have suggested, the two magma chambers were separate lobes. This allows us to reject the model of Wolff et al. (2008) where they proposed that a centralized magma chamber located under the Oregon Plateau fed all the CRBG. It is clearly difficult for a centralized magma chamber to have fed depleted Grande Ronde Basalt while simultaneously feeding the undepleted Picture Gorge Basalt.

Wanapum Basalt and Saddle Mountains Basalt represent the waning stages of the CRBG magmatism. By this point the Yellowstone plume had been sheared off by the southwestward movement of the North American Plate and only residual magma from the plume head remained (Camp and Ross 2004). PGEs have been depleted and Cu is minor in the residual magma, but Zn has concentrations similar to other CRBG formations. Cu, Zn and Ni behave independently in the Frenchman Springs and Roza Members and the Wanapum Basalt, and show no correlation with other elements. Copper is independent in the Saddle Mountains Basalt and is not correlated with any oxide or element; Zn, however, is correlated with FeO, $TiO_2$, $P_2O_5$, Zr, Y and Nb suggesting that it probably is incorporated in ilmenite and titanomagnetite as well.

## CONCLUSIONS

The plume that produced the Columbia River Basalt Group was fertile with PGEs and chalcophile elements. The magma was erupted along the thinned edge of the craton where it was juxtaposed to both cratonic rocks and oceanic accreted terranes. The earliest formations, Lower Steens, Imnaha and Picture Gorge, contain the greatest amounts of PGEs and chalcophile elements. The correlation of PGEs with chalcophile elements in the Imnaha Basalt indicates PGEs are contained within sulphides. Sulphur was readily available from both the initial magma and assimilation of cratonic rock. The eruption of the Picture Gorge Basalt through accreted oceanic crust indicates that PGEs may not occur in sulphides because of the lack of abundant sulphur in the accreted oceanic crust. This is further supported by the absence of sulphide minerals or immiscible sulphides in the study by Bailey (1989).

The general absence of PGEs and depleted chalcophile elements in the voluminous, contaminated and evolved Grande Ronde Basalt flows and evolved Upper Steens Basalt indicate that the magma assimilated sufficient crustal material containing sulphur and the PGEs were depleted from the magma before eruption. The chalcophile elements Cu and Zn were present in the earliest erupted GRB lava probably as immiscible sulphides. Much lower concentrations of Cu and Zn in the GRB flows probably were incorporated into basaltic minerals – Cu in pyroxene and Zn in ilmenite and titanomagnetite with some minor substitution for $Fe^{+2}$ in pyroxenes. The final eruptions of the CRBG, the Wanapum Basalt and Saddle Mountains Basalt were erupted from a magma that already had been depleted of PGEs and chalcophile elements.

## ACKNOWLEDGEMENTS

We thank Marty Ross and Michael Zientek for reviewing an earlier draft of this manuscript. Brent Barnett's son helped collect samples. We especially thank John Greenough and Richard Ernst for valuable reviews that greatly improved the manuscript. We thank Simon Jowitt for explaining and clarifying many of the important aspects of PGEs in LIPS. Finally, we thank Don Schissel for inspiring us to take on this study.

## REFERENCES

Andreasen, R., Sharma, M., Horan, P., Burgmann, G., and Subbarao, K.V., 2002, Evolution of Deccan Lavas: Insights from Re–Os isotopes and Platinum Group Elements (Abstract): American Geophysical Union, Fall Meeting 2002, San Francisco, CA, V52C-1296.

Armstrong, R.L., Taubeneck, W.H., and Hales, P.O., 1977, Rb–Sr and K–Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition: Oregon, Washington, and Idaho: Geological Society of America Bulletin, v. 88, p. 397–411, https://doi.org/10.1130/0016-7606(1977)88<397:RAKGOM>2.0.CO;2.

Bailey, M.M., 1989, Revisions to stratigraphic nomenclature of the Picture Gorge Basalt Subgroup, Columbia River Basalt Group, *in* Reidel, S.P., and Hooper, P.R., *eds.*, Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper, v. 239, p. 67–84, https://doi.org/10.1130/SPE239-p67.

Baker, L.L., Camp, V.E., Reidel, S.P., Martin, B.S., Ross, M.E., and Tolan, T.L., 2019, Alteration, mass analysis, and magmatic compositions of the Sentinel Bluffs Member, Columbia River flood basalt province: COMMENT: Geosphere, v. 15, p. 1436–1437, https://doi.org/10.1130/GES02047.1.

Barry, T.L., Self, S., Kelley, S.P., Reidel, S.P., Hooper, P.R., and Widdowson, M., 2010, New $^{40}$Ar/$^{39}$Ar dating of the Grande Ronde lavas, Columbia River Basalts, USA: Implications for duration of flood basalt eruption episodes: Lithos, v. 118, p. 213–222, https://doi.org/10.1016/j.lithos.2010.03.014.

Barry, T.L., Kelley, S.P., Reidel, S.P., Camp, V.E., Self, S., Jarboe, N.A., Duncan, R.A., and Renne, P.R., 2013, Eruption chronology of the Columbia River Basalt Group, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Paper, v. 497, p. 45–66, https://doi.org/10.1130/2013.2497(02).

Beeson, M.H., Fecht, K.R., Reidel, S.P., and Tolan, T.L., 1985, Correlations within the Frenchman Springs Member of the Columbia River Basalt Group: New insights into the middle Miocene tectonics of northwest Oregon: Oregon Geology, v. 47, p. 87–96.

Begg, G.C., Hronsky, J.A.M., Arndt, N.T., Griffin, W.L., O'Reilly, S.Y., and Hayward, N., 2010, Lithospheric, cratonic and geodynamic setting of Ni–Cu–PGE sulfide deposits: Economic Geology, v. 105, p. 1057–1070, https://doi.org/10.2113/econgeo.105.6.1057.

Bevier, M.L., 1983, Regional stratigraphy and age of Chilcotin Group basalts, south-central British Columbia: Canadian Journal of Earth Sciences, v. 20, p. 515–524, https://doi.org/10.1139/e83-049.

Blake, S., Self, S., Sharma, K., and Sephton, S., 2010, Sulfur release from the Columbia River Basalts and other flood lava eruptions constrained by a model of sulfide saturation: Earth and Planetary Science Letters, v. 299, p. 328–338, https://doi.org/10.1016/j.epsl.2010.09.013.

Brandon, A.D., and Goles, G.G., 1988, A Miocene subcontinental plume in the Pacific Northwest: geochemical evidence: Earth and Planetary Science Letters, v. 88, p. 273–283, https://doi.org/10.1016/0012-821X(88)90084-2.

Brandon, A.D., and Goles, G.G., 1995, Assessing subcontinental lithospheric mantle sources for basalts: Neogene volcanism in the Pacific Northwest, USA as a test case: Contributions to Mineralogy and Petrology, v. 121, p. 364–379, https://doi.org/10.1007/s004100050102.

Brown, A.C, 2006, Genesis of native copper lodes in the Keweenaw District, northern Michigan: A hybrid evolved meteoric and metamophogenic model: Economic Geology, v. 101, p. 1437–1444, https://doi.org/10.2113/ gsecongeo.101.7.1437.

Cahoon, E.B., Streck, M.J., Koppers, A.A.P., and Miggins, D.P., 2020, Reshuffling the Columbia River Basalt chronology—Picture Gorge Basalt, the earliest- and longest-erupting formation: Geology, v. 48, p. 348–352, https://doi.org/10.1130/G47122.1.

Camp, V.E., 1995, Mid-Miocene propagation of the Yellowstone mantle plume head beneath the Columbia River basalt source region: Geology, v. 23, p. 435–438, https://doi.org/10.1130/0091-7613(1995)023<0435:MMPOTY>2.3.CO;2.

Camp, V.E., 2013, Origin of Columbia River Basalt: Passive rise of shallow mantle, or active upwelling of a deep-mantle plume?, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Paper, v. 497, p. 181–199, https://doi.org/10.1130/2013.2497(07).

Camp, V.E., and Hanan, B.B., 2008, A plume-triggered delamination origin for the Columbia River Basalt Group: Geosphere, v. 4, p. 480–495, https://doi.org/10.1130/GES00175.1.

Camp, V.E., and Ross, M.E., 2004, Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest: Journal of Geophysical Research, v. 109, B08204, https://doi.org/10.1029/2003JB002838.

Camp, V.E., Ross, M.E., and Hanson, W.E., 2003, Genesis of flood basalts and Basin and Range volcanic rocks from Steens Mountain to the Malheur River Gorge, Oregon: Geological Society of America Bulletin, v. 115, p. 105–128, https://doi.org/10.1130/0016-7606(2003)115<0105:GOFBAB>2.0.CO;2.

Camp, V.E., Ross, M.E., Duncan, R.A., Jarboe, N.A., Coe, R.S., Hanan, B.B., and Johnson, J.A., 2013, The Steens Basalt: Earliest lavas of the Columbia River Basalt Group, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Paper, v. 497, p. 87–116, https://doi.org/10.1130/2013.2497(04).

Caprarelli, G., and Reidel, S.P., 2004, Physical evolution of Grande Ronde Basalt magmas, Columbia River Basalt Group, north-western USA; Mineralogy and Petrology, v. 80, p. 1–25, https://doi.org/10.1007/s00710-003-0017-1.

Carlson, R.W., 1984, Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle: Geochimica et Cosmochima Acta, v. 48, p. 2357–2372, https://doi.org/10.1016/0016-7037(84)90231-X.

Carlson, R.W., Lugmair, G.W., and Macdougall, J.D., 1981, Columbia River volcanism: The question of mantle heterogeneity or crustal contamination: Geochimica et Cosmochimica Acta, v. 45, p. 2483–2499, https://doi.org/10.1016/0016-7037(81)90100-9.

Catchings, R.D., and Mooney, W.D., 1988, Crustal structure of the Columbia Plateau: Evidence for rifting: Journal of Geophysical Research, v. 93, p. 459–474, https://doi.org/10.1029/JB093iB01p00459.

Cawthorn, R.G., 2005, Stratiform Platinum-Group Element deposits in layered intrusions, *in* Mungall, J.E., *ed.*, Exploration for Platinum Group Element Deposits: Mineralogical Association of Canada, Short Course Series, v. 35, p. 57–74.

Chazey III, W.J., and Neal, C.R., 2005, Platinum-group element constraints on source composition and magma evolution of the Kerguelen Plateau using basalts from ODP Leg 183: Geochimica et Cosmochimica Acta, v. 69, p. 4685–4701, https://doi.org/10.1016/j.gca.2005.02.006.

Chesley, J.T., and Ruiz, J., 1998, Crust-mantle interaction in large igneous provinces: Implications from Re–Os isotope systematics of the Columbia River flood basalts: Earth and Planetary Letters, v. 154, p. 1–11, https://doi.org/10.1016/S0012-821X(97)00176-3.

Condie, K.C., 2001, Mantle plumes and their record in Earth history: Cambridge University Press, Cambridge, UK, 326 p., https://doi.org/10.1017/CBO9780511810589.

Czamanske, G.K, Wooden, J.L., Zientek, M.L., Fedorenko, V.A., Zen'ko, T.E., Kent, J., King, B.S., Knight, R.L., and Siems, D.F., 1994, Geochemical and isotopic constraints on the petrogenesis of the Noril'sk-Talnahk ore-forming system, *in* Lightfoot, P.C., and Naldrett, A.J., *eds.*, Proceedings of the Sudbury-Noril'sk Symposium, Sudbury: Ontario Geological Society, p. 313–342.

Czamanske, G.K, Zen'ko, T.E, Fedorenko, V.A., Calk, L.C., Budahn, J.R., Bullock Jr., J.H., Fries, T.L., King, B.S., and Seims, D.F., 1995, Petrography and geochemical characterization of ore-bearing intrusions of the Noril'sk type, Siberia, with discussion of their origin: Resource Geology Special Issue, v. 18, p. 1–48.

Davis, K.N., Wolff, J.A., Rowe, M.C., and Neill, O.K., 2017, Sulfur release from main-phase Columbia River Basalt eruptions: Geology, v. 45, p. 1043–1046, https://doi.org/10.1130/G39371.1.

Dodson, A., Kennedy, B.M., and DePaolo, D.J., 1997, Helium and neon isotopes in the Imnaha Basalt, Columbia River Basalt Group: evidence for a Yellowstone plume source: Earth and Planetary Science Letters, v. 150, p. 443–451, https://doi.org/10.1016/S0012-821X(97)00090-3.

Draper, D.S., 1991, Late Cenozoic bimodal magmatism in the northern Basin and Range Province of southeastern Oregon: Journal of Volcanology and Geothermal Research, v. 47, p. 299–328, https://doi.org/10.1016/0377-0273(91)90006-L.

Duncan, R.A., 1982, A captured island chain in the Coast Range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 10827–10837, https://doi.org/10.1029/JB087iB13p10827.

Ernst, R.E., 2014, Large Igneous Provinces: Cambridge University Press, Cambridge, UK, 653 p., https://doi.org/10.1017/CBO9781139025300.

Ernst, R.E., and Buchan, K.L., *editors,* 2001, Mantle Plumes: Their identification through time: Geological Society of America Special Papers, v. 352, 261 p., https://doi.org/10.1130/SPE352.

Ernst, R.E., and Buchan, K.L., 2010, Geochemical database of Proterozoic intraplate mafic magmatism in Canada: Geological Survey of Canada, Open File 6016, 1 CD-ROM, https://doi.org/10.4095/261831.

Ernst, R.E., and Hulbert, L.J., 2003, Background Pt-Pd levels in mafic Large Igneous Provinces (LIPs) in Canada (Poster): Geological Survey of Canada Open File 4472, https://doi.org/10.4095/214416.

Ernst, R.E., and Jowitt, S.M., 2013, Large Igneous Provinces (LIPs) and Metallogeny, *in* Colpron, M., Bissig, T., Rusk, B.G., and Thompson, J.F.H., *eds.*, Tectonics, Metallogeny, and Discovery: The North American Cordillera and Similar Accretionary Settings: Society of Economic Geologists Special Publications, v. 17, p. 17–51, https://doi.org/10.5382/SP.17.02.

Flanagan, F.J., 1976, Descriptions and analyses of eight new USGS rock standards: US Geological Survey Professional Paper 840, 192 p., https://doi.org/10.3133/pp840.

Geist, D., and Richards, M., 1993, Origin of the Columbia Plateau and Snake River plain: deflection of the Yellowstone plume: Geology, v. 21, p. 789–792, https://doi.org/10.1130/0091-7613(1993)021<0789:OOTCPA>2.3.CO;2.

Ho, A.M., and Kashman, K.V., 1997, Temperature constraints on the Ginkgo flow of the Columbia River Basalt Group: Geology, v. 25, p. 403–406, https://doi.org/10.1130/0091-7613(1997)025<0403:TCOTGF>2.3.CO;2.

Hofmann, A.W., 1988, Chemical differentiation of the Earth: The relationship between mantle, continental crust, and oceanic crust: Earth and Planetary Science Letters, v. 90, p. 297–314, https://doi.org/10.1016/0012-821X(88)90132-X.

Holden, G.S., and Hooper, P.R., 1976, Petrology and chemistry of a Columbia River basalt section, Rocky Canyon, west-central Idaho: Geological Society of America Bulletin, v. 87, p. 215–225, https://doi.org/10.1130/0016-7606(1976)87<215:PACOAC>2.0.CO;2.

Hooper, P.R., 1974, Petrology and chemistry of the Rock Creek flow, Columbia River Basalt, Idaho: Geological Society of America Bulletin, v. 85, p. 15–26, https://doi.org/10.1130/0016-7606(1974)85<15:PACOTR>2.0.CO;2.

Hooper, P.R., 1988, The Columbia River Basalt, *in* Macdougall, J.D., *ed.*, Continental Flood Basalts: Petrology and Structural Geology, v. 3, Springer, Dordrecht, p. 1–34, https://doi.org/10.1007/978-94-015-7805-9_1.

Hooper, P.R., 1997, The Columbia River Flood Basalt Province: Current status, *in* Mahoney, J.J., and Coffin, M.F., *eds.*, Large igneous provinces: Continental, Oceanic and Planetary Flood Volcanism: American Geophysical Union Geophysical Monograph, v. 100, p. 1–27, https://doi.org/10.1029/GM100p0001.

Hooper, P.R., 2000, Chemical discrimination of Columbia River basalt flows: Geochemistry, Geophysics, Geosystems, v. 1, 1024, https://doi.org/10.1029/2000GC000040.

Hooper, P.R., and Hawkesworth, C.J., 1993, Isotopic and geochemical constraints on the origin and evolution of the Columbia River Basalt: Journal of Petrology, v. 34, p. 1203–1246, https://doi.org/10.1093/petrology/34.6.1203.

Hooper, P.R., Kleck, W.D., Knowles, C.R., Reidel, S.P., and Thiessen, R.L., 1984, Imnaha Basalt, Columbia River Basalt Group: Journal of Petrology, v. 25, p. 473–500, https://doi.org/10.1093/petrology/25.2.473.

Hooper, P.R., Gillespie, B.A., and Ross, M.E., 1995, The Eckler Mountain basalts and associated flows, Columbia River Basalt Group: Canadian Journal of Earth Sciences, v. 32, p. 410–423, https://doi.org/10.1139/e95-035.

Hooper, P.R., Binger, G.B., and Lees, K.R., 2002, Ages of the Steens and Columbia River flood basalts and their relationship to extension-related calc-alkalic volcanism in eastern Oregon: Geological Society of America Bulletin, v. 114, p. 43–50, https://doi.org/10.1130/0016-7606(2002)114<0043:AOTSAC>2.0.CO;2.

Hooper, P.R., Camp, V.E., Reidel, S.P., and Ross, M.E., 2007, The origin of the Columbia River flood basalt province: Plume vs nonplume models, *in* Foulger, G.R., and Jurdy, D.M, *eds.*, Plates, Plumes and Planetary Processes: Geological Society of America Special Papers, v. 430, p. 635–668, https://doi.org/10.1130/2007.2430(30).

Humphreys, E., and Schmandt, B., 2011, Looking for mantle plumes: Physics Today, v. 64, p. 34–41, https://doi.org/10.1063/PT.3.1217.

Ivanov, A., 2007, The origin of the Columbia River flood basalt province: Plume vs nonplume models: Discussion of Hooper et al. 2007, *in* Foulger, G.R., and Jurdy, D.M, *eds.*, Plates, Plumes and Planetary Processes: Geological Society of America Special Papers, v. 430, p. 659–662, 665.

Jarboe, N.A., Coe, R.S., Renne, P.R., Glen, J.M.G., and Mankinen, E.A., 2008, Quickly erupted volcanic sections of the Steens Basalt, Columbia River Basalt Group: Secular variation, tectonic rotation, and the Steens Mountain reversal: Geochemistry, Geophysics, Geosystems, v. 9, Q11010, https://doi.org/10.1029/2008GC002067.

Jowitt, S.M., and Ernst, R.E., 2013, Geochemical assessment of the metallogenic potential of Proterozoic LIPs of Canada: Lithos, v. 174, p. 291–307, https://doi.org/10.1016/j.lithos.2012.03.026.

Jowitt, S.M., Williamson, M.-C., and Ernst, R.E. 2014, Geochemistry of the 130 to 80 Ma Canadian High Arctic Large Igneous Province (HALIP) event and implications for Ni–Cu–PGE prospectivity: Economic Geology, v. 109, p. 281–307, https://doi.org/10.2113/econgeo.109.2.281.

Kasbohm, J., and Schoene, B., 2018, Rapid eruption of the Columbia River flood basalt and correlation with the mid-Miocene climate optimum: Science Advances, v. 4, eaat8223, https://doi.org/10.1126/sciadv.aat8223.

Keays, R.R., 1995, The role of komatiitic and picritic magmatism and S-saturation in the formation of ore deposits: Lithos, v. 34, p. 1–18, https://doi.org/10.1016/0024-4937(95)90003-9.

Kerrich, R., Goldfarb, R.J., and Richards, J.P.R., 2005, Metallogenic provinces in an evolving geodynamic framework: Economic Geology, 100th Anniversary Volume, p. 1097–1136, https://doi.org/10.5382/AV100.33.

Korzendorfer, D.P., 1979, The opaque minerals of two flows of the Imnaha Basalt formation, Columbia River Basalt Group, in west-central Idaho: Unpublished MSc thesis, Washington State University, WA, 104 p.

La Bas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali–silica diagram: Journal of Petrology, v. 27, p. 745–750, https://doi.org/10.1093/petrology/27.3.745.

Latypov, R.M., 2002, Phase equilibria constraints on relations of ore-bearing intrusions with flood basalts in the Noril'sk region, Russia: Contributions to Mineralogy and Petrology, v. 143, p. 438–449, https://doi.org/10.1007/s00410-002-0355-8.

Latyshev, A.V , Rad'ko, V.A., Veselovskiy, R.V., Fetisova, A.M., and Pavlov, V.E., 2020, Correlation of the Permian–Triassic ore-bearing intrusions of the Norilsk region with the volcanic sequence of the Siberian Traps based on the paleomagnetic data: Economic Geology, v. 115, p. 1173–1193, https://doi.org/10.5382/econgeo.4746.

Lightfoot, P., and Hawkesworth, C., 1988, Origin of Deccan Trap lavas: evidence from combined trace element and Sr–, Nd–, and Pb–isotope studies: Earth and Planetary Science Letters, v. 91, p. 89–104, https://doi.org/10.1016/0012-821X(88)90153-7.

Lightfoot, P.C., Hawkesworth, C.J., Devey, C.W., Rogers, N.W., and Van Calsteren, P.W.C., 1990, Source and differentiation of Deccan Trap lavas: Implications of geochemical and mineral chemical variations: Journal of Petrology, v. 31, p. 1165–1200, https://doi.org/10.1093/petrology/31.5.1165.

Macdougall, J.D., *editor*, 1988, Continental Flood Basalts: Springer, Dordrecht, 341 p., https://doi.org/10.1007/978-94-015-7805-9.

Mahoney, J.J., and Coffin, M.F., *editors*, 1997, Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism: American Geophysical Union Monograph, v. 100, 438 p., https://doi.org/10.1029/GM100.

Mangan, M.T., Wright, T.L., Swanson, D.A., and Byerly, G.R., 1986, Regional correlation of Grande Ronde Basalt flows, Columbia River Basalt Group, Washington, Oregon, and Idaho: Geological Society of America Bulletin, v. 97, p. 1300–1318, https://doi.org/10.1130/0016-7606(1986)97<1300:RCOGRB>2.0.CO;2.

Martin, B.S., Tolan, T.L., and Reidel, S.P., 2013, Revisions to the stratigraphy and distribution of the Frenchman Springs Member, Wanapum Basalt, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, p. 155–179, https://doi.org/10.1130/2013.2497(06).

Mathews, W.H., 1989, Neogene Chilcotin basalts in south-central British Columbia: geology, ages, and geomorphic history: Canadian Journal of Earth Sciences, v. 26, p. 969–982, https://doi.org/10.1139/e89-078.

Mavrogenes, J.A., and O'Neill, H.St.C., 1999, The relative effects of pressure, temperature and oxygen fugacity on the solubility of sulfide in mafic magmas: Geochimica et Cosmochimica Acta, v. 63, p. 1173–1180, https://doi.org/10.1016/S0016-7037(98)00289-0.

McDonough, W.F., and Sun, S-s., 1995, The composition of the Earth: Chemical Geology, v. 120, p. 223–253, https://doi.org/10.1016/0009-2541(94)00140-4.

Mege, D., and Ernst, R.E., 2001, Contractional effects of mantle plumes on Earth, Mars, and Venus, *in* Ernst, R.E., and Buchan, K.L., *eds.*, Mantle Plumes: Their Identification through Time: Geological Society of America Special Papers, v. 352, p. 103–140, https://doi.org/10.1130/0-8137-2352-3.103.

Momme, P., Tegner, C., Brooks, K.C., and Keays, R.R., 2002, The behaviour of platinum-group elements in basalts from the East Greenland rifted margin: Contributions to Mineralogy and Petrology, v. 143, p. 133–153, https://doi.org/10.1007/s00410-001-0338-1.

Moore, N.E., Grunder, A.L., Bohrson, W.A., Carlson, R.W., and Bindeman, I.N., 2020, Changing mantle sources and the effects of crustal passage on the Steens Basalt, SE Oregon: Chemical and isotopic constraints: Geochemistry, Geophysics, Geosystems, v. 21, e2020GC008910, https://doi.org/10.1029/2020GC008910.

Mungall, J.E., *editor*, 2005, Exploration for Platinum Group Element Deposits: Mineralogical Association of Canada, Short Course Series, v. 35, p. 57–74.

Naldrett, A.J., 1997, Key factors in the genesis of Noril'sk, Sudbury, Jinchuan, Voisey's Bay and other world-class Ni–Cu–PGE deposits: implications for exploration: Australian Journal of Earth Sciences, v. 44, p. 283–315, https://doi.org/10.1080/08120099708728314.

Naldrett, A.J., Lightfoot, P.C., Fedorenko, V.A., Doherty, W., and Gorbachev, N.S., 1992, Geology and geochemistry of intrusions and flood basalts of the Noril'sk region, USSR with implications for the origin of the Ni–Cu ores: Economic Geology, v. 87, p. 975–1004, https://doi.org/10.2113/gsecongeo.87.4.975.

Naldrett, A, Kinnaird, J., Wilson, A., Yudovskaya, M., Chunnett, G., Li, C., and Ripley, E.M., 2011, Genesis of the PGE-enriched Merensky Reef and chromitite seams of the Bushveld Complex: Reviews in Economic Geology, v. 17, p. 235–296.

Naldrett, A.J., Wilson, A., Kinnaird, J., Yudovskaya, M., and Chunnett, G., 2012, The origin of chromitites and related PGE mineralization in the Bushveld Complex: New mineralogical and petrological constraints: Mineralium Deposita, v. 47, p. 209–232, https://doi.org/10.1007/s00126-011-0366-3

Palme, H., and St.C. O'Neill, H., 2005, Cosmochemical estimates of mantle composition, *in* Carlson, R.W., *ed.*, The Mantle and Core: Treatise on Geochemistry, v. 2, p. 1–38, https://doi.org/10.1016/B0-08-043751-6/02177-0.

Pavlov, V.E., Fluteau, F., Latyshev, A.V., Fetisova, A.M., Elkins Tanton, L.T., Black, B.A., Burgess, S.D., and Veselovshiy, R.V., 2019, Geomagnetic secular variations at the Permian Triassic boundary and pulsed magmatism during eruption of the Siberian Traps: Geochemistry, Geophysics, Geosystems, v. 20, p. 773–791, https://doi.org/10.1029/2018GC007950.

Peach, C.L., Mathez, E.A., and Keays, R.R., 1990, Sulfide melt-silica melt distribution coefficients for noble metals and other chalcophile elements as deduced from MORB: Implications for partial melting: Geochimica et Cosmochimica Acta, v. 54, p. 3379–3389, https://doi.org/10.1016/0016-7037(90)90292-S.

Pearce, J.A., 2008, Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust: Lithos, v. 100, p. 14–48, https://doi.org/10.1016/j.lithos.2007.06.016.

Pierce, K.L., and Morgan, L.A., 2009, Is the track of the Yellowstone hotspot driven by a deep mantle plume? – Review of volcanism, faulting, and uplift in light of new data: Journal of Volcanology and Geothermal Research, v. 188, p. 1–25, https://doi.org/10.1016/j.jvolgeores.2009.07.009.

Ramos, F.C., Wolff, J.A., and Tollstrup, D.L., 2005, Sr isotopic disequilibrium in Columbia River flood basalts: Evidence for rapid, shallow-level open-system processes: Geology, v. 33, p. 457–460, https://doi.org/10.1130/G21512.1.

Ramos, F.C., Wolff, J.A., Starkel, W., Eckberg, A., Tollstrup, D.L., and Scott, S., 2013, The changing nature of sources associated with Columbia River flood basalts: Evidence from strontium isotope ratio variations in plagioclase phenocrysts, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, p. 231–257, https://doi.org/10.1130/2013.2497(09).

Reidel, S.P., 1978, Stratigraphy and petrogenesis of the Grande Ronde Basalt in the lower Salmon and adjacent Snake River canyons: Unpublished PhD thesis, Washington State University, WA, 415 p.

Reidel, S.P., 1983, Stratigraphy and petrogenesis of the Grande Ronde Basalt from the deep canyon country of Washington, Oregon and Idaho: Geological Society of America Bulletin, v. 94, p. 519–542, https://doi.org/10.1130/0016-7606(1983)94<519:SAPOTG>2.0.CO;2.

Reidel, S.P., 1998, Emplacement of Columbia River flood basalt: Journal of Geophysical Research, v. 103, p. 27393–27410, https://doi.org/10.1029/97JB03671.

Reidel, S.P., 2005, A lava flow without a source: The Cohassett flow and its compositional components, Sentinel Bluffs Member, Columbia River Basalt Group: Journal of Geology, v. 113, p. 1–21, https://doi.org/10.1086/425966.

Reidel, S.P., 2015, Igneous Rock Associations 15. The Columbia River Basalt Group: A flood basalt province in the Pacific Northwest, USA: Geoscience Canada, v. 42, p. 151–168, https://doi.org/10.12789/geocanj.2014.41.061.

Reidel, S.P., and Fecht, K.R., 1987, The Huntzinger flow: Evidence of surface mixing of the Columbia River Basalt and its petrogenetic implication: Geological Society of America Bulletin, v. 98, p. 664–677, https://doi.org/10.1130/0016-7606(1987)98<664:THFEOS>2.0.CO;2.

Reidel, S.P., and Tolan, T.L., 1992, Eruption and emplacement of flood basalt: An example from the large-volume Teepee Butte Member, Columbia River Basalt Group: Geological Society of America Bulletin, v. 104, p. 1650–1671, https://doi.org/10.1130/0016-7606(1992)104<1650:EAEOFB>2.3.CO;2.

Reidel, S.P., and Tolan, T.L., 2013, The Grande Ronde Basalt, Columbia River Basalt Group, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, p. 117–153, https://doi.org/10.1130/2013.2497(05).

Reidel, S.P., Tolan, T.L., Hooper, P.R., Beeson, M.H., Fecht, K.R., Bentley, R.D., and Anderson, J.L., 1989a, The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho, *in* Reidel, S.P., and Hooper, P.R., *eds.*, Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Papers, v. 239, p. 21–53, https://doi.org/10.1130/SPE239-p21.

Reidel, S.P., Fecht, K.R., Hagood, M.C., and Tolan, T.L., 1989b, The geologic evolution of the Central Columbia Plateau, *in* Reidel, S.P., and Hooper, P.R., *eds.*, Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Papers, v. 239, p. 247–264, https://doi.org/10.1130/SPE239-p247.

Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *editors*, 2013a, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, 440 p., 1 Plate, https://doi.org/10.1130/SPE497.

Reidel, S.P., Camp, V.E., Tolan, T.L., and Martin, B.S., 2013b, The Columbia River flood basalt province: Stratigraphy, areal extent, volume, and physical volcanology, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L, and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, p. 1–43, https://doi.org/10.1130/2013.2497(01).

Reidel, S.P., Camp, V.E., Tolan, T.L., Kauffman, J.D., and Garwood, D.L., 2013c, Tectonic evolution of the Columbia River flood basalt province, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, p. 293–324, https://doi.org/10.1130/2013.2497(12).

Reidel, S.P., Fecht, K.R., Hutter,, I.L., Tolan, T.L., and Chamness, M.C., 2020, The Olympic- Wallowa Lineament: a new look at an old controversy: Geological Society of America Bulletin, https://doi.org/10.1130/B35454.1.

Rodriguez, S., and Sen, G., 2013, Eruption of the Grande Ronde Basalt lavas, Columbia River Basalt Group: Results of numerical modeling, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, p. 259–272, https://doi.org/10.1130/2013.2497(10).

Ryabov, V.V., Shevko, A.Ya., and Gora, M.P., *editors,* 2014, Trap Magmatism and Ore Formation in the Siberian Noril'sk Region: Trap Petrography, v. 1, 390 p., https://doi.org/10.1007/978-94-007-6881-9.

Schuster, J.E., 1993, Geologic map of the Clarkston 1:100,000 quadrangle, Washington-Idaho, and the Washington portion of the Orofino 1:100,000 quadrangle: Washington Geological Survey Open-file Map 93-4.

Smith, A.D., and others, 2007, Discussions on Hooper et al. 2007, The origin of the Columbia River flood basalt province: Plume vs nonplume models, *in* Foulger, G.R., and Jurdy, D.M, *eds.*, Plates, Plumes and Planetary Processes: Geological Society of America Special Papers, v. 430, p. 656–658, 664–665.

Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: US Geological Survey Bulletin 1457-G, 59 p.

Takahahshi, E., Nakajima, K., and Wright, T.L., 1998, Origin of the Columbia River basalts: melting model of a heterogeneous mantle plume head: Earth Planetary Science Letters, v. 162, p. 63–80, https://doi.org/10.1016/S0012-821X(98)00157-5.

Taylor, S.R., and McLennan, S.M., 1985, The continental crust: Its composition and evolution: An examination of the geochemical record preserved in sedimentary rocks: Blackwell Scientific, Oxford, UK, 312 p.

Thordarson, Th., and Self, S., 1996, Sulfur, chlorine and fluorine degassing and atmospheric loading by the Roza eruption, Columbia River Basalt Group, Washington, USA: Journal of Volcanology and Geothermal Research, v. 74, p. 49–73, https://doi.org/10.1016/S0377-0273(96)00054-6.

Tolan, T.L., Reidel, S.P., Beeson, M.H., Anderson, J.L., Fecht, K.R., and Swanson, D.A., 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, *in* Reidel, S.P., and Hooper, P.R., *eds.*, Volcanism and Tectonism in the Columbia River Flood-Basalt Province: Geological Society of America Special Papers, v. 239, p. 1–20, https://doi.org/10.1130/SPE239-p1.

Vye-Brown, C., Gannoun, A., Barry, T.L., Self, S., and Burton, K.W., 2013, Osmium isotope variations accompanying the eruption of a single lava flow field in the Columbia River Flood Basalt Province: Earth and Planetary Science Letters, v. 368, p. 183–194, https://doi.org/10.1016/j.epsl.2013.02.003.

Wager, L.R., and Brown, G.M., 1967, Layered Igneous Rocks: W.H. Freeman and Company, San Francisco, 588 p.

Wierman, C.T., 2018, Copper partitioning in mid-Miocene basalt from the Northern Great Basin (U.S.A.): implications for Cu behavior in flood basalt provinces:

Unpublished MSc thesis, Kansas State University, KS, 147 p.

Wolff, J.A., and Ramos, F.C., 2013, Source materials for the main phase of the Columbia River Basalt Group: Geochemical evidence and implications for magma storage and transport, *in* Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L., and Wells, R.E., *eds.*, The Columbia River Flood Basalt Province: Geological Society of America Special Papers, v. 497, p. 273–291, https://doi.org/10.1130/2013.2497(11).

Wolff., J.A., Ramos, F.C., Hart, G.L., Patterson, J.D., and Brandon, A.D., 2008, Columbia River flood basalts from a centralized crustal magmatic system: Nature Geoscience, v. 1, p. 177–180, https://doi.org/10.1038/ngeo124.

Wright, T.L., Grolier, M.J., and Swanson, D.A., 1973, Chemical variation related to the stratigraphy of the Columbia River Basalt: Geological Society of America Bulletin, v. 84, p. 371–386, https://doi.org/10.1130/0016-7606(1973)84<371:CVRTTS>2.0.CO;2.

Wright, T.L., Mangan, M., and Swanson, D.A., 1989, Chemical data for flows and feeder dikes of the Yakima Basalt Subgroup, Columbia River Basalt Group, Washington, Oregon, and Idaho, and their bearing on a petrogenetic model: U.S. Geological Survey Bulletin 1821, 71 p.

**Received July 2020**
**Accepted as revised October 2020**

# GAC–MAC: FIELD GUIDE SUMMARY

## London 2021 GAC–MAC Joint Annual Meeting Field Trips

**Patricia Corcoran and Phil McCausland**

*Department of Earth Sciences*
*Western University, London, Ontario, N6A 5B7, Canada*
*E-mail: pcorcor@uwo.ca*

### GAC–MAC FIELD GUIDE SUMMARY

GAC–MAC London 2021 is offering five field trips; four that will run virtually or in person depending on circumstances dictated by the state of the pandemic, and one that will run virtually only. Conference participants will have the option to take part in visiting:

1) The deep karstic basin of Crawford Lake on the Niagara Escarpment to examine varves containing light inorganic and dark organic couplets;
2) The geological wonders of the Niagara Escarpment in the Hamilton area, including the sedimentary deposits, fossils, and lateral changes in lithological characteristics that have been affected by continuous erosion;
3) The 1140 to 1105 Ma volcanic and intrusive rocks of the Early Midcontinent Rift from the spectacular Lake Superior shoreline to as far east as Timmins (virtual only), including ‘visits’ to dykes, interlayered alkaline and tholeiitic basalt, and alkaline rocks of the Coldwell Complex;
4) The well-preserved outcrops of the Paleoproterozoic Huronian Supergroup, including evidence of early life, glacial activity, and effects of the Sudbury meteorite impact; this trip is dedicated to the memory of Grant Young;
5) An informative field trip for earth science educators that will take participants to the Oil, Gas and Salt Resources Library and Hungry Hollow to learn about the paleoenvironment and to create a fossil collection for use in their classrooms, and a tour of the newly-renovated Arkona Lions Museum and Information Centre.

Further field trip details are given below, and updates may be found on the GAC–MAC London 2021 website: https://gacmac2021.ca/.

### The Unusual Hydrology and Sedimentary Record of Crawford Lake

Leader: Francine McCarthy (Brock University)

**[1 day and/or virtual]**

Sediments containing varves accumulate in the deep karstic basin of Crawford Lake on the Niagara Escarpment, allowing changes in water chemistry and the lake ecosystem to be dated with annual resolution. These disturbances were primarily anthropogenic, and archeological evidence of Iroquoian and subsequent Euro-Canadian activities can still be seen in its small watershed. Calcite precipitates in the alkaline waters of the mixolimnion (upper wind-mixed layer) of this permanently stratified lake, forming a summer light-coloured layer, and the dark part of the couplet is organic matter, primarily from mass mortality of plankton after fall turnover. Unlike most meromictic lakes, the bottom waters are highly oxygenated, and a diverse micro-invertebrate fauna is found below the chemocline, including ostracods, cladocerans, copepods and rotifers. Groundwater flowing into this sinkhole via aquifers in the Lockport Group contains enough dissolved oxygen to allow aerobic metabolism year-round in the monimolimnion (lower water layer). Because light inorganic- dark organic couplets accumulate in a non-reducing environment, the varved sequence of Crawford Lake is being assessed as a potential Global Stratotype Section and Global Standard Stratotype Section and Point for the Anthropocene Epoch.

Crawford Lake view from interpretive boardwalk on dolomitic bedrock. Photo taken by Francine McCarthy.

*Geoscience Canada,* v. 47, https://doi.org/10.12789/geocanj.2020.47.167 pages 215–217

### A Drive Through the City of Waterfalls: Exploring the Niagara Escarpment in Hamilton, Ontario

Leaders: Rebecca Lee (McMaster University), Carolyn Eyles (McMaster University), Alexander Peace (McMaster University)

**[1 day and/or virtual]**

The Niagara Escarpment is a steep-sloped cuesta that stretches from New York State through Ontario and into Michigan and Wisconsin. It is composed of Ordovician to Devonian sedimentary deposits, primarily dolostones, shales and sandstones. Across the length of the escarpment, there is significant variation in its lithological characteristics, including unit thicknesses and jointing patterns. This field trip will explore outcrops of the Niagara Escarpment in the city of Hamilton, an area that shows significant change in the nature of exposed sedimentary rocks. The escarpment runs through Hamilton, separating the lower and upper city which are connected by 19 access roads. Hamilton is also known as the "city of waterfalls", a moniker related to the over 100 waterfalls that cascade over the escarpment edge. The escarpment here is of interest to the local community, to researchers, and to city planners as its continuous erosion and change cause issues with the safety of the roads and complicate building near its edge. The trip will include stops at the Devil's Punchbowl in east Hamilton, the Jolley Cut in central Hamilton, and the Chedoke Radial Trail in west Hamilton. At each of these locations the sedimentary deposits, fossils, and other features of interest will be discussed in detail. Throughout the trip, the lateral changes in lithological characteristics occurring across the escarpment within the city will be discussed and highlighted. Other sites may be included, time permitting, to further elucidate the lithological characteristics of the Niagara Escarpment.

One of the many waterfalls highlighting the sedimentary strata of the Niagara Escarpment. Photo taken by Rebecca Lee.

### A Virtual Field Trip to the Eastern Midcontinent Rift – Canada

Leader: David Good (Western University)

**[virtual only]**

This field trip will focus on ca. 1140–1105 Ma volcanic and intrusive rocks related to the Early Midcontinent Rift, emplaced onto or into the Archean terrane northeast of Lake Superior. Because we are virtual, we can visit many of the best outcrop exposures located off the beaten path, from the spectacular Lake Superior shoreline to as far east as Timmins. We will look at a very diverse range of alkaline and tholeiitic igneous rocks with planned stops at: 1) Chippewa Falls and Mamainse Point to see pahoehoe lava flows and interflow conglomerates, 2) Rift perpendicular dykes including the Great Abitibi and Kipling dykes, 3) Rift parallel alkaline dykes in Pukaskwa National Park, 4) interlayered alkaline and tholeiitic basalt at Penn Lake, 5) the Coldwell Complex, the largest alkaline intrusion in North America, to see partial melting at the Archean footwall contact and classic intrusive relationships between nepheline syenite and alkaline gabbro at Neys Provincial Park, and 7) Pebble beach in Marathon. We will finish the field trip by examining some of the highly unusual but distinguishing igneous textures at two of the best-known copper-palladium deposits located in the eastern Midcontinent Rift, i.e. the Geordie Lake and Marathon deposits within the Coldwell Complex.

Pukaskwa dyke (~ 1106 Ma) intruded along plane of weakness in deformed Archean pillow basalt (in left cliff face). Photo taken by David Good.

### Geology of the Huronian Supergroup North of Lake Huron, Canada – a Fieldtrip in Memory of Grant M. Young

Leaders: Patricia Corcoran (Western University), Gordon Osinski (Western University), Carolyn Hill-Svehla (Western University)

**[4 days and/or virtual]**

The rocks of the Paleoproterozoic Huronian Supergroup will be examined at various locations in Ontario. We will view most Huronian sedimentary formations, including: 1) the Matinenda Formation, which hosts the uranium-rich deposits in Elliot Lake, 2) the mudstone-siltstone deposits of the McKim and Gowganda formations in Espanola, 3) the dropstones, varves and other glaciogenic deposits of the Gowganda and Ramsey Lake formations near Iron Bridge, Elliot Lake and Whitefish Falls, 4) the carbonate-rich Espanola Formation in Espanola, 5) the quartz-rich sandstone deposits of the Lorrain, Bar River, and Serpent formations at various localities, and 6) evidence for early life in the Gordon Lake Formation near Flack Lake. Participants will also visit the Sudbury basin, which is host to the Sudbury Igneous Complex, Whitewater Group and Huronian sedimentary rocks containing impact-related structures. A short trip to Manitoulin Island will introduce participants to Ordovician oil shales and fossil-rich carbonate units, as well as the Huronian–Ordovician unconformity.

Paleoproterozoic Lorrain quartzite of the Huronian Supergroup, exposure overlooking Whitefish Falls, Ontario. Photo taken by Patricia Corcoran.

### Earth Sciences Field Trip for Educators – London and Arkona

Leaders: Lesley Hymers (Mining Matters), Deana Schwarz (Association of Professional Geoscientists of Ontario Education Foundation)

**[1 day and/or virtual]**

The field trip will include 3 site visits, beginning with the Oil, Gas and Salt Resources Library. Participants will tour the facility, learn about the Paleozoic geology of Ontario, and be introduced to cutting samples, core, and well information. Next, participants will visit the Hungry Hollow site near Arkona, with permission and guidance from Bob O'Donnell, to learn about the paleoenvironment of the location and to create a fossil collection for use in their classrooms. The field trip will conclude with a tour of the newly renovated Arkona Lions Museum and Information Centre, led by Bob O'Donnell, the Museum Steward. Here, educators will learn more about the geology of the area, the history of fossil collecting in southwestern Ontario, and how to identify the fossils they discovered at Hungry Hollow. Transportation to and from Western University will be included.

Brachiopod fossils at Hungry Hollow, Arkona, Ontario. Photo taken by Deana Schwarz.

https://doi.org/10.12789/geocanj.2020.47.167

GEOLOGICAL
ASSOCIATION OF CANADA
ASSOCIATION
GÉOLOGIQUE DU CANADA

MINERALOGICAL
ASSOCIATION OF CANADA
ASSOCIATION
MINÉRALOGIQUE DU CANADA

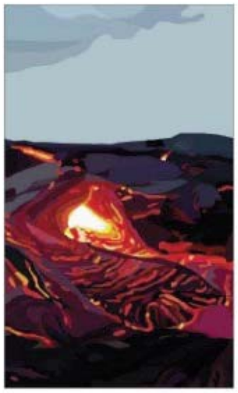
# GAC-MAC London 2021

Joint Annual Meeting
May 17-19, 2021

**Exploring Geosciences Through Time and Space**
**Explorer les géosciences à travers le temps et l'espace**


Earth & Planetary Systems


Life, Climate & Environment


Tectonic Processes & Geohazards


Resource Geoscience

**MEETING THEMES**

## *Make this your meeting!*

**GAC-MAC London 2021 :: Local Organizing Committee**

LOC Chair (GAC) - **Gordon Osinski**
LOC Co-Chair (MAC) - **Roberta Flemming**
General Secretary - **Erika Gongora**
Finance - **Catherine Neish**
Exhibits, Sponsors, Fundraising - **Bob Linnen**
Science Program & Publications and Abstract Volume - **Phil McCausland**
Field Trips - **Patricia Corcoran**
Workshops / Short Courses - **Roberta Flemming**
Outreach and Education - **Alysha McNeil**
Communications and Website - **Cindy Mora Stock, Carolyn Hill-Svehla**
Abstracts and Registration – **Nigel Blamey**
Venue, Technical Services - **Eric Pilles**
Special Events / Social Events - **Cassandra Marion**

**CONTACT:**
**W: https://gacmac2021.ca/ :: E: gacmac2021@uwo.ca :: T: #gacmac2021**

# ANNOUNCEMENTS

## London 2021 GAC–MAC Joint Annual Meeting Workshops and Short Courses

**Roberta L. Flemming**

*Department of Earth Sciences*
*Western University, London, Ontario, N6A 5B7, Canada*
*E-mail: rflemmin@uwo.ca*
*https://www.gacmac2021.ca*

### ONE DAY WORKSHOPS OR SHORT COURSES
### Saturday May 15 or Sunday May 16, 2021

### Gaming the Earth: Geoscience Applications of Game Engines, Augmented Reality, and Virtual Reality

*Organizers:* Rob Harrap (Queen's University), Jean Hutchinson (Queen's University), David Bonneau (Queen's University), Paul-Mark DiFrancesco (Queen's University)

**1-day pre-meeting short course – Saturday May 15, 2021**

Visualization, model building, and simulation in the geosciences traditionally rely on software tools like GIS, mining and geophysical visualization packages, custom code in environments like MATLAB, and custom tools created for specific tasks such as rockfall simulation, groundwater modelling, and the like. While many of these tools are powerful, custom built tools tend to emphasize one aspect of a situation. With the increasing power of game engines – which after all have to be able to represent 3-D environments and simulate phenomena such as smoke, fire, and explosions to be engaging – researchers have begun to apply these engines as general-purpose platforms for geoscience needs.

Two examples from screen shots, illustrating software that can be adapted for geoscientific problems.

These tools also strongly support multiple interaction modes from touch screen to augmented reality to virtual reality, all flexibly using the same world model. Recent events have led to dramatically increased interest in how to interact with geological spaces remotely, whether for education or research communication needs, and game environments handle this very well. This course will cover the range from simple model construction in the Unity game engine, through applications in geoscience education and simulation. We will also cover the construction of game objects from LiDAR or photographs, the use of online assets, plug in tools to solve specific needs such as terrain shaping, and other practical issues in making projects happen. Hands on exercises with real-world data will be emphasized.

*Intended audience:* Industry, Government and Academic Researchers, Students, Educators (K–12)

### Rates and Dates: Dating Methods and Applications

*Organizers*: Eva Enkelmann (University of Calgary) and William Mattews (University of Calgary)

**1-day pre-meeting virtual short course – Saturday May 15, 2021**

The objective of this one-day course is to introduce geoscientists to the fundamentals of radiometric dating techniques. Geo- and thermochronology techniques allow scientists to quantify the timing of geological events and with this the duration and rates of geological processes. These methods differ in their sensitivity to temperatures ranging from mineral crystallization at > 800°C to upper crustal heating and cooling at 50–100°C. This one-day short course will provide the principles of radiometric dating. Emphasis will be given to geochronology and thermochronology methods such as U–Pb, Ar–Ar, U–Th/He, and fission track dating, and the possibilities to combine multiple methods on individual samples and single grains. Focus will be given to practical aspects that will allow scientists to choose the best method, conduct sampling in the field and core storage facilities, and project budgeting for a wide range of applications.

*Topics* covered in this short course:

- Differences between geo- and thermochronology
- Basics of the U-Pb, fission track and U-Th/He methods
- Application of geochronology to various geological settings
- Applications of low-temperature thermochronology
- Common tools for data analyses, data presentation and interpretation
- Use of multi-method, single-grain analyses
- Sampling strategies, what and how to sample, budget, and time considerations

*Intended audience:* Industry, Government and Academic Researchers, Students

*Geoscience Canada,* v. 47, https://doi.org/10.12789/geocanj.2020.47.168 pages 219–222

### Quantifying Sediment Provenance and Basin Thermal Histories

*Organizers*: Eva Enkelmann (University of Calgary) and William Mattews (University of Calgary)

**1-day pre-meeting virtual short course – Sunday May 16, 2021**

The objective of this one-day course is to introduce geoscientists to the fundamentals of radiometric dating techniques and their use in studying sediment basins. New developments in geo- and thermochronology techniques allow effectively dating large quantities of individual grains and the application of multiple methods on single grains. This offers to answer a wide range of geological questions regarding sedimentary basins. These include: 1) sediment provenance and identify sediment recycling; 2) reconstructing the tectonic evolution of the sediment source region; 3) quantifying maximum and minimum temperature of sediment burial; 4) quantifying timing and rate of basin inversion; 5) determining sediment deposition age; 6) quantifying amount of removed sediment strata or tectonic overburden. Focus will be given to practical aspects that will allow scientists to choose the best method, conduct sampling in the field and core storage facilities, and project budgeting and time planning.

*Topics* covered in this short course:

- Differences between geo- and thermochronology
- Application of geochronology and low-temperature thermochronology to basin strata
- Multi-method dating of detrital minerals
- Common tools for data analyses, data presentation and interpretation
- Thermal history modelling of basin strata
- Sampling strategies, what and how to sample, budget, and time considerations

*Intended audience:* Industry, Government and Academic Researchers, Students

### A New Exploration Model for Silurian Lockport Group "Guelph" Carbonate Plays, Southwestern Ontario and Great Lakes Region

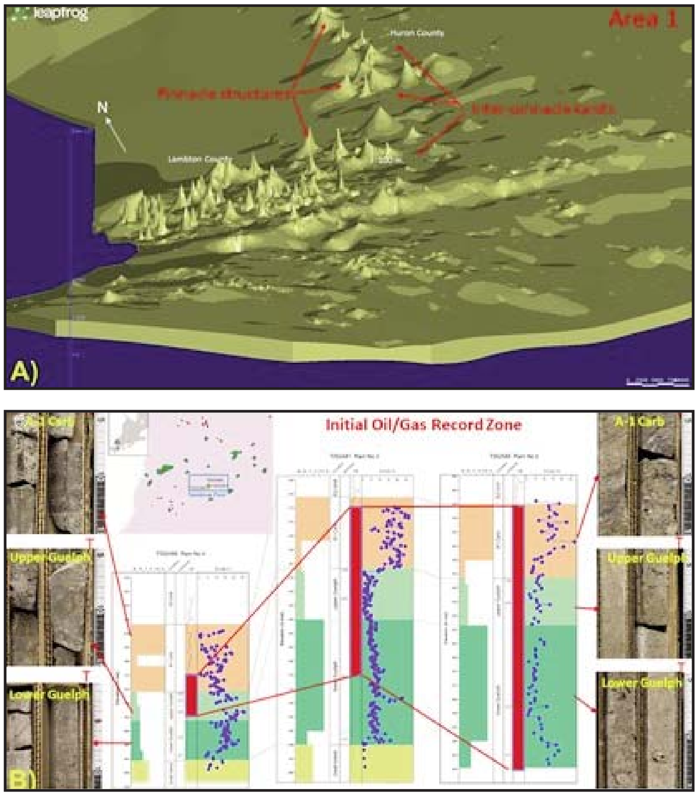
*Organizers:* Shuo Sun (Western University; Oil, Gas and Salt Resources Library), Frank Brunton (Ontario Geological Survey, Western University), Jordan Clark (Oil, Gas and Salt Resources Library), and Jisuo Jin (Western University)

**1-day pre-meeting workshop – Sunday May 16, 2021**

Regional-scale outcrop/subcrop and deeper subsurface mapping by staff/students at Ontario Geological Survey with staff at the Oil, Gas and Salt Resources Library has resulted in the development of a revised stratigraphic nomenclature and paleoenvironmental interpretation for the mature early Silurian petroleum play formerly referred to as the "Guelph" pinnacle play in southwestern Ontario. This predominantly dolostone succession is now referred to as the Lockport Group and comprises, in ascending order: Gasport, Goat Island, Eramosa and Guelph formations. Recognition of subregional disconformities within the revised lithofacies relationships indicate that these stacked carbonate units were deposited on a complex, structurally-influenced, carbonate ramp that dipped towards the Appalachian foreland basin.

This core workshop includes the recent study on regional porosity and permeability variations of these Lockport Group pinnacles and inter-pinnacle areas in southwestern Ontario. Data from cored wells in various depositional regimes will be displayed to show the regional stratigraphic architecture, depositional and diagenetic attributes, and geological controls on porosity and permeability distributions. This workshop will also provide: 1) geo-spatial analysis of the porosity-permeability distributions of the stacked carbonate cycles relative to the re-interpretation of the largely non-reefal pinnacle structures as paleokarstic remnant landforms; 2) descriptions of the re-interpreted paleokarstic rubble that characterizes the dramatically thinner Lockport Group inter-pinnacle settings; 3) case studies of the reef mound cycles in middle to outer ramp areas where paleokarstic features are less well developed. Virtual reality tools are also employed for videos demonstrating the 3-D model of the preserved carbonate structures in the subsurface.

*Intended audience:* Industry, Government and Academic Researchers, Students, General Public



A) A 3-D model image of the pinnacle structures and inter-pinnacle karst areas of the Silurian Lockport Group, southwestern Ontario. Thickness of the pinnacle structures are exaggerated x30. B) An example of the Guelph Formation lithofacies vs. porosity variations in one of the pinnacle plays, southwestern Ontario. These non-reefal lithofacies display various karstic surfaces that are correlative on varying scales.

## TWO-DAY WORKSHOPS OR SHORT COURSES
## Saturday–Sunday May 15–16, 2021

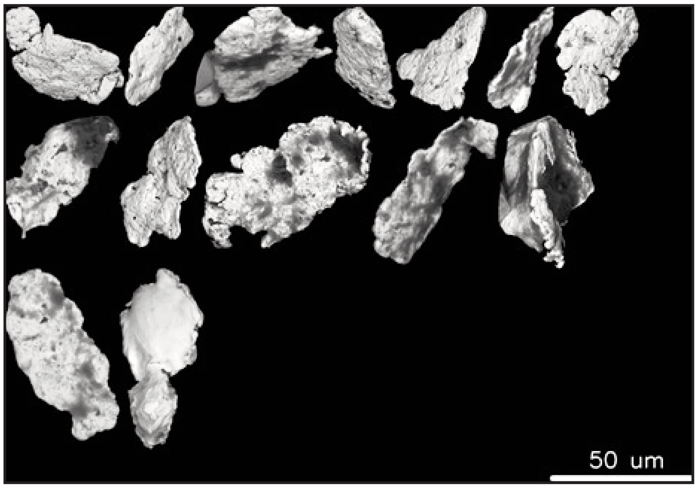
### Modern Scanning Electron Microscope: The Most Versatile Tool for Geoscience

*Organizers*: Réjean Girard and Jonathan Tremblay (IOS Services Géoscientiques Inc.)

**2-day pre-meeting workshop – Saturday May 15 to Sunday May 16, 2021**

Although often perceived as the old dusty machine, scanning electron microscopes underwent rapid technological evolution in the last decade that makes them the most powerful tool available to geoscientists. A large array of detectors, fulfilling different functions, can be attached, synchronized and automated, fulfilling various needs such as fast EDS-SDD fully quantitative chemical analysis out-performing an electron microprobe, wavelength-dispersive spectrometry (WDS) for minor element analysis, micro-XRF for trace elements measurement, electron diffraction (EBSD) to reveal the crystalline structure, near-atomic scale TEM imaging, cathodoluminescence imaging and spectroscopy, microtomography or surface ablation for 3-D imaging, QEMSCAN and MLA for automated mineralogy, etc. The workshop aims to familiarize geoscientists with operation of the instruments and its capabilities for their daily research work as well as presenting a series of automated applications and case studies.

*Intended audience:* Students and Industry, Government or Academic Researchers



Gold grain mosaic automated routine.

### Fluid and Melt Inclusions: Applications to Geological Processes

*Organizers:* Matthew Steele-MacInnis (University of Alberta) and Pilar Lecumberri-Sanchez (University of Alberta)

**2-day pre-meeting virtual MAC Short Course – Saturday May 15 to Sunday May 16, 2021**

The short course will focus on application of fluid inclusions to solve geological problems, and includes talks from world experts in fluid and melt geochemistry applied to hydrocarbons, diagenesis, metamorphic and igneous processes, Earth's deep interior, and economic mineral deposits.

Lecturers will include:

- Jaques Pironon (University of Lorraine)
- Andras Fall (UT Austin)
- Martin Appold (University of Missouri)
- Omar Bartoli (University of Padua)
- Evan Smith (Gemological Institute of America)
- Jake Hanley (Saint Mary's University)
- Rosario Esposito (Colorado College)
- Matthew Steele-MacInnis (University of Alberta)
- Pilar Lecumberri-Sanchez (University of Alberta)
- Simone Runyon (University of Wyoming)

*Intended Audience:* Industry, Government and Academic Researchers, Students

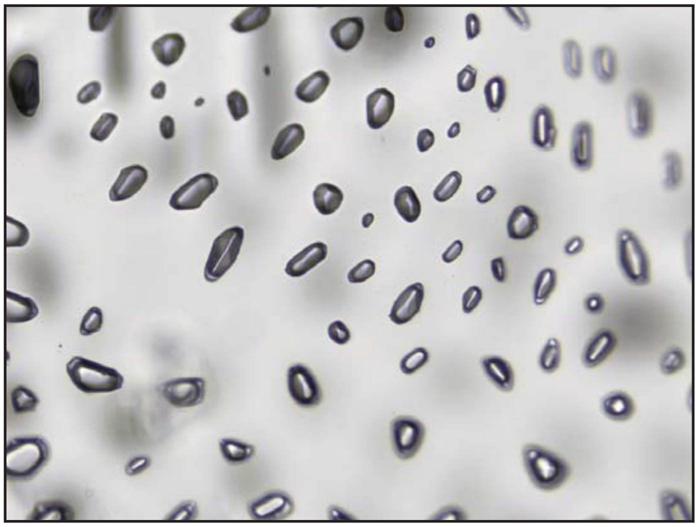


Image shows vapor-rich fluid inclusions in quartz from The Schneckenstein (Germany).

### Introduction to Data Analytics and Machine Learning for Geologists

*Organizers:* Jessica Stromberg (CSIRO Mineral Resources) and Shawn Hood (Goldspot Discoveries)

**2-day pre-meeting virtual workshop – Saturday May 15 to Sunday May 16, 2021**

A practical introductory course aimed at geologists in mineral exploration and mining. The participants will be given an overview of modern data analytics methods, including machine learning, illustrated by practical case studies across multiple commodities. There will be exercises using a range of geoscience datasets including geochemistry, geophysics and hyperspectral mineralogy for the participant to practice with the new methods they have learnt. These tutorials will use a diverse range of software, including free machine learning software (KNIME), a Python package for geochemical data analysis (Pyrolite) and CSIRO-developed multiscale wavelet analysis for drill hole data (Data Mosaic). Knowledge of intro-

https://doi.org/10.12789/geocanj.2020.47.168

ductory statistics and some Python could be useful but is not required.

Instructors:
- Dr. June Hill, CSIRO Mineral Resources
- Dr. Shawn Hood, Goldspot Discoveries
- Dr. Morgan Williams, CSIRO Mineral Resources
- Shervin Azad, MSc, Goldspot Discoveries
- Dr. Jessica Stromberg, CSIRO Mineral Resources

*Intended audience:* Industry, Government and Academic Researchers

## FOUR DAY WORKSHOP – BERRY SCHOOL
## May 13–16, 2021

### Canadian Powder Diffraction Workshop 14 – Berry School

Organizers: Roberta Flemming (Western University) and Jim Britten (McMaster University)

**4-day pre-meeting workshop – May 13–16, 2021**

This workshop is intended for students and practitioners who would benefit from an improved understanding of the basic theory and practice of powder and related X-ray diffraction techniques for analyzing crystalline materials. Sessions will cover the basic theory of powder diffraction, experimental considerations, sample preparation, and data analysis. Examples of some simple and some more difficult powder diffraction, Rietveld, 2-D, and 3-D diffraction analyses will be presented. Other diffraction and scattering techniques will also be presented, appropriate for the characterization of powders, *in situ* solids, thin films, single crystals, nanostructured and disordered materials. A variety of diffraction software will be introduced during the presentations and used in the afternoon's practical sessions. Several practice data sets will be supplied. Participants are also invited to bring data from their own research to be worked out at the Workshop with expert advice from the Instructors who will be present. There may also be an opportunity to collect diffraction data on various instruments at Western University (if on-site, pandemic permitting). On-site participation in the Workshop will be limited to 40 participants. The workshop is intended to be run in person, but a virtual format will be implemented if necessary (in the event of COVID-19 restrictions).

*Intended Audience:* Industry, Government and Academic Researchers, Students

GAC-MAC London 2021

May 17-19, 2021

GEOLOGICAL ASSOCIATION OF CANADA
ASSOCIATION GÉOLOGIQUE DU CANADA

MINERALOGICAL ASSOCIATION OF CANADA
ASSOCIATION MINÉRALOGIQUE DU CANADA

Exploring Geosciences Through Time and Space
Explorer les géosciences à travers le temps et l'espace

# A TRIBUTE

Frank in his managerial role as Director of the Geological Survey of Newfoundland and Labrador.

## R. Frank Blackwood: 1950–2020

On the 4th of August, 2020, I, together with the geoscience community of Newfoundland and Labrador, learned with shock of the death of Frank Blackwood, long one of our principal champions of geoscience in the Province and indeed the entire country.

I first met Frank in the summer of 1974 when I was engaged in my post-graduate field work in southern New Brunswick and he in a similar endeavor in eastern Newfoundland. I took Frank on a tour of my field area and rapidly came to realize that here was a force of nature with a remarkable ability to challenge established thinking in an articulate and erudite manner.

Our paths crossed again in 1976 when we both joined the Geological Survey of Newfoundland and Labrador at the time when Frank was engaged in extending his MSc thesis work into a broader part of eastern Newfoundland, very close to the area of Bonavista Bay where he had been born and raised. Frank had studied geology at Memorial University of Newfoundland (as it was then) and completed his MSc degree at the same institution, also in 1976. These were halcyon days for geological surveys as new federal-provincial funding agreements led to a surge in growth of government geoscience activities across Canada. As part of this surge, Frank went on to extend his work into southern Newfoundland around the remote communities of Grey River and McCallum. In this, his work contributed greatly to application of the then relatively new principles of plate tectonics to the development of models for the amalgamation of the Avalon zone, representing part of proto Africa, with the internal zones of the Appalachian orogen.

In 1986 Frank hung up his field boots and became editor of the Newfoundland and Labrador Geological Survey's publications system where he introduced high standards of map and report production, following which he moved into management as head of the Publications and Information section. Here he took on the additional responsibility of overseeing the Survey's efforts to promote the province as an attractive place for mineral exploration. In 1998, Frank took another step up the management ladder to become Director of the Survey. Under his guidance, the Survey continued its expansion to provide a full spectrum of services, including bedrock mapping, terrain science, geophysical and geochemical surveys, all tied together by a robust publication and promotions system that with time became increasingly dominated by digital applications and computerization. It was during the 1980s – early 1990s that the Newfoundland and Labrador Survey established its reputation as one of the most active surveys in Canada and greatly expanded its contribution to the understanding of the evolution of the Canadian landmass and its resource endowment. However, in the latter half of the 1990s, the growing problem of financial deficits began to constrain the ability of both federal and provincial governments to fund geoscience surveys at the previous levels. As a consequence, various financial reviews forced surveys to reduce their activities – a problem that affected the Newfoundland and Labrador Survey as much as any. In dealing with this challenge, Frank proved to be an example of the right man for the time and provided exemplary leadership in dealing with successive crises. In this his strategy was to take advantage of whatever opportunity presented itself to use his formidable powers of oratory and persuasion to promote the value, indeed the necessity, of geoscience surveys to senior bureaucrats and politicians. I was privileged to see Frank in action in this respect when on one occasion he took advantage of the publication of a new geological map of Labrador to get himself in front of the provincial Minister of Natural Resources and his staff, and then proceeded to successfully persuade them of the necessity of maintaining geoscience (including of course the survey budget) in resource dependent provinces such as Newfoundland and Labrador.

In his every-day duties, Frank was a strong and effective manager who could always be relied upon to rise to the chal-

Geoscience Canada, v. 47, https://doi.org/10.12789/geocanj.2020.47.169 pages 223–225

Frank addressing the (somewhat wet) masses in 1976 on a GAC field trip to his project area in eastern Newfoundland.

lenges of the day. He preferred to manage through his powers of charm and persuasion but ran a tight ship and could clamp down when required. Even then he had the rare managerial gift of being able to administer a rebuke in a positive and encouraging manner that left no rancor behind.

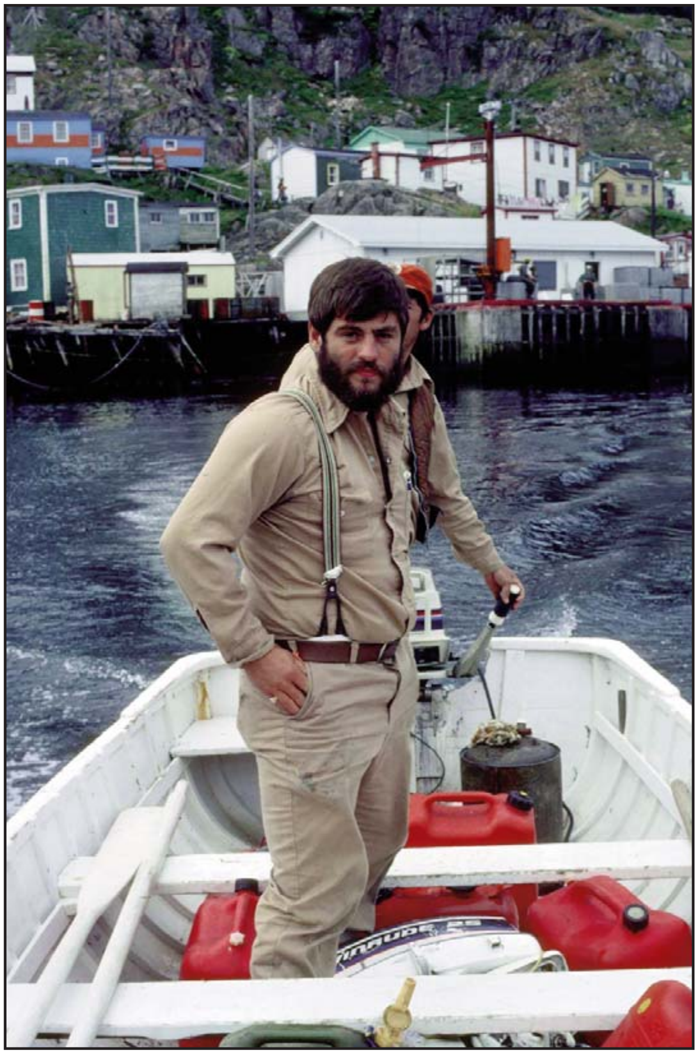
Also in his Director role, Frank was active on the national scene as a member of the Committee of Provincial and Territorial Geologists, which reported to the annual Mines and Energy Ministers conference. This committee undertook as one of its key missions to garner the support of the principal mineral industry associations of Canada in order to promote the importance of government geoscience to the federal, provincial and territorial ministers. This work was critical in reducing the impact of continued financial pressure through the 1990s and into the 2000s.

Frank had two passions in his professional career. One was, as outlined above, the Geological Survey of Newfoundland and Labrador; the other was the Geological Association of Canada (GAC), a passion that was probably initially inspired by Dr. Ward Neale, Chair of the Department of Earth Sciences at Memorial University during Frank's university days and a passionate advocate for the GAC. Frank became a fellow of GAC early in his career and went on to become its Secretary-Treasurer during the period 1987 to 1990 and then President in 1993–94. During these years Frank contributed to the growth of the Association and to its increased national and international recognition. Frank's interest in GAC culminated in 2001 with his chairmanship of the hugely successful joint GAC/MAC/CSPG annual meeting in St. John's.

In 2002 Frank became chair of the Canadian Geoscience Foundation (CGF), a charitable organization set up to fund worthy geoscience outreach projects across Canada. During his tenure (2002–2008), Frank was able to significantly increase the CGF's funding base through the securement of the Jerome H. Remick III endowment and left behind a legacy of strong, well-organized governance and a solid investment policy that set the CGF up for long term success.

Frank's interest in public outreach also brought him to the attention of Paul Johnson, a prominent St. John's businessman, who in the late 1990s was in the conceptual stages of creating a geoscience facility that would promote interest in Newfoundland's spectacular geology to the general public. Frank was initially asked to assist in defining the scope and theme of the facility, then moved on to the development committee where he played an influential role in steering the project through its design and construction phases. The dream was realized in 2002 when the Johnson Geo Centre opened its doors on Signal Hill, adding a major tourist attraction to the scenic park that overlooks downtown St. John's. Frank continued to maintain his involvement in the new Geo Centre as a member of the Board of Directors and contributed significantly to the acquisition of new exhibits, including the ExxonMobil Oil and Gas gallery.

Frank eventually decided to retire in 2007, however he maintained an active role in the geoscience community and went on to administer a granting system to fund selected private sector mineral exploration research projects under the auspices of the provincial Research and Development Corporation, which was set up in 2007. Frank also became involved in professional geoscience through membership of the Awards



Frank engaged in field work, southern Newfoundland in 1982.

Committee of the Professional Engineers and Geoscientists of Newfoundland and Labrador. His final involvement in public geoscience was assisting the Shorefast Foundation with its "Geologists in Residence" project on Fogo Island in eastern Newfoundland.

Frank also continually sought honours and awards for his many deserving colleagues, whether in government, industry or academia, but was self-effacing about his own recognition and on several occasions refused to accept nominations that he felt should go to others. However, GAC did manage to persuade him to accept a Distinguished Fellow Award in 1996, followed in 2002 by a Distinguished Service Award and then in 2008 the J. Willis Ambrose Medal, which is awarded for sustained, dedicated service to the Canadian Earth Science community. The Ambrose medal in particular provided fitting recognition of Frank's work to build GAC and to promote the importance of geoscience to governments and the general public.

Frank was above all a gifted communicator, and whether chairing a committee or delivering a major public address, will long be admired for his command of the English language and ability to distil complex issues into readily understandable summations. Listening to his presidential address at the 1994 GAC/MAC annual meeting on "The Poetry of Geology" (Blackwood 1994; https://journals.lib.unb.ca/index.php/GC/issue/view/402), was to see a master orator in action as Frank delivered his views on the importance of geoscience to society and our way of life to a rapt and attentive audience.

On August 4th, Frank passed away after a battle with bile duct cancer. His passing has left a deep sense of loss in the geoscience community. He was a strong and effective leader who could always rise to the challenge of difficult times and who commanded respect for his thoughtful and respectful eloquence. He was also a tireless advocate for the importance of geoscience, particularly public geoscience. He will long be remembered with great admiration and respect as a colleague, a friend, a manager and a leader. His loss is also a terrible tragedy for his family, notably his wife Verna, his mother Evelyn and his sons Michael and Alexander.

In keeping with Frank's desire to help others in geoscience, an annual award is in the process of being established at Memorial University where it will be given to a full time graduate student in the Department of Earth Sciences.

He will be sorely missed.

Richard J. Wardle, with contributions from Baxter Kean, Dave Liverman, Paul Dean, Jeremy Hall, Lawson Dickson and Andy Kerr.

## REFERENCE

Blackwood, R.F., 1994, Presidential Address: The Poetry of Geology: Geoscience Canada, v. 21, p. 45–48.

*With the support of the family, a scholarship fund has been established at the Department of Earth Sciences, Memorial University, in recognition of Frank's many contributions. The fund will provide an annual award for a graduate student engaged in field-based geoscience research.*

*Contributions in memory of Frank can be made online at https://www.mun.ca/give/Donate.php.*
*Select "Other" from the dropdown list located in the "Area of Designation" and enter 'R.F. Blackwood Memorial Award' in the "Designation Information" field.*
*Receipts for tax purposes will be issued.*

*For more information about the fund and its objectives, please contact Dr. Stephen Piercey at Memorial University (spiercey@mun.ca).*

https://doi.org/10.12789/geocanj.2020.47.169

# GEOSCIENCE CANADA

JOURNAL OF THE GEOLOGICAL ASSOCIATION OF CANADA
JOURNAL DE L'ASSOCIATION GÉOLOGIQUE DU CANADA

2020 VOLUME 47 GSCNA7 47 167-226
PRINT EDITION ISSN 0315-0941
ONLINE EDITION ISSN 1911-4850