

Centre of Excellence for Sustainable Mining and Exploration (CESME)

Annual Report to the Office of Research Services

August 2023





Executive Summary

In the past year CESME has achieved the following:

- Co-hosted a successful in-person event associated with the PDAC meeting
- Supported a successful application to the Ontario Research Excellence competition
- Provided scholarships to support graduate research
- Sponsored an in-person workshop
- Facilitated new research initiatives between local industry and LU researchers

CESME goals & objectives

As outlined in the original proposal to the Senate Research Committee the purpose, rationale, mission and goals of the Centre of Excellence in Sustainable Mining and Exploration (CESME) are as follows:

Purpose

CESME will encourage and support research, education and outreach activities regarding the nature and impacts of mineral resource exploration and extraction particularly in Northern Ontario.

Rationale

Northern Ontario's dynamic mining sector is booming, creating challenges regarding how best to undertake sustainable economic development while ensuring environmental protection and respecting constitutionally protected Aboriginal and Treaty rights. CESME will help address these challenges by linking Lakehead University researchers with partners from First Nation, Métis and local communities, government, and industry. This collaborative approach recognizes that Canadian natural resource development requires sophisticated planning, collaboration, assessment, implementation, and remediation strategies that are calculated to minimize negative environmental, socio-economic, and cultural impacts. CESME uses the term "sustainable" to imply reconciliation of the three pillars of environmental, social equity, and economic demands (2005 World Summit on Social Development) that is now widely recognized by the mining industry. To this end, CESME is structured under three pillars: 1) Mining, Exploration and Mineral Processing; 2) Environmental Impacts; and 3) First Nation, Métis and Local Community Engagement.

Through the Centre academic, community, government, and industry partners will carry out cutting-edge research in discovery, advanced exploration, and development, and address the environmental, social and cultural aspects of mineral extraction.

Mission

CESME will:



- Support the development of community-based research and outreach activities in both the Lakehead University community and the region as a whole;
- Generate research projects that facilitate sustainable resource development in Northern Ontario and evaluate the current and future ecological, social, cultural and economic impacts of development; and
- Apply research outcomes from Northern Ontario projects to broader sustainable development issues in other northern Canadian and international jurisdictions and apply the lessons learned in other jurisdictions to Northern Ontario.

Goals

CESME will:

- Increase the capacity for mineral deposit research at Lakehead University and enhance the reputation of the institution in the region, nationally and internationally;
- Increase the capacity for research into the environmental impacts of mining and the sustainability of this activity in Northern Ontario;
- Increase the capacity for research into the social and cultural impacts of mining, especially the involvement of local and First Nation and Métis communities and the recognition of Aboriginal and treaty rights;
- Increase the capacity for research into mining and mineral processing;
- Initiate interdisciplinary research into these fields and develop multidisciplinary research proposals for funding agencies and research partners;
- Bring together a diverse range of researchers at Lakehead University working in fields related to mining exploration, sustainable mining, and environmental and community impacts; and
- Make Lakehead University the hub for sustainable resource extraction research in Northern Ontario.

Progress towards the Centre's goals

In our original proposal to the Senate Research Committee we indicated that we would achieve the goals of the Centre by undertaking a number of activities. This section lists those activities and highlights progress made.

1. Initiate discussions with the wider community to shape the research activities of the Centre.

We have continued discussions with a diverse group of research partners including First Nations educational organisations. We continue to work with Mining Matters to facilitate their engagement with schools and communities in Northern Ontario. We are also continuing discussions with Dr. Melville, Dean of Education, to provide geoscience education to pre-service teachers.

2. Generate multidisciplinary research proposals and apply for external funding



CESME has supported the establishment of research partnerships with Wyloo, Nighthawk Gold, Northisle Copper and Evolution Mining that have lead to successful Alliance Grant applications. The Centre also supported a successful application to the Ontario Research Excellence competition that led to a \$2 million award for a grant titled "Finding the Next Mine: Developing new deposit models to enhance exploration in Northern Ontario". We have also worked with Green Technology Metals to establish an NOHFC Industrial Research Chair in Critical Minerals Processing. The faculty of Engineering is currently conducting a search to recruit a candidate for this position.

3. Invite and fund proposals for research and outreach activities

We continue to solicit proposals from the University community

4. Recruit and foster faculty, postdoctoral fellows, postgraduate, graduate, and undergraduate student participation

CESME is supporting the MSc research of Michael Nwakanma and Jordan Peterzon, both MSc students in the Department of Geology through the Dr. Melville Bartley Memorial CESME award. Michael is working to better understand the paragenesis of the Moss Lake Au deposit and Jordan is investigating the structure of the Camp Lake fault at the Lac des Iles mine.

5. Establish working relationships with similar national and international centres (e.g., Mineral Deposit Research Unit (MDRU) at the University of British Columbia, Mineral Exploration Research Centre (MERC) at Laurentian, CODES – ARC Centre of Excellence in Ore Deposits at the University of Tasmania, Centre for Exploration Targeting (CET) at the University of Western Australia)

We have a very successful collaboration with CODES and continue our partnership with the Mineral Deposit Research Unit at UBC

6. Develop and maintain a website for the Centre

We have established a website that highlights CESME activities and acts as a repository for our publications and videos of our guest speakers.

Members of CESME

The Advisory Board for CESME continues to operate efficiently having met three times by teleconference in the past year. The membership comprises:

- Ms. Sue Craig, Consultant Chair
- Mr. John Mason, CEDC
- Mr. Glenn Nolan, Noront
- Dr. James Franklin, Consultant
- Dr. Scott Jobin-Bevans, Consultant
- Mr. Gord Maxwell, Consultant

The following faculty members have agreed to lead the three research pillars of CESME:

- Dr. Pedram Fatehi continues as the leader of the Mining, Exploration and Mineral Processing pillar
- Dr. Michael Rennie, continues as the leader of the Environmental pillar



• We are currently seeking a leader for the Indigenous pillar.

The following faculty members have signed up as CESME members:

Dr.	Matthew	Boyd	Anthropology
Dr.	Andrew	Conly	Geology
Dr.	Jian	Deng	Civil Engineering
Dr.	Amanda	Diochon	Geology
Dr.	Martha	Dowsley	Anthropology
Dr.	A. Ernest	Ерр	History
Dr.	Pedram	Fatehi	Chemical Engineering
Dr.	Philip	Fralick	Geology
Dr.	Scott	Hamilton	Anthropology
Dr.	Rachel	Jekanowski	English, Memorial University
Dr.	Peter	Lee	Biology (emeritus)
Dr.	Kam	Leung	Biology
Dr.	Baoqiang	Liao	Chemical Engineering
Dr.	Nancy	Luckai	Natural Resources Management
Dr	Rob	Petrunia	Economics
Dr.	Mike	Rennie	Biology
Dr.	Karl	Skogstad	Economics
Dr.	Robert	Stewart	Geography
Dr.	Shannon	Zurevinski	Geology

The following adjunct faculty are also members of CESME:

Dr.	Greg	Ross	NOSM
Dr.	Robert	Mackereth	Centre for Northern Forest Ecosystem
			Research

In addition, two Postdoctoral Fellows (Wyatt Bain and Matt Brzozowski) are affiliated with CESME. Unfortunately, both moved on to positions with the BC Geological Survey this year.

Research Projects & Scholarly Activities

Other activities

CESME is continuing to engage with local mining companies by hosting "Discovery Days" when researchers at Lakehead present their work to company representatives in order to develop new partnerships. This year we ran a day for Newmont which included presentations from Pedram Fatehi, Mike Dohan, Vicki Kristman, Kam Leung, Denise Baxter, Kathryn Sanderson and Thomas Collins. We have also been in discussions with Kinross to organize a similar day for them.

CESME participated in the Cen Can Expo in Thunder Bay where we both co-hosted a booth with the Economic Development team.



Educational Activities

CESME sponsored the Lakehead University SEG student chapter's short course on "Geological work in Greenstone belts" by Dr. Howard Poulsen. The workshop took place on February 4th, 2023 with 35 attendees.

Undergraduate and graduate training

We have supported two graduate students through the Dr. Melville Bartley Memorial CESME Award as discussed above.

Between 2022 and mid-2023, Dr. Matthew Brzozowski published a manuscript in Lithos entitled "Osmium isotopes record a complex magmatic history during the early stages of formation of the North American Midcontinent Rift - Implications for rift initiation" and continued revisions on a second manuscript that was submitted to Mineralium Deposita entitled "Characterizing the supra- and subsolidus processes that generated the Current PGE–Cu–Ni deposit, Thunder Bay North Intrusive Complex, Canada: insights from trace elements and multiple S isotopes of sulfides". He sent samples to the University of Western Australia for multiple sulfur isotope analyses; many of the analyses have been completed. although additional work on these samples is still being completed at the sulfur isotope laboratory. This data will be used on a project aimed at characterizing the contamination history of the Eastern Gabbro and how it relates to Cu-PGE mineralization. Working with Dr. Peter Hollings, Matt also developed a project in collaboration with Generation Mining Ltd. to characterize the genesis of the Geordie Lake Cu-PGE deposit using whole-rock and mineral chemistry. Samples for this project have already been collected and made into thin sections in preparation for petrographic and chemical characterization. The research that Matt completed during this year was presented at the Institute of Lake Superior Geology (ILSG) conference in Eau Claire, Wisconsin and as a keynote presentation at the International Platinum Symposium in Cardiff, England. He also contributed to two poster and oral presentations at ILSG that were given by two MSc students. Finally, Matt assisted with developing and assisting in a sampling campaign for the third MSc student working in collaboration with Clean Air Metals Inc. on the Current deposit, assisted in the development of an analytical plan for this student, and helped in the preparation of Connor Caglioti for his MSc defense.

Dr. Wyatt Bain advanced the Impala Canada, Ltd PDF project focused on constraining the geology, geochemistry, and magmatic evolution of the Lac Des Iles intrusive suite. This suite of mafic-ultramafic intrusions is located to the South-West of the Lac Des Iles deposit in northwestern Ontario and includes the Legris Lake, Tib Lake, Wakinoo Lake, Demars Lake, Buck Lake, and Dog River intrusions. These systems are of key interest to the mining industry in northwestern Ontario as they contain variable amounts of platinum group element (PGE)-bearing sulfide mineralization and share a spatial, temporal, and geochemical relationship with the Lac Des Iles system.

Over the 2022 field season Dr.Bain conducted a sampling campaign focused on the sulfidebearing cumulate rocks and host rock lithologies associated with the Buck Lake, Demars Lake, Wakinoo Lake, and Dog River localities. Samples from that work were subsequently submitted for whole rock trace element analysis, thin section preparation, whole-rock Sm-Nd



CENTRE OF EXCELLENCE FOR SUSTAINABLE MINING & EXPLORATION isotope analysis, µXRF analysis, and U-Pb geochronology. During the Fall of 2022 Sm-Nd data form the country rock lithologies surrounding the Lac Des Iles intrusive suite was used to contextualize data from the 2021 field season and included in a manuscript (Title: Geochemical Evolution and Parental Magma of the Lake Legris mafic-ultramafic Complex, Ontario) that was recently accepted the Mineralium Deposita (May 2023). Similarly, data gathered during the 2022 field season is being compiled into a companion manuscript (Title: Parental magmas, tectonic setting, and magmatic evolution of the Lac Des Iles Intrusive Suite) that will discuss the geochronology, parental magma compositions, and magmatic evolution of the Lac Des Iles intrusive suite as a whole. A key part of this manuscript will employ a new approach to parental melt modelling of cumulate rocks using modal mineral abundances calculated with uXRF data and an in-house, excel-based parental melt calculator developed as part of this project. This manuscript will also present a model for the formation of the Lac Des Iles intrusive suite involving a northward sweeping sequence of subduction-related arc magmatism in which crustal contamination and magma mixing become increasingly pervasive over time. Moreover, our analysis shows that the crystallization of orthopyroxene and efficient retention of early formed sulfide melts during magma emplacement are both associated with the presence of PGE-bearing sulfide mineralization. This will be highlighted in the fourth coming manuscript as a factor that could guide PGE exploration in these systems. These points were recently presented at the 2023 GAC-MAC conference in Sudbury Ontario, and the manuscript is expected to be submitted to *Mineralium Deposita* in late summer/early fall 2023.

In addition, due to lab constraints, a planned multiple sulfur isotope study using thin sections from the Tib Lake, Wakinoo Lake, Buck Lake, and Archean host rock lithologies was postponed in early fall 2022. However, sample preparation and characterization for this analysis was completed in the late fall of 2022 and is now targeted for the Spring of 2024.

In addition to the PDF project described here, analysis associated with a companion project focused on melt inclusions form four mid-continent rift related systems (Pukaskwa Dikes, the Osler Volcanics, and the Seagull and Thunder layered mafic complexes) was carried out during the summer of 2022, at the University of Alberta and the USGS facility in Denver, Colorado, USA. This analysis generated a robust, high-quality petrographic and geochemical data set on both glassy and polycrystalline inclusions from all four systems. Among several key out comes from this work is a manuscript describing platinum group mineral-bearing salt melt inclusions from the Seagull and Thunder intrusions that is being prepared for the journal *Geology*. In addition, data from the Pukaskwa dikes is being incorporated with a larger geochemical data set on this system and set and is currently being prepared into a manuscript for the *Journal of Petrogeology*.

Financial statement

The main CESME account has been relying on residual funds left from running our conference and occasional donations. These funds have been expended meaning that the only funds available to directly support CESME activities come from the Research Support Fund. While this support is appreciated there are limits to how those funds can be used which may impact future activities.

The statement provided below covers the 2022-2023 financial year.



Item	Credit	Debit
Carry Forward	\$00.00	
Transfer from Research Support Fund	\$18,0000	
Donations		
Travel & Conferences (this includes cost to		
attend Roundup in Jan 23, PDAC in June 22		
and March 23)		\$ 12934.95
Sponsorship (SEG Workshop)		\$500.00
Printing		\$205.00
Catering for Newmont Research Day		\$394.38
Booth at Cen Can expo		\$1163.36
PDAC booth		\$2097.31
Promotional materials		\$200
Returned to Research Support Fund		\$505
Subtotal	\$18,000.00	\$18,000.00
Balance	\$0.00	

One-year and five-year plans

The immediate goals of CESME are as follows:

- Work with the Advisory Board to implement the new Strategic Plan for CESME and the Action Items within it
- We continue to seek funding both from research councils and donors to support graduate and undergraduate research.
- We are still considering the possibility of hosting another conference at Lakehead or alternatively providing support to other related events on campus.
- We continue to engage with faculty across campus to encourage them to participate in and identify CESME activities.

Having met one of our medium-term goals of establishing a research Chair under the Mining and Exploration Pillar we are still seeking to establish two research chairs, one related to each of the remaining CESME pillars (Environmental Impacts and First Nation, Métis and Local Community Engagement). These chairs are critical to the long-term success of CESME as they will provide the core researchers around which Centre activities can be developed. In addition to funding the Chair we are seeking ways to support graduate students and Post-Graduate Fellows who will undertake much of the research. We are investigating a number of mechanisms to fund these chairs, including:

- Corporate donations;
- Philanthropy

We are working closely with the Office of Research Services and External Relations to achieve this goal.



2023-2024 Budget*

Item	Cost
Attend PDAC meeting to promote CESME	\$4,000
(2 x\$2,000 people)	
Attend Roundup meeting to promote CESME	\$4,000
(2 x\$2,000 people)	
Conferences for CESME members	\$4,000
Promotional materials	\$1,000
Invited speakers	\$3,500

* Scholarships provided by CESME are not included here.

Emerging Trends

CESME activities are more important than ever in the face of changing developments and conditions in the mining sector in northern Ontario. The mining industry is very active in Northern Ontario which has led to high employment rates and a number of funding opportunities for research, however, it has also highlighted the need for a greater number of graduates from the geoscience programs at Lakehead. Enrolments are down across Canada and we are working to expose school age students to geology and mining through collaborations with organisations like Mining Matters and working directly with local schoolboards and the Faculty of Education. The need for increased training to meet the growing economic development needs in Northern Ontario means that this will continue to be a priority for the Centre.



Appendix 1

Media reports, posters and publications





Industry Researcher Presentation Day CASES Main Boardroom FB 2005 9:00am EST - 5:30pm EST

Via Zoom:

ADD Zoom link here

Meeting ID:

Passcode:

Morning Agenda:

9:00am	Meet in CASES Main Boardroom
	**set up, coffee, open Zoom link
9:15am - 9:45am	Pete Hollings – CESME (Intro to CESME and some discussion of Geology research at Lakehead)
9:45am – 10:45am	Pedram Fatehi (Director, Biorefining Research Institute – will talk about his research into replacing chemicals in refining processes with greener alternatives)
10:45am – 11:00am	BREAK
11:00am – 12:00pm	Mike Dohan (Director, Center for Innovation and Entrepreneurship Research) https://www.lakeheadu.ca/research-and-innovation/facilities-centres/-centre-for-innovation-and-entrepreneurship-research-
12.00pm – 12.30pm	Meeting with External Relations team

Lunch

12:30pm – 1:30pm Lunch

Afternoon Agenda – Part Two – One on One Sessions

1:30pm – 2:30pm	Kathryn Sinden/Vicki Kristman. Vicky is Director for EPID@Work (our
	occupational health / safety centre)
2:30pm – 3:15pm	Kam Leung/Peter Lee – mine remediation

3:15pm – 3:30pm	BREAK
3:30pm – 4:30pm	Kathryn Sanderson - recently been researching newcomers to Canada, looking at welcoming, discrimination, and skills development. New project starting on mental health stigma at work
4:30pm – 5:30pm	Thomas Collins/Ryan Wilkie/Scott Hamilton – Thomas will discuss development and testing of remote controlled motorized kayaks for sonar mapping, perhaps in potentially hazardous places like tailings ponds. Ryan/Scott will be available to speak about aerial mapping operations and training
	Review and regroup

GEOLOGICAL WORK IN GREENSTONE BELTS

A SHORT COURSE

PRESENTED BY: SEG LAKEHEAD UNIVERSITY STUDENT CHAPTER





About the Presenter

Howard Poulsen attended the University of Waterloo (HBSc, Physics, 1970), Lakehead University (MSc, Structural Geology, 1980) and Queen's University (PhD, Economic Geology, 1984). With more than 25 years in total of prior research experience at Lakehead University, the Ontario Geological Survey and the Geological Survey of Canada, he has worked for the last 25 years as a consulting economic geologist who specializes in the structural geology of ore deposits. From 1998 to 2010 he was an adjunct professor at Queen's University where he taught a graduate course in structural geology and ore deposits for the mineral exploration (MINEX) program. His research has mainly focused on problems of significance to the global mineral exploration industry. He served as an associate editor for Economic Geology from 1993 to 1998 and is a fellow of the Society of Economic Geologists as well as a member of the Association of Geoscientists of Ontario.



Course Details

The one day course will focus on examples of common technical issues faced by geologists who conduct work in granite greenstone belts. It will consist of a brief introduction followed by four 90-minute technical modules and will conclude with a short summary of the main takeaways. The modules will discuss some of the recurring problems relating to stratigraphy, rock alteration and metamorphism, structural geology and various mineral deposit types using examples from granite-greenstone bels globally. A recurring theme will be the difficulty of making reliable geological maps, cross-sections and three-dimensional models that make clear and consistent distinctions among primary protoliths and the effects of overprinting fluid-dominated metasomatism and deformation.

Course content booklets, coffee breaks, and lunch will be provided.

ARTICLE



The geology, geochemistry, and magmatic evolution of the Legris Lake mafic–ultramafic complex, Ontario, Canada

Wyatt M. Bain^{1,2} · Pete Hollings¹ · Lionnel M. Djon³ · Matthew J. Brzozowski^{1,2} · Daniel Layton-Matthews⁴ · Agatha Dobosz⁴

Received: 18 October 2022 / Accepted: 23 May 2023 © The Author(s) 2023

Abstract

The Archean Legris Lake mafic–ultramafic complex (LLC) is spatially (~12 km east) and temporally (2690.59±0.77 Ma) associated with the world-class Lac des Iles (LDI) palladium deposit. Modeling of whole-rock major-element compositions suggests that this complex, previously interpreted as gabbroic, is gabbronoritic in composition, adding to the likely association between LDI and the LLC. Mantle normalized trace-element profiles and modeled parental melt compositions from the cumulate lithologies indicate initial melt extraction from a metasomatized mantle source in an arc setting and subsequent crystallization of olivine, orthopyroxene, and plagioclase at depth following assimilation of SiO₂ and S from tonalitic country rock. External S assimilation contributed to sulfide saturation at depth prior to or during emplacement, but sulfide melt entrainment in intruding magmas and its retention at the site of emplacement was variable. These interpretations are supported by (1) variations in Cu/Pd ratios between PGE-rich and PGE-poor lithologies, (2) the strongly negative Eu/Eu* of paragenetically early lithologies, (3) the overlap between whole-rock $\epsilon Nd_{(T)}$ values of LLC lithologies and Wabigoon tonalite, and (4) the positive $\delta^{34}S$ and uniformly non-zero $\Delta^{33}S$ values of magmatic sulfides. During emplacement the intruding melts also assimilated metasedimentary country rock. This effect likely became more pervasive during later stages and resulted in additional melt fractionation and inheritance of the trace-element signature of the metasedimentary country rock by the intruding magmas. This assimilation does not, however, seem to have been an important driver of sulfide saturation in this system.

Keywords Ore deposit—Layered mafic intrusions—Ni-Cu-PGE · Archean · Sm-Nd isotopes—Multiple sulfur isotopes

Introduction

A key part of meeting future demand for platinum-group elements (PGE) is exploration and development of layered mafic intrusions, and the development of petrologic models that can

Editorial handling: W. D. Maier

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Published online: 09 August 2023

contextualize the source (Maier et al. 2003; Barnes and Picard 1993), tectonic setting (Naldrett 2004, 2011; Barnes et al. 2016), and magmatic evolution of these systems (Fiorentini et al. 2010; Naldrett 2011; Mungall 2014). The Legris Lake mafic-ultramafic complex (LLC) is one such layered intrusive system located in northwestern Ontario, Canada, ~81 km northnorthwest of Thunder Bay and ~12 km southeast of the worldclass Lac des Iles (LDI) PGE deposit (Fig. 1). This system comprises the easternmost extent of an~30-km-wide, ring-shaped array of variably hornblende-rich, mafic-ultramafic intrusions located in the Archean Superior Province. These include the Tib Lake, Demars Lake, Wakinoo Lake, Tomle Lake, Buck Lake, Taman Lake, and Dog River intrusions (Sutcliffe 1986; Stone et al. 2003; hereafter referred to as the Lac des Iles Intrusive Suite). These intrusive systems are spatially related to the LDI system (Djon et al. 2018; Gupta and Sutcliffe 1990), and show textural, petrologic, and geochemical similarities that suggest a cogenetic relationship (Stone et al. 2003) and similar potential for hosting LDI-style PGE mineralization.



Fig. 1 a Regional geologic map showing locations of Thunder Bay, the Lac des Iles (LDI) mine (in red), and the Lac des Iles intrusive suite (in blue). b Geologic map of Legris Lake Intrusive Complex (after Pettigrew and Hattori 2002). Geologic domains are outlined with gray dotted lines and include the Northeastern Border Zone

Preliminary mapping, sampling, and exploration drilling in and around the LLC between 1999 and 2010 (Pettigrew and Hattori 2001, 2002; North American Palladium Ltd.) showed that this complex is associated with deep regional structures (i.e., tectonic sutures), contains large breccia-hosted zones of sulfide mineralization, and contains 0.5–1m-thick zones at depth with Pd grades as high as 4.5 ppm and Pd/Pt up to 23.6 (median of 2; Impala Canada Ltd.; Pettigrew and Hattori 2002). These features are consistent with the criteria recommended by Djon et al. (2018) for PGE exploration in and around the LDI system and, together, are indicative of a high degree of PGE prospectivity for the LLC relative to the other intrusions in the LDI intrusive suite.

Pettigrew and Hattori (2001, 2002) present a model for the LLC involving crystallization of olivine and orthopyroxene at depth, and subsequent emplacement of an evolved silicate magma that underwent sulfide saturation via external S assimilation from metasedimentary country

(NEBZ), Southeastern Border Zone (SEBZ), Central Zone (CZ), Southwestern Border Zone (SWBZ), and Northwestern Border Zone (NWBZ). Location of study area is denoted with a yellow star on the gray inset image (lower right)

rock. Here we further evaluate this model using new petrographic, geochemical, isotopic (Sm–Nd and multiple sulfur isotopes), and geochronologic (U–Pb) data sets, and present a detailed analysis of the source, setting, and role of crustal contaminants in driving the magmatic evolution of the LLC.

Geology of the Legris Lake mafi –ultramafic complex

Previous descriptions of the geology of the LLC have been provided by Pettigrew and Hattori (2001, 2002), and are briefly described here. The LLC has a surface exposure of ~ 19.5 km² and is situated near the Eastern margin of the Archean Wabigoon Subprovince (Superior Province) along its tectonic suture with the Quetico Subprovince (Fig. 1a). The igneous rocks of the Wabigoon Subprovince are subdivided into tonalites (~ 3 Ga), granitoid complexes (2732–2708 Ma), and post-tectonic granitoid stocks (2709–2685 Ma; Blackburn et al. 1991). The latter group includes several ~ 2.69-Ga mafic–ultramafic complexes that intrude earlier granitic–tonalitic lithologies of the Wabigoon Subprovince (Blackburn et al. 1991; Sutcliffe et al. 1989). The mafic–ultramafic intrusive complexes of the LDI Intrusive Suite are likely part of this group (Pettigrew and Hattori 2001).

Along its northern, southern, and eastern margins, the LLC is bordered by greenschist-facies metasedimentary and metavolcanic rocks of the Quetico Subprovince (Fig. 1b). The Quetico metavolcanic rocks are basaltic in composition and only contact the LLC along its northern boundary. The metasedimentary rocks are primarily greywackes, siltstones, conglomerates, and minor oxidefacies iron formations (Pettigrew and Hattori 2002) that are commonly interbedded with or crosscut by mafic metavolcanic rocks. Together these lithologies comprise part of an accretionary complex (Percival and Williams 1989) that formed during collision of the Wawa-Abitibi and Wabigoon terranes at ~ 2.696 Ga following docking of the Wabigoon and Winnipeg River terranes at ~ 2.7 Ga. The country rocks around the LLC contain well-developed NE-trending space cleavage that is associated with this accretionary episode (Williams 1990) and is overprinted by N-trending Midcontinent Rift-related fracture sets (~1100 Ma; Paces and Miller 1993). The intrusive rocks of the LLC are crosscut by the N-trending fracture sets but lack NE-trending space cleavage. This relationship roughly brackets the formation of the LLC between the accretion of the Wabigoon and Quetico Subprovinces and formation of the Midcontinent Rift (Pettigrew and Hattori 2001, 2002).

The LLC is composed primarily of gabbroic cumulate lithologies and scattered ultramafic occurrences (Fig. 1b). Most of the central and western portions of the LLC are covered by a biotite-rich variety of leucogabbro (plagioclase > pyroxene) that cross cuts a central mass of more mafic gabbro (plagioclase = pyroxene). Along the northern and western boundaries of the complex, biotite-poor leucogabbro and gabbro dominate, and are the main host for sulfide mineralization. In the eastern and southern half of the complex, gabbro surrounds isolated pods of melanogabbro (plagioclase < pyroxene) and clinopyroxenite, which contain small zones of ultramafic dunite and wehrlite that comprise the only olivine-bearing rocks in the complex (encountered during exploration drilling; Pettigrew and Hattori 2001, 2002). To the south, biotite-bearing leucogabbro is in sharp contact with an isolated mass of melanogabbro-clinopyroxenite and a large roof pendant of Quetico metasedimentary rock (Fig. 1b). Based on the distribution of these lithologies, Pettigrew and Hattori (2001, 2002) divided the LLC into five domains — the Central Zone (CZ), Southwestern Border Zone (SWBZ), Southeastern Border Zone (SEBZ), Northeastern Border Zone (NEBZ), and Northwestern Border Zone (NWBZ; Fig. 1b). These geologic domains are described in detail in Supplementary Material ESM1.

Sulfide-associated PGE mineralization in the LLC is concentrated in the fault-bounded Northwestern Border Zone (Fig. 1b). This area is primarily composed of biotite-poor leucogabbro and country rock-bearing heterolithic breccia, but exhibits significant variability in the texture, composition, degree of alteration, and sulfide content over areas of < 5 m. For example, a 70-m transect through this area might encounter partially melted metaconglomerate (Fig. 2a), partially assimilated xenoliths of amphibolite-grade metasedimentary rock (Fig. 2b, c), altered leucogabbro with primary magmatic layering (Fig. 2d), deformed clinopyroxenite breccia fragments in a leucogabbro matrix with well-developed flow textures (Fig. 2e), pods of sulfide mineralization (Fig. 2f), and cross-cutting zones of variably mineralized intrusive rocks showing textures indicative of high-temperature deformation (Fig. 2g, h). This complexity is also present at depth, with structures, textures, and rock types observed in drill core displaying little continuity with those observed at the surface (Pettigrew and Hattori 2002; North American Palladium Ltd.). The large compositional and textural diversity of this area is indicative of a dynamic igneous environment involving repeated episodes of silicate melt injection, host rock brecciation and deformation, and extensive interaction with country rocks (Pettigrew and Hattori 2002). This latter point is illustrated by the presence of abundant metasedimentary xenoliths in the LLC that exhibit textural features indicative of partial melting and assimilation (Pettigrew and Hattori 2002) such that xenoliths commonly grade into the intrusive rocks (Fig. 2a, b).

The central portion of the Northwestern Border Zone contains the greatest abundance of PGE-bearing sulfide mineralization in the LLC (Pettigrew and Hattori 2002; Impala Canada Ltd.), with previous exploration drilling intersecting multiple mineralized intervals (1 m or more) containing > 1 ppm Pd (up to 4.5 ppm Pd in hole LL01-14, median Pd/Pt of 1.2; Pettigrew and Hattori 2002). Additional drilling focused on the southern portion of the Northwestern Border Zone by North American Palladium Ltd. produced several holes with up to 2.25 ppm Pd (average 0.1) and average Pd/Pt of 2.73 (up to 27). This is less than the mineralized zones in the Mine Block Intrusion at LDI (average Pd concentration of 0.5-3.0 ppm and average Pd/Pt of 7-14; North American Palladium Ltd.), but comparable to ultramafic rocks in the northern extent of the LDI system (Djon et al. 2018).

Fig. 2 Outcrop photos of the Northwestern Border Zone of the Legris Lake Complex. a Partially melted metaconglomerate, with matrix material completely consumed by silicate melt. b Partially assimilated Quetico metasedimentary xenolith in leucogabbro. Note the reaction rim around the xenolith. c Contact between metasedimentary rock (left) and leucogabbro (right). Contact denoted by a red dotted line. **d** Leucogabbro with primary magmatic layers of pyroxenerich melanogabbro (outlined in red). e Clinopyroxenite breccia with leucogabbro matrix. f Oxidized, sulfide-bearing zone in leucogabbro. g Mineralized leucogabbro crosscut by later, unmineralized leucogabbro (denoted by yellow dotted line). Note the fragments of mineralized leucogabbro (red arrows) in the cross-cutting leucogabbro. h Partially deformed melanogabbro crosscut by later leucogabbro. Note the tapered ends of the melanogabbro masses that indicate partial solidification and subsequent deformation by the intruding leucogabbro



Methods

Sampling and preparation

A total of 100 samples were collected from surface localities throughout the LLC that were mapped and excavated as part of previous exploration and drilling campaigns in the early 2000s. A representative sample set of the major lithologies present in the LLC was collected from outcrops in each of the five major geologic domains of the LLC. It should be noted, however, that some rock types that were identified during previous exploration activities, but which represent volumetrically minor components of the intrusive suite within the LLC system (e.g., anorthosite, dunite, gabbrodiorite, and websterite), were not observed in outcrop and, thus, not sampled as part of this study. In addition, 60 samples of drill core that crosscut an ~ 527-m-long segment of sulfide- and PGE-bearing mafic cumulates (i.e., drill hole LL10-005, 47-527 m; Fig. 1) in the Northwestern Border Zone were also collected as part of this study. Relative to the highly variable suite of lithologies present in the Northwestern Border Zone, drill hole LL10-005 contains intervals of up to 60 m in which the rock types are continuous, well preserved, and ideal for petrographic and isotopic characterization. Following sample collection, a representative set of polished thin sections was prepared using the in-house rock preparation facility at Lakehead University.

Analytical methods

Analytical methods include petrography, whole-rock geochemistry, U–Pb geochronology, whole-rock Sm–Nd isotope analysis, in situ multiple S isotope analysis of sulfides via secondary ion mass spectrometry, and scanning electron microscope–mineral liberation analysis (SEM-MLA). Detailed descriptions of these methods are presented in the Supplementary Material ESM1.

Results

Petrography of the major rock types in the LLC system

The LLC contains a wide variety of rock types ranging from mafic–ultramafic cumulate rocks to amphibolitefacies volcanic and siliciclastic metasedimentary rocks. Table 1 summarizes the modal mineralogy of each lithology and accompanies a more detailed description of each lithology in ESM1 and previous work by Pettigrew and Hattori (2001, 2002).

The cumulate lithologies of the LLC are primarily plagioclase- and clinopyroxene-rich orthocumulate to adcumulate gabbros (Fig. 3a-c; ESM1, Fig. 1a-g), clinopyroxenite (Fig. 3d; ESM1, Fig. 1f, h), and minor volumes of other ultramafic lithologies (not observed). Here we differentiate the gabbroic rocks of the LLC based on the relative abundance of plagioclase and pyroxene into leucogabbro (Fig. 3a, b), gabbro, and melanogabbro (Fig. 3c) subvariants. The eastern half of the complex is primarily mesocumulate gabbro (Fig. 1b) that surrounds isolated masses of melanogabbro and clinopyroxenite. The western half of the complex is dominantly unaltered, adcumulate to mesocumulate leucogabbro, with abundant primary biotite and minor intergranular orthopyroxene (hereafter referred to as biotite-leucogabbro; Fig. 3b). This biotite-leucogabbro variant cross-cuts all other igneous lithologies and is paragenetically the youngest intrusive unit.

Platinum-group element-rich sulfide mineralization in the LLC is localized to the Northwestern Border Zone and is primarily hosted in a biotite-poor leucogabbro (Table 1), referred to hereafter as leucogabbro. This unit occurs in outcrop as finely layered masses with 1-10-cm-wide bands of melanogabrro and clinopyroxenite (Fig. 2b) and as matrix in heterolithic breccias. Sulfide mineralization occurs primarily as net-textured (Fig. 3e, f) and disseminated pyrite and chalcopyrite, with minor pyrrhotite and pentlandite (ESM1, Fig. 2a–f) and commonly comprises up to 5 vol% or more of the modal mineral abundance. Mineralized zones are typically surrounded by green alteration halos and orange sulfide weathering in outcrop (Fig. 2f, g), and are invariably associated with ilmenite, magnetite (Fig. 3f), and intercumulus biotite and quartz in thin section (ESM1, Fig. 2a). Though not observed in this study, platinumgroup minerals (PGM; Pd-Bi and Pt-Pd-Bi tellurides) are associated with Cu-Ni sulfides (Pettigrew and Hattori 2002). Outside of the Northwestern Border Zone, PGE-bearing sulfide mineralization is mostly absent or limited to small, isolated showings.

Much of the LLC is overprinted by hydrous alteration that is expressed as uralitization of primary pyroxene to hornblende-actinolite-chlorite-epidote-talc and sericitization of primary plagioclase. This alteration is most pervasive in the Northwestern Border Zone where primary pyroxene and plagioclase are commonly only discernable as hornblende and sericite pseudomorphs (ESM1, Fig. 1h). In contrast, the paragenetically late biotite-leucogabbro is relatively unaltered (Fig. 2b; ESM1, Fig. 1c-e).

Table 1 Summary of major lithologies in the LLC describing modal mineralogy of cumulate and intercumulate mineral phases

Lithology	Description of observed composition *,†	Comments	
Leucogabbro (LGAB)	Cumulus plagioclase (~60–75%) and cpx (~15–40%) with intergranular quartz (~1–5%) and biotite (~1–5%; up to~10% locally). Up to~5% sulfides, when observed. Includes course-grained varitextured varieties	Main host for sulfide mineralization	
Biotite-leucogabbro (LGAB-Bio)	Cumulus plagioclase (~60–65%), ophitic cpx (~15–18%), euhedral opx (~10–12%), apatite- and zircon-bearing biotite (~5–15%), and quartz (~<5%)	Least altered and paragenetically latest intrusive phase	
Gabbro (GAB)	Cumulus plagioclase (~40–50%) and cpx (~40–50%) with variable intergranular quartz and apatite- and zircon-bearing biotite (up to ~15% total). Sulfide/oxides are com- monly < 1% but can be up to 5% in the North- western Boarder Zone	Comprises most of the LLC	
Melanogabbro (MGAB)	Cumulus cpx (\sim 50–70%) and plagioclase (30–40%) with minor intergranular quartz and magnetite (\sim <15%, total). Sulfide mineraliza- tion is <2% when observed	Occurs as segregated bands in layered lithologies or as isolated masses	
Clinopyroxenite (CPXTY)	Cumulus cpx (~90–95%) and plagioclase (<5%) with intergranular biotite (<5%). Sulfide mineralization is $<1\%$ when observed	Occurs as segregated bands in layered lithologies or as isolated masses	
Quetico metasedimentary rocks (MTSD)	Arkose sandstone, siltstone, graywacke, coarse pebble conglomerate, banded volcaniclastic rock, and iron formations. Commonly occurs as a component of heterolithic breccias or as xenoliths and roof pendants	Altered to amphibolite facies along the LLC's periphery	
Alteration	Hydrous alteration involving the uralitiza- tion of primary cpx/opx and sericitization of primary plagioclase. Pyroxene pseudomorph of hornblende–actinolite–chlorite–epidote–talc and sericite pseudomorph of plagioclase are common in heavily altered lithologies	Pyroxene throughout the complex are significantly more altered than plagioclase	

*Estimated modal abundances observed in transmitted light represent the observed abundance of primary phases plus alteration products (i.e., amphibole, sericite, talc, chlorite, epidote) that occur either within partly altered primary mineral phases or as pseudomorphs. It should be noted that orthopyroxene (opx) was only directly observed in biotite-leucogabbor, but is likely to comprise up to 40% of the total pyroxene abundance that occur along with clinopyroxene (cpx). See discussion for details

[†]All modal abundances reported in vol%

Petrography and chemostratigraphy of layered intrusive rocks in the LLC

Drill hole LL10-005 samples a continuous interval of sulfide-bearing cumulate rock. The dominant rock type here is orthocumulate leucogabbro, with well-preserved, horizontally (Fig. 2d) oriented magmatic layering. The layering occurs in discrete packages (units) that include zones of heterolithic breccia with abundant fragments of Quetico metasedimentary rock (visible in hand sample and outcrop). Boundaries between individual units are visible in thin section and are characterized by an abrupt change in phenocryst grain size and the modal abundance of primary plagioclase and clinopyroxene at the tops and bottoms of each layer.

Individual layers commonly have more mafic lithologies (melanogabbro with intervals of clinopyroxenite) at their stratigraphic tops that grade downward into bands of mineralized gabbro and leucogabbro at their stratigraphic bottoms. This pattern is visible in downhole plots as systematic trends in MgO, CaO, Fe_2O_3 , S, Cu, Ni, Pd, and Pt enrichment or depletion that are truncated or reversed at the stratigraphic tops and bottoms of each unit in a cyclic manner (Fig. 4). Five geochemical segments (referred to hereafter as cyclic units; CU) are identified in Fig. 4 between 0- and 500-m depth in drill hole LL10-005: CU1 (0–67 m), CU2 (68–136 m), CU3 (137–277 m), CU4 (278–397 m), and CU5 (398–497 m). Within a single cyclic unit, MgO, CaO, and Fe_2O_3 concentrations decrease systematically from top to bottom and track a modal increase in plagioclase abundance.

Fig. 3 Photomicrographs of cumulate lithologies from the LLC in cross-polarized light. a Leucogabbro showing plagioclase (pl) phenocrysts with minor sericite (ser) alteration and intergranular clinopyroxene (cpx; replaced by amphibole: amp) and pyrite (Py). b Biotite-leucogabbro with tightly interlocking plagioclase and ophitic clinopyroxene (cpx). Note the opaque magnetite (mag) surrounding plagioclase in the lower left-hand corner. c Melanogabbro with tightly interlocking plagioclase, with clinopyroxene partially replaced by amphibole. d Least altered clinopyroxenite showing tightly interlocking clinopyroxene altered to amphibole. Note that these images are of adcumulate varieties of major lithologies. e Cross-polarized photomicrograph (XPL) of plagioclase and pyroxene phenocrysts (altered to amphibole) surrounded by opaque net-textured sulfides (sul). f Area shown in panel "a" in reflected light showing intergrown pyrite (py), chalcopyrite (ccp), and magnetite (mag). Scale bar in inset image is 50 µm



This pattern matches the paragenesis of mineral phases in gabbroic lithologies in hand sample where plagioclase is the paragenetically earliest cumulus phase and pyroxene either surrounds plagioclase or is an intergranular phase.

Pyrite mineralization occurs throughout LL10-005 and is reflected in the high S concentrations along the length of most cyclic units (Fig. 4). However, chalcopyrite, pentlandite, and PGE mineralization is most abundant in CU1 and CU5 and is concentrated near the stratigraphic bottoms of each unit where the highest S, Cu Ni, Pd, and Pt concentrations are observed (Fig. 4). In contrast CU2–CU4 have very low concentrations of base metal sulfides and essentially no PGE mineralization. In addition, the abundance of chalcopyrite in hand sample is negatively correlated with the occurrence of metasedimentary rock xenoliths. This is the case in CU2–CU4, which commonly contained abundant metasedimentary rock fragments and have the lowest PGE, Ni, and Cu concentrations.

Geochronology of the mineralized leucogabbro

A single sample of coarse-grained leucogabbro from the Northwestern Border Zone was selected for zircon U–Pb ID-TIMS geochronology. Analytical results and transmittedlight photomicrographs of representative zircons chosen for analysis are provided in Supplementary Table 1 in ESM2. The analyzed sample yielded an abundant population of non-magnetic, skeletal, inclusion-free zircon crystals. Most grains were subhedral and elongate in form, without any well-developed facets, suggestive of relatively late, but rapid crystallization conditions.

Four of the analyzed single grain fractions contain ~ 170–600 ppm, moderate Th/U ratios (0.47–0.64), and a narrow range in 207 Pb/ 206 Pb ages, with an age of 2690.6 ± 0.8 Ma (2 SD, n = 4). Geochronological results for all four zircon fractions overlap and fall within the 2σ

Fig. 4 Downhole plots from drill hole LL10-005. Individual layered intrusive units (cyclic units) are bracketed with red dotted lines. Note the systematic decrease in the MgO with depth in each unit (e.g., CU2 and CU3). This is related to a modal increase in plagioclase with depth. Also note the correlation between S. Ni, Cu. Pt. and Pd. indicative of base-metal sulfide and sulfide-associated PGE mineralization and a general lack of olivine in the layered units. The area highlighted in yellow contains an interval of metasedimentary rock-bearing heterolithic breccia; note the more complicated and less systematic variation in majorelement compositions in this section



uncertainty limits of the Concordia band (0.0–0.2% discordant). Considering the four zircon fractions together yield a weighted average age of 2690.59 ± 0.77 Ma (MSWD=0.1, probability of fit=96%).

Whole-rock geochemistry

Whole-rock major and trace element geochemical data gathered form surface exposures and drill hole LL10-005 in the Northwestern Border Zone (this study and Impala Canada Ltd., geochemical data bases) are summarized in Table 2 and Supplementary Table 3 in ESM2. See Supplementary Tables 2 and 4 in ESM2 for full data set.

Generally, the major-element compositions of intrusive lithologies from the LLC fall into two distinct groups. The first group accounts for the majority of samples collected in the LLC and is visualized in CaO vs. MgO space primarily as a linear trace of data points between 5.0–15.0 wt% CaO and 4.0–16.0 wt.% MgO that intersects, and is subparallel to, the clinopyroxene–albite control line (Fig. 4a). A subset of data points systematically skews away from the trend towards a cluster of data points near the origin that closely overlaps the composition of the Quetico metasedimentary

Table 2 Summary of whole-rock geochemistry of major lithologies in the Legris Lake Complex

	CPXY	T(n=5)	j)	MGAI	B (n=4)		GAB	(n=121))*	LGAB	s (n=5)		LGAB-Bio $(n=1)$	$\begin{array}{c} \text{MTSD} \\ (n=1) \end{array}$	Ton $(n=1)$
	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med			
SiO ₂	40.2	55.9	46.9	49.4	51.8	50.9				48.3	64.2	50.2	56.5	68.8	66.9
Al_2O_3	4.0	15.8	9.6	13.6	15.2	14.8	1.1	20.6	3.7	12.6	20.7	19.9	14.9	13.2	15.4
Fe ₂ O ₃	12.4	23.0	19.3	10.9	13.4	13.2	5.1	35.7	8.4	3.0	18.1	10.5	9.1	7.3	5.4
CaO	3.9	12.6	8.4	8.9	10.3	9.7	0.3	12.6	7.6	4.5	10.2	9.4	6.5	2.2	4.6
MgO	5.2	18.0	11.8	6.3	9.2	7.7	0.5	13.1	6.1	1.7	11.7	4.1	4.9	3.5	1.9
Na ₂ O	0.6	3.0	0.9	2.4	2.9	2.7	0.0	4.6	2.8	1.4	5.7	3.4	3.7	2.6	4.1
K2O	0.1	2.7	0.3	0.3	0.7	0.4	0.0	4.4	1.1	0.6	1.0	0.9	2.9	1.4	1.4
Cr_2O_3	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TiO_2	0.8	2.8	1.3	0.8	1.1	0.8	0.0	2.5	0.7	0.3	0.7	0.6	0.8	0.7	0.5
MnO	0.1	0.3	0.2	0.2	0.3	0.2	0.0	0.2	0.1	0.0	0.2	0.1	0.1	0.1	0.1
P_2O_5	0.0	0.3	0.1	0.1	0.4	0.2	0.0	0.8	0.3	0.0	0.3	0.1	0.5	0.1	0.1
SrO	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0
BaO	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.0
LOI	0.4	1.9	0.7	0.3	1.7	1.3				0.6	3.4	1.8	0.1	2.7	0.9
Cs	0.1	2.5	0.3	0.2	1.2	0.6				1.0	2.5	1.9	2.1	1.9	1.5
Rb	1.8	73.7	2.7	2.8	23.3	8.0				18.9	32.6	20.8	62.8	35.2	57.9
Ba	57.9	870.6	83.9	136.7	383.3	294.3	0.5	1000.0	307.0	204.1	464.6	255.1	854.4	425.2	326.0
Th	0.2	4.1	0.7	0.1	2.1	0.3				0.1	1.3	0.4	6.5	4.4	6.6
U	-	0.5	0.2	-	0.6	0.1				0.1	0.4	0.2	1.5	1.1	0.9
Та	0.1	0.8	0.2	0.1	0.4	0.2				0.1	0.2	0.1	0.5	0.4	1.3
Nb	1.1	13.1	3.6	1.0	6.4	2.4				0.6	2.9	2.2	8.9	4.8	10.2
La	6.5	20.9	10.1	7.6	24.4	17.5	1.6	39.8	9.7	5.0	10.7	6.8	56.0	15.7	18.0
Ce	21.9	45.6	37.3	16.2	58.6	40.1				11.0	24.5	14.2	125.1	31.7	39.1
Pb		2.0					1.0	20.0	4.0		5.0		11.0	11.3	9.0
Pr	3.9	6.7	4.7	2.3	8.7	5.4				1.6	3.2	1.9	16.4	3.9	4.5
Sr	92.9	565.1	465.9	188.6	973.9	591.0	7.0	1160.0	475.0	140.9	874.0	514.3	844.4	173.2	240.0
Nd	18.6	34.0	22.7	9.7	40.1	23.2				5.8	14.1	7.2	65.9	14.5	16.8
Zr	30.1	184.3	44.6	29.5	89.3	34.9	0.5	313.0	39.0	10.1	70.4	33.2	165.1	125.2	143.0
Hf	1.1	5.2	1.7	1.1	2.6	1.1				0.4	1.9	0.9	4.5	3.1	3.8
Sm	3.5	8.9	6.0	2.2	9.0	5.2				1.1	3.1	1.7	12.6	2.8	4.0
Eu	1.1	2.5	1.5	0.9	2.8	1.7				0.5	1.1	0.9	3.0	0.8	0.9
Gd	3.3	7.6	5.3	2.4	7.5	4.9				1.2	2.8	1.8	9.3	2.6	3.9
Tb	0.5	1.1	0.7	0.4	0.9	0.7				0.2	0.4	0.3	1.1	0.4	0.7
Dy	2.7	6.0	3.5	2.6	4.2	3.8				0.8	2.2	1.6	4.9	2.7	4.3
Y	12.8	27.4	15.9	14.6	22.0	17.4	0.5	38.0	16.0	4.5	11.3	8.4	22.5	13.2	28.7
Но	0.6	1.1	0.7	0.6	0.8	0.7				0.2	0.5	0.3	0.9	0.5	0.9
Er	1.5	2.9	1.6	1.6	2.4	1.7				0.4	1.3	0.9	2.1	1.6	2.6
Tm	0.2	0.4	0.3	0.2	0.4	0.2				0.1	0.2	0.1	0.3	0.2	0.4
Yb	1.1	2.2	1.4	1.4	2.4	1.5				0.4	1.1	1.0	1.8	1.5	2.9
Lu	0.2	0.3	0.2	0.2	0.3	0.2				0.1	0.2	0.1	0.3	0.2	0.4
V	268.1	966.0	424.1	213.5	341.0	289.8	16.0	2540.0	168.0	49.3	299.3	223.2	178.1	173.3	89.0
Sc	24.2	70.0	29.1	28.5	37.3	31.3	0.5	51.0	21.0	4.0	23.3	17.4	17.0	21.1	9.0
La/Sm	1.1	6.0	1.2	2.7	3.5	3.3				3.0	5.4	3.7	4.4	5.6	4.6
Gb/Yb	2.3	4.6	4.1	1.5	5.2	2.8				1.3	3.0	2.1	5.3	1.7	1.3
La/Yb	5.1	14.7	6.8	4.7	16.9	10.7				4.5	16.6	7.8	32.0	10.4	6.2
Ta/Yb	0.1	0.4	0.2	0.1	0.2	0.1				0.1	0.5	0.1	0.3	0.2	0.5
Th/Yb	0.1	2.9	0.4	0.1	0.9	0.2				0.1	1.3	0.4	3.7	2.9	2.3
Nb/Yb	1.0	5.9	2.8	0.7	2.7	1.6				0.5	7.1	2.3	5.1	3.2	3.5

Table 2 (continued)

	CPXYT $(n=5)$)	MGAB $(n=4)$		GAB (n=121)*		LGAB $(n=5)$		LGAB-Bio $(n=1)$	$\begin{array}{c} \text{MTSD} \\ (n=1) \end{array}$	Ton $(n=1)$			
	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med			
Ba/Th	78.2	439.5	189.7	115.7	3427.3	922.9				162.8	1775.0	922.2	131.4	95.8	49.6
Th/Nb	0.1	0.7	0.2	0.1	0.3	0.1				0.1	0.7	0.2	0.7	0.9	0.7
Th/La	0.0	0.2	0.1	0.0	0.2	0.0				0.0	0.2	0.0	0.1	0.3	0.4
Zr/Nb	10.3	27.3	14.1	13.1	29.0	15.6				13.3	24.1	18.3	18.5	26.2	14.1
Zr/Y	2.0	10.6	2.3	1.6	4.1	2.3			2.4	1.1	15.6	4.0	7.3	9.5	5.0
Zr/Hf	24.7	38.3	27.3	26.4	34.5	31.2				25.0	44.0	35.6	36.7	39.9	37.2
Eu/Eu*	0.6	1.1	0.8	1.0	1.3	1.1				1.1	1.6	1.4	0.9	0.9	1.1
Nb/Nb*	0.2	1.1	0.5	0.2	0.7	0.3				0.2	0.5	0.4	0.2	0.2	0.1
Sr/Sr*	0.2	1.6	1.2	0.8	1.6	1.5				1.2	6.3	3.0	0.7	0.6	0.9
Zr/Zr*	0.2	1.2	0.2	0.1	0.9	0.4				0.2	1.5	0.5	0.4	1.4	4.2
Ti/Ti*	0.6	1.3	1.0	0.4	1.0	0.7				0.8	1.5	1.0	0.4	0.8	0.9
Y/Ho*	0.8	0.9	0.8	0.9	0.9	0.9				0.8	1.0	0.9	0.9	0.9	0.9

Data shown here is compiled for the Impala Canada Ltd., geochemical database. All oxide concentrations are shown in wt%. All trace elements are shown in ppm

*Calculated using trace element data normalized with values of Sun and McDonough (1989)

†From Impala Canada Ltd., database

Fig. 5 Bivariate plots showing whole-rock major-element data from surface samples (a and c) and drill hole LL10-005 (b and d). Bimodal mixing lines for pure albite (ab)-orthopyroxene (opx), anorthite (an)orthopyroxene (opx), anorthite-clinopyroxene (cpx), and albite-clinopyroxene are shown as dotted lines (see legend for details). The composition of Quetico metasedimentary rock is outlined with a black dotted line. Note that the misalignment between data from this study (symbols outlined in black in d and b) and data from the Impala Canada Ltd., geochemical database (semi-transparent symbols in d and b) in Al₂O₃ vs. MgO space (outlined with gray dotted line in "d") is the result of incomplete dissolution of aluminous mineral phases during the analysis obtained by Impala Canada Ltd



rocks that envelope the complex along its eastern edge. These data clusters within the primary group are observed in all major-element data (e.g., Na_2O , TiO_2 , Fe_2O_3 , Cr vs. MgO) from intrusive lithologies in the LLC.

The second group represents data from mineralized cyclic units and metasedimentary rock-bearing lithologies observed in drill hole LL10-005. These data points plot mostly between the orthopyroxene-albite and orthopyroxene-anorthite control lines, and can be visualized in Al₂O₃ and CaO vs. MgO space (Fig. 5b, d) as upward arcing arrays (between ~ 1.0 and 23.0 wt% Al₂O₃, ~ 2.0 and 12.0 wt% CaO, and ~1.0 and 16.0 wt% MgO), with an inflection point at ~5 wt% MgO. The low MgO segment of this array consists of samples from the bottoms of cyclic units (described below) and, in all cases, overlaps with the upper compositional range of the local Quetico metasedimentary rock. The higher MgO (~5.0-22.0 wt% MgO) segment of this array is representative of the middle and tops of the cyclic units identified in LL10-005, and occurs between the orthopyroxene-albite and orthopyroxene-anorthite control lines in CaO vs. MgO space and roughly parallel to, or slightly overlapping the orthopyroxene-albite control line in Al₂O₃ vs. MgO space.

Primitive-mantle normalized trace-element profiles of all lithologies (e.g. leucogabbro and clinopyroxenite; Fig. 6a, b) are nearly identical: they have strongly fractionated light REE (LREE; median primitive-mantle normalized La/Sm of 1.35-2.87) and heavy REE (HREE; median primitive-mantle normalized Gd/Yb of 1.67-4.37) patterns, are enriched in the fluid-mobile large-ion lithophile elements (LILE; Cs, Rb, Ba, and K) and Pb, have generally high Ba/Th ratios (median values of absolute concentrations: clinopyroxenite = 190, melanogabbro = 923, leucogabbro = 922), have Hf/Zr and Y/Ho ratios that are uniformly near unity, and have negative Nb (range of median Nb/Nb* of 0.16–0.45; Nb/Nb* = Nb_n/(Th_n•La_n)^{0.5}) and Zr anomalies (range of median Zr/Zr* of 0.22-0.45; Zr/ $Zr^* = Zr_n/(Nd_n \bullet Sm_n)^{0.5}$). In addition, Th/Nb, Zr/Nb, and Zr/Y ratios are consistently near primitive mantle values (PM: 0.12, 15.96, and 2.44, respectively), varying within 1 order of magnitude or less (Table 2). However, Eu concentrations do show some variability between rock types and are positively correlated with estimated modal plagioclase abundances, with Eu/Eu* (Eu/Eu*= $Eu_n/(Sm_n \bullet Gd_n)^{0.5}$) being slightly negative (median=0.84) in clinopyroxenite, and moderately to strongly positive in melanogabbro (median = 1.07) and leucogabbro (median = 1.36). Likewise, Sr concentrations are variable across all rock types, but are typically strongly enriched in melanogabbro and leucogabbro (median Sr/Sr*=1.94 and 2.97, respectively; $Sr/Sr^* = Sr_n/(Ce_n \bullet Nd_n)^{0.5}$), and mostly flat in clinopyroxenite (median $Sr/Sr^* = 1.17$). Titanium is also highly variable, with Ti/Ti* ranging from positive to strongly negative (median Ti/Ti* of 0.37–1.10; Ti/Ti* = $Ti_n/(Gd_n \bullet Dy_n)^{0.5}$).

The trace-element compositions of the sulfide-bearing cyclic units in the Northwestern Border Zone (Fig. 6c, d)



Fig. 6 Primitive mantle-normalized trace-element profiles for leucogabbro (a), clinopyroxene (b), and cyclic units from drill hole LL10-005 (c: CU1 and d: CU5). The average trace-element profile for LLC lithologies in each panel is shown as a purple dotted line in each panel. Profiles for Quetico metasedimentary rock (pink line) and Wabigoon hornblende-tonalite (yellow) are shown in "a" and "d." The trace-element profile for biotite-leucogabbro is shown in blue in "a." Note the contrast in the magnitude and polarity of Zr-Hf anomalies in Quetico metasedimentary rock, tonalite, and LLC lithologies. e Primitive mantle-normalized trace-element profiles for N-MORB, E-MORB, and OIB (Sun and McDonough 1989), continental arc gabbro (Sierra Nevada: McCarthy et al. 2016), and oceanic arc basalt (Tonga arc: Ewart and Hawkesworth 1987; Mariana arc: Yanhong et al. 2021) overlain on the average range of trace-element compositions of all lithologies in the LLC (gray field). Normalization values from Sun and McDonough (1989)

are similar to the unmineralized leucogabbbro elsewhere in the complex. These similarities include enrichment in the fluid-mobile lithophile elements (Cs, Rb, Ba, K; high absolute Ba/Th ratios, with median values of 144–615) and Pb, negative Nb and Zr anomalies (median Nb/ Nb*=0.15–0.33; median Zr/Zr*=0.25–0.87), Hf/Zr and Y/Ho ratios that are uniformly near unity, flat to negative Ti/Ti* anomalies (median Ti/Ti*=0.67–0.99), flat to strongly positive Eu/Eu* and Sr/Sr* anomalies (median Eu/Eu* and Sr/Sr* between 0.96–1.28 and 0.84–2.97), and Th/Nb, Zr/Nb, and Zr/Y ratios near that of the primitive mantle. However, the mineralized lithologies tend to have more fractionated LREE (median La/Sm_{pm}=2.22–3.54) and HREE (median Gd/Yb_{nm}=1.57–2.09) compositions.

A general feature of the trace-element data for all major lithologies is that the upper range of variability matches the composition and pattern of enrichment/depletion observed in the local Quetico metasedimentary country rock (e.g., Fig. 6a, d). This feature is particularly apparent in the cyclic units in which primitive mantle trace-element profiles occur along a continuum between more primitive profiles (closer to PM for most elements) with strongly negative Nb and Zr anomalies and more evolved profiles with more fractionated REE patterns and flatter Nb and Zr anomalies (Fig. 6d). Moreover, the paragenetically late biotite-leucogabbro has much more evolved composition with highly fractionated LREE (La/Sm_{pm} = 2.87) and HREE profiles (median Gd/Yb_{pm} = 4.34), but displays many of the same trends in trace-element depletion/enrichment as the Quetico metasedimentary country rock. These include similar Ba/Th ratios, Nb/Nb*, Sr/Sr*, and Ti/Ti*. However, the magnitude of the Zr/Zr* in the biotite-leucogabbro (0.40) is similar to the other lithologies in the LLC.

Sulfur, Se, PGE, and base-metal concentrations of surface samples from the LLC are summarized in Supplementary Table 5 in ESM2. Sulfide mineralization in the LLC is relatively sparse outside the Northwestern Border Zone, with concentrations of S, Se, Pd, Pt, Cu, and Au generally quite low across all lithologies (ESM2, Table 5), except in isolated zones of pyrite- and chalcopyrite-bearing leucogabbro and gabbro (up to 2.50 wt% S, 4.71 ppm Se, 1.40 ppm Pd, 0.53 ppm Pt, 5000 ppm Cu, and 1 ppm Au). In these zones, S-Cu and Pd-Pt are correlated with one another, consistent with the presence of chalcopyrite- and sulfide-associated PGE mineralization. More mafic lithologies (i.e., clinopyroxenite and melanogabbro) exhibit consistently lower metal concentrations relative to the more felsic lithologies (gabbro and leucogabbro), but have similar Pd/Pt ratios (range of median Pd/ Pt across all lithologies: 1.17–1.71).

The highest concentrations of, and most clear correlation between, base and precious metals and S occur in the Northwestern Border Zone in the basal portions of cyclic units CU1 and CU5 (Fig. 4). Here the abundances of Cu, Pd, and S are strongly correlated with depth and the modal abundance of chalcopyrite (Fig. 7a, c). Palladium and Pt strongly correlate with one another in all lithologies (Fig. 7d) but form two groups of data points relative to the concentration of PGE-bearing mineralization: one with median Pd/Pt of 4.21-5.03 (CU1, CU2, CU5; Fig. 7d) and another with 0.85-1.71 (CU3, CU4; Fig. 7d). Palladium and Cu are positively correlated and mostly within the range of the primitive mantle (Fig. 7e) in CU1 and CU5. In contrast, Cu and Pd show little correlation in CU2-CU4 and, with the exception of CU2, data plot below the mantle range in Pd vs. Cu space (Fig. 7e). Cu/Pd ratios vary widely across all cyclic units (overall range: 235-128,800), with data from CU1 (median value of 4663) and CU5 (median value of 4381) falling within the range of the primitive mantle (~1000-10,000; Barnes et al. 1993), and CU2-CU4 forming a cluster at higher values (median values of 8029, 23,533, and 28,833, respectively; Fig. 7f). Similarly, S/Se ratios are above the mantle range (2632-4350; Eckstrand and Hulbert 1987) in CU2-CU4 (median values of 5735, 8220, and 8699, respectively), near the mantle range in CU5 (median value of 4542), and at or below the mantle range in CU1 (median value of 1902; Fig. 7f).

The concentration of Ni throughout the LLC is generally quite low (typically < 194 ppm in all rock types) and shows a strong positive correlation with MgO and little to no correlation with S (Fig. 7b). Departures from this trend are only observed in CU5 and CU1, where high Ni concentrations correlate with the presence of pentlandite in the sulfide assemblage. This is consistent with the correlation between S and Ni at S concentrations > 8000 ppm in CU1 and CU5 (Fig. 7b).

Sm-Nd isotope composition of sulfide-bearing cyclic units

Whole-rock Sm-Nd isotope data from cyclic units in drill hole LL10-005 and Quetico metasedimentary rock (this study) are summarized in Supplementary Table 6 in ESM2 and shown in Fig. 8. The εNd_T values for LLC lithologies and Quetico metasedimentary rock were calculated using a zircon U-Pb age of 2690.59 (± 0.77) Ma (this study) and ~ 2703 Ma (Davis et al. 1990), respectively. Cumulate lithologies from the LLC have εNd_T values between -0.06and +1.34 with most samples having positive, mantle-like values (DePaolo 1988). The total range of εNd_T values for the LLC are within the overall range of the ϵNd_T values for the LDI system (recalculated from Brügmann et al. 1997; Fig. 8), but cluster at positive values similar to Wabigoon tonalite (+0.76 to + 1.43). Quetico metasedimentary rocks bracket the lower range of LLC data at -0.28 and -0.58. Samples from CU1 and CU5 (the most mineralized cyclic

Fig. 7 Metal, S, and Se concentrations of whole-rock samples from mineralized cyclic units from drill hole LL10-005 (symbols outlined in black) and surface whole-rock samples from across the LLC (semi-transparent symbols). a-c Bivariate plots of whole-rock Pd, Ni, and Cu vs. S. Note that Ni concentrations are low in the LLC and are only correlated with S in CU1 and CU5 where pentlandite was observed. d Bivariate plots showing whole-rock Pd vs. Pt showing average Pd/Pt for each cyclic unit. e Bivariate plots showing whole-rock Pd vs. Cu. Mantle range from Barnes et al. (1993). f Comparison of whole-rock Cu/Pd and S/Se ratios. Gray field illustrates the mantle range of Cu/Pd and S/Se from Barnes et al. (1993; 1000-10,000) and Eckstrand and Hulbert (1987; 2632-4350), respectively. Colored fields represent the Cu/ Pd vs. S/Se range of various other Ni-Cu-PGE deposits (after Brzozowski et al. 2020)



units) show the least variability relative to CU2–CU4 (Fig. 8) and are nearly identical range as that of the Wabigoon tonalite.

Sulfur isotopes

Multiple sulfur isotope data form pyrite, pyrrhotite, pentlandite, and chalcopyrite from the LLC are summarized in Table 3 (full data set in ESM2, Table 7). Figure 9 shows the average measured δ^{34} S values for individual sulfide grains by sulfide phase in each cyclic unit. The majority of the data points are within the mantle range ($0 \pm 1\%$; Sakai et al. 1984; Ripley and Li 2003; Seal 2006) and skew toward more positive values (Fig. 9a). No clear systematic difference is observed in the measured δ^{34} S that might indicate significant fractionation between sulfide phases. The average Δ^{33} S for individual sulfide grains across all sulfide phases are uniformly negative, non-zero values (Fig. 9b), and are beyond the range of variability that could arise for mass-dependent fractionation processes ($0 \pm 0.1\%$; Farquhar and Wing 2003). The average range of δ^{34} S values for Quetico metasedimentary rock are bracketed by the δ^{34} S values of mineralized intrusive rocks form the LLC (Fig. 10a). Likewise, the Δ^{33} S values for Quetico metasedimentary rock are also non-zero, but are less negative than most LLC cumulate lithologies.



Fig. 8 Whole-rock eNd_T values for LDI, Tib Lake (Tib), and Wabigoon tonalite and Shelby Lake Diorite (from Brügmann et al. 1997) alongside that of the layered intrusive units from the LLC (yellow symbols) and Quetico metasedimentary rock (Q Meta Sed). Mantel value from Depaolo (1988). See legend for more details. eNd_T values for tonalite varieties (Gn=gneiss, Hbl=hornblende, Bt=biotite), Shelby Lake Diorite, and gabbroic rocks form the LDI systems were recalculated using Sm–Nd data from Brügmann et al. (1997) and average zircon U–Pb ages of~2917–2728 Ma,~2690 Ma, and~2689 Ma, respectively (Ontario Geological Survey 2019)

Discussion

LDI and the LLC: Temporally associated intrusive complexes in a larger intrusive suite

The mafic–ultramafic systems of the LDI intrusive suite have similar petrographic and geochemical features, crosscutting relationships with Archean host rocks, and NEtrending space cleavage parallel to the suture between the Wabigoon and Quetico Subprovinces (Stone 2010). These features suggest contemporaneous emplacement of the LDI intrusive suite during the subduction of the Wawa–Abitibi slab and formation of the Quetico Subprovince (Beakhouse and Davis 2005; Percival et al. 2012) following its accretion with the Wabigoon Subprovince at approximately 2.696–2.690 Ga (Williams 1990; Pettigrew and Hattori 2002; Stone 2010; Percival et al. 2012). When compared to the reported ages of the Mine Block Intrusion at LDI (2693.3 ± 1.3 Ma, and 2689.0 ± 1.0 Ma; Stone 2010) and the nearby Tib Lake Complex (2685.9 ± 1.6 Ma; Stone 2010), the U–Pb zircon age of 2690.59 ± 0.77 Ma for the LLC reported here is consistent with this interpretation, and indicates that the emplacement of the LDI intrusive suite was coeval with the formation of arc-related Alaskan-type ultramafic intrusions in the Quetico terrane (Pettigrew 2004). This suggests that the intrusive complexes of the LDI intrusive suite are also arc-related and part of a larger Archean arc-like setting.

Cyclic units in the LLC

The magmatic layering visible in downhole geochemical data from LL10-005 (Fig. 4) strongly resembles the cyclic units observed in many layered mafic intrusions globally (Great Dyke: Wilson and Prendergast 1989; Jimberlana intrusions: Campbell 1977; Duke Island Complex: Irvine 1974; Bushveld: Eales and Cawthorn 1996; Stillwater: McCallum 1996, Jackson 1961; Skaergaard: Boudreau and McBirney 1997; Sept Iles intrusion: Namur et al. 2010; North Lac De Iles: Djon et al. 2017a, b). A characteristic feature of cyclic units is the presence of systematic or repeating trends of element enrichment and depletion with depth that are truncated or reversed at the stratigraphic tops and bottoms of individual intrusive layers (Jackson 1961). This pattern reflects the formation of cyclic units by repeated injections of melt from a source reservoir and continuous fractionation at the site of emplacement with little external modification (Jackson 1961). A similar interpretation is applied to the cyclic units in the LLC (Fig. 4). However, a distinctive feature of the cyclic units in the LLC is that they are characterized by an upward modal increase in pyroxene rather than plagioclase. This is the opposite of what is commonly observed in cyclic units elsewhere (Campbell 1977) and likely relates to a systematic increase in SiO₂ activity via the progressive assimilation of Quetico metasedimentary rock fragments entrained in the intruding melt during emplacement (Campbell 1985). This is discussed in more detail in the following sections.

Mixing between compositionally distinct magmas prior to emplacement is a common process driving melt evolution in layered mafic systems (Maier 2005; Naldrett 2010, 2011; Mungall 2014), including LDI (Djon et al. 2017a, b). However, magma mixing does not appear to have occured during the formation of the LLC. This is illustrated by the consistent

Table 3 Summary of multiple sulfur isotope data from sulfides in drill hole LL10-005

LL10-005			Quetico metasedimentary rock				
LL10-005	δ34S‰	Δ33S (‰)	S/Se (WR)	LL10-005	δ34S‰	Δ33S (‰)	_
Min	-2.18	-0.41	2708.13	Min	-0.70	-0.17	
Max	2.34	0.02	11,777.98	Max	1.16	0.02	
Median	0.27	-0.15	4709.74	Median	0.07	-0.06	



Fig. 9 a The δ^{34} S values for pentlandite (pn), pyrrhotite (po), chalcopyrite (ccp), and pyrite (py) from drill hole LL10-005 versus wholerock S/Se data from the corresponding sulfide-bearing whole-rock samples (this study). Solid data points represent the average δ^{34} S value for individual sulfide grains. Mantle range of δ^{34} S and S/Se from Eckstrand and Hulbert (1987) and Farquhar and Wing (2003). The compositional range of sulfide pods and disseminated sulfides from LDI are outlined with a red dotted line (after Duran et al. 2015). δ^{34} S from LDI-tonalite from Jonsson (2023). Note that the S/Se (WR) of Quetico metasedimentary rock is 9109.47. **b** Range of Δ^{33} S ‰ for sulfides from drill hole LL10-005. Solid data points represent the average Δ^{33} S ‰ value for individual sulfide grains

sequence of crystallization relative to depth in individual cyclic units where the abundance of plagioclase increases with depth. This is consistent with the systematic decrease in MgO and CaO with depth (Fig. 4), and the low variability in incompatible trace-element compositions of LLC lithologies, which are sensitive tracers of magma source and evolution (Miller and Ripley 1996; Arndt et al. 2005; Maier 2005; Eckstrand and Hulbert 2007; Lightfoot 2007; Naldrett 2010, 2011; Mungall 2014; Charlier et al. 2015). For instance, magmas from contrasting source reservoirs are predicted to have contrasting Zr/Y ratios owing to the slightly differing incompatibilities of these elements (Pearce and Norry 1979). The range of Zr/Y ratios for LLC lithologies tightly overlap with less than an order of magnitude variability (Table 2; ESM2,

Table 3). Together, this suggests that the formation of cyclic units in the LLC was indeed associated with nearly identical pulses of magma from a single parental source reservoir. Moreover, the parental melt appears to have had high SiO_2 and H_2O activity as suggested by the early crystallization of plagioclase and the presence of hydrous primary minerals such as biotite (Campbell 1985).

Mantle metasomatism prior to melt extraction

The strong enrichment of fluid-mobile incompatible trace elements (e.g., Cs, Rb, Ba; LILEs) in cumulate lithologies throughout the LLC could reflect a variety of processes, including hydrothermal alteration, crustal assimilation during emplacement, and mantle metasomatism. The possibility of LILE enrichment via hydrothermal alteration is supported by the presence of pervasive alteration in the Northwestern Border Zone, the general overprint of low temperature, chloriterich alteration throughout the LLC, and the observed variability in the relative abundances of LILEs and HFSE (e.g., K/Hf and Ba/Hf; ESM1, Fig. 3). However, this variability is highly localized to certain areas of the Northwestern Border Zone and is not representative of the LLC as a whole. For instance, the K/Hf and Ba/Hf ratios are strongly correlated in CU2–CU4 (R^2 =0.9). In contrast, Ba is anomalously enriched in CU1 as is evident in its higher Ba/Hf ratios. LILE enrichment is ubiquitous throughout LLC lithologies, so the more common consistency of K/Hf and Ba/Hf ratios in most cyclic units suggests that LILE enrichment was a preexisting feature of LLC parental melts, and was variably overprinted by metasomatic LILE enrichment. Enrichment in LILE via crustal assimilation is supported by the clear textural and geochemical evidence of country rock assimilation in this system (e.g., Fig. 2a, b). However, variability in Ba/Th and Th/Nb ratios of the LLC lithologies, which can be modified by addition of LILE from metasomatic and crustal sources (Pirnia et al. 2020; Rahmani et al. 2020), indicates that this process likely overprinted existing LILE enrichment in LLC parental magmas prior to emplacement. In Ba/Th vs. Th/ Nb space (ESM1, Fig. 4), crustal assimilation (i.e., Th addition) results in a range of Th/Nb ratios with little variation in Ba/Th, whereas addition of components by subductionrelated fluids (e.g., Ba addition) produces the opposite pattern (Pirnia et al. 2020; Rahmani et al. 2020). Data points from the LLC show both patterns, with arrays parallel to the horizontal and vertical axes in Fig. 11 that converge near the origin. This pattern is hard to explain without the influence of both processes. In addition, Ba/La_{pm} and the magnitude of Sr anomalies are strongly correlated in lithologies throughout the LLC, whereas the magnitude of Eu anomalies and Al₂O₃ concentrations are less so (ESM1, Fig. 5). This pattern might reflect the presence of primary LILE-bearing hydrous minerals (i.e., amphibole and phlogopite) in the mantle source

Fig. 10 Major element bivariate plots of whole-rock data (Impala Canada, Ltd.) from surface samples (**a** and **c**) and layered cyclic units in drill hole LL10-005 (**b** and **d**). Data from this study is shown as symbols outlined in black in b and d. Modeled mixing lines are shown as solid lines. See text for details





Fig. 11 Range of calculated parental melt compositions for major rock types in the LLC (solid lines). Example profiles of a modern continental arc gabbro (Sierra Nevada: McCarthy et al. 2016) and oceanic arc basalt (Tonga arc: Ewart and Hawkesworth 1987; Mariana arc: Yanhong et al. 2021) are shown as dotted lines. Note the similar pattern in enrichment but more evolved compositions of the calculated parental melts relative to the example profiles. Normalization values from Sun and McDonough (1989)

region formed via the addition of water prior to melt extraction (Good and Lightfoot 2019). This process is common in arc settings and is consistent with structural models of the southern Superior Province that suggest contemporaneous buckling of the Wawa–Abitibi slab and influx of mantle material during the formation of Alaskan-type ultramafic intrusions (which includes the LLC; Pettigrew 2004) in the Quetico Subprovince (Beakhouse and Davis 2005; Percival et al. 2012).

Crustal contamination

Mafic intrusions in the Superior Province commonly exhibit geochemical evidence of extensive crustal assimilation (Rudnick and Fountain 1995; Tomlinson et al. 1999; Hollings et al. 1999, 2007; Pearce 2008). In layered mafic systems, crustal assimilation is often a key driver of sulfide saturation and sulfide liquid immiscibility via the addition of external S or SiO₂ (Fiorentini et al. 2010; Naldrett 2011; Mungall 2014). A previous petrogenetic model for the LLC by Pettigrew and Hattori (2002) invoked the addition of external S and SiO₂ from assimilated metasedimentary rocks as the drivers of sulfide saturation and PGE mineralization. In contrast, sulfide melt immiscibility and extreme Pd enrichment in the LDI system is thought to be related to interactions between magmas and cumulate rocks with contrasting degrees of crustal contamination and S saturation at depth (Barnes and Gomwe 2011; Djon et al 2018). Thus, the nature of crustal contamination in the LLC and LDI systems likely influenced their relative PGE prospectivities.

The two most likely sources of crustal contamination in the LLC are Quetico metasedimentary rocks and Wabigoon tonalite. The LLC contains abundant evidence for extensive assimilation of Quetico metasedimentary rock. This is apparent in outcrop (Fig. 2a, b) and in the systematic variation of primitive mantle-normalized trace-element profiles from a more primitive, mantle-like profile to a more evolved profile that overlaps that of Quetico metasedimentary rock (Fig. 6c, d). In contrast, the hornblende-bearing tonalite exhibits a distinctive trace-element profile relative to LLC lithologies characterized by a flat LILE pattern, a low Ba/ Th_{pm} ratio, a strongly negative Nb/Nb* anomaly, fractionated LREE, and a strongly positive Zr/Zr* anomaly (relative to the LLC; Fig. 6a, d). Thus, the trace-element compositions of the cumulate lithologies suggest equilibration of the LLC magmas with Quetico metasedimentary rock rather than tonalite, with this process having played a key role in controlling the trace-element composition of the system. However, the systematic variability in trace-element data suggests that assimilation of, and equilibration with, Quetico metasedimentary rock was itself variable and likely occurred during emplacement at shallow levels. Had it occurred a depth where higher temperature conditions persisted and where melt was more actively mixed, the inheritance of its geochemical signature would have been more uniform across the LLC.

A key implication of the mixing patterns described above is that the more primitive profiles in Fig. 6a and d represent samples that partially preserve the initial geochemical and isotopic compositions of the primary melts in the LLC prior to emplacement. These samples have εNd_T values (Fig. 8; -0.06 to +1.34) that are close to that of Quetico metasedimentary rock (-0.58 to - 0.20) at their negative extent, but cluster at a tight range of positive values (+0.82)to + 1.34) that are bracketed by that of the tonalitic country rock north and west of the LLC (Fig. 8; +0.76 to +1.43; Brügmann et al. 1997). This is particularly true in CU1, which does not exhibit textural or geochemical evidence of equilibration with Quetico metasedimentary rock (Fig. 5c), and has εNd_T values between + 1.18 and + 1.34. Based on this, we argue that the parental melts in the LLC initially had a mantle-like εNd_T (+2.44 at ~2.69 Ga; DePaolo 1988) and inherited the εNd_T signature of the tonalitic country rock at depth. During subsequent emplacement at shallow levels, variable assimilation of Quetico metasedimentary rock produced the more variable spread to negative εNd_T values in the LLC lithologies. This interpretation is supported by the fact that cyclic units with unambiguous geochemical and textural evidence for Quetico metasedimentary rock assimilation have the most variable and most negative εNd_T values (i.e., CU2-CU4), whereas those that lack this evidence consistently cluster at more positive values. It is possible that the spread in ϵNd_T values could arise solely from the mixing of mantle melts with Quetico metasedimentary rock; however, the observed clustering of data at positive values that are nearly identical to tonalitic country rock would be difficult to produce if this were the case. Moreover, the LLC occurs along the tectonic suture between the Ouetico and Wabigoon Subprovinces, which would have served as a preferred pathway for the upward movement of silicate melts during the formation of the LLC and would have allowed for extensive interaction between all three components. Therefore, both crustal components likely contributed to the εNd_T signature of the LLC.

Sulfur saturation in the Legris Lake Complex

The concentration of sulfide mineralization at the bottoms of cyclic units and the high Cu/Pd ratios of unmineralized cyclic units (Fig. 6) are indicative of sulfide saturation prior to emplacement and loss of early formed sulfide liquid. This was driven by the addition of external sulfur as indicated by the high S/Se ratios (greater than that of the mantle range of Eckstrand and Hulbert 1987; 2632-4350), and corresponding positive δ^{34} S and non-zero Δ^{33} S values of the mineralized cyclic units (Fig. 9), which together provide robust constraints on the source of sulfur (Ripley and Li 2003; Penniston-Dorland et al. 2008; Sharman et al. 2013; Smith et al. 2016; Magalhães et al. 2019). The reliability of these constraints are due to the lower mobility of Se relative to S (Queffurus and Barnes 2015a, b), the distinctive isotopic signature of surface-derived material in the Archean (Farquhar and Wing 2003; Johnston 2011), and robustness of non-zero Δ^{33} S signatures during magmatic and metamorphic processes (Sharman et al. 2013). Most magmatic sulfides from the LLC have mantle-like δ^{34} S signature (Fig. 9a; $\delta^{34}S = 0 \pm 1\%$; Sakai et al. 1984; Ripley and Li 2003; Seal 2006), but skew towards more positive values. The corresponding S/Se ratios for each sample fall within or above the mantle range (Eckstrand and Hulbert 1987; Queffurus and Barnes 2015a, b). This is suggestive of crustal S addition (Smith et al. 2016) and is consistent with the uniformly non-zero Δ^{33} S values (between 0 and ~ -0.3) of the sulfide mineralization. A non-zero Δ^{33} S signature is related to massindependent fractionation of sulfur isotopes in the Archean atmosphere and are a well-defined tracer for Archean crustal inputs (Farquhar and Wing 2003; Seal 2006; Johnston 2011).

A comparison between the S/Se ratios and multiple sulfur isotope signature of LLC sulfide mineralization and the Quetico metasedimentary rock suggests that the latter is likely not the main source of external sulfur in the LLC. The average δ^{34} S signature of sedimentary pyrite in Quetico metasedimentary rock is within the range of the mantle and within the overall compositional range of magmatic sulfides in the mineralized cyclic units (Fig. 9a). A similar statement is true for the Δ^{33} S values of magmatic sulfides from the LLC, which are uniformly more negative than pyrite in Quetico metasedimentary rock (Fig. 9b). In both cases, the maximum range of error in the calculated sulfur isotope signature of the metasedimentary pyrite does not account for the range of variability in the average values or full range of error of the magmatic sulfides from the LLC. Moreover, the S/Se ratios of the metasedimentary pyrite are lower than the maximum S/Se ratio of the mineralized cyclic units (Fig. 9a). Together with the observation that the abundance of sulfide mineralization is inversely correlated with Quetico metasedimentary rock assimilation in individual cyclic units, the metasedimentary material is likely not a key source of sulfur in this system. Rather, the tonalitic country rock is likely a more dominant source of external sulfur given its average $\delta^{34}S$ (+2.12; Jonsson 2023) that essentially overlaps the maximum δ^{34} S signature of the LLC (+2.15). This interpretation is also in good agreement with (i) the εNd_T signature of the LLC that is suggestive of tonalite assimilation at depth, (ii) the concentration of sulfide mineralization at the bottoms of cyclic units suggesting sulfur saturation prior to melt emplacement, and (iii) the S/Se and δ^{34} S signature of the LDI system that tightly overlaps the LLC data and in which tonalite is likely a dominant crustal contaminant (Duran et al. 2015; Fig. 10a).

Petrogenesis and mineralogy of the Legris system

Mixing with Quetico metasedimentary rock clearly influenced the major-element compositions of the intruding melts of the LLC. This effect must be accounted for when modeling the mineralogy of the LLC, and is illustrated in Fig. 10 using mixing lines between pure and contaminated mineral end-member assemblages. Melt emplaced at early stages in the LLC initially crystallized along a single trend (T1) that is modeled using an andesine and oligoclase end member (in 1:1 proportions) and a pyroxene end member (clinopyroxene and orthopyroxene in 3:2 proportions). This mixing line is representative of the least contaminated leucogabbro, gabbro, and clinopyroxenite. During each episode of melt injection at shallow levels, the fraction of assimilated Quetico metasedimentary rock was highly variable, producing compositional variation in the LLC lithologies that commonly overlaps with the composition of the Quetico metasedimentary rock. Samples of this type are represented by the data cluster near the origin in Fig. 10, and are modeled by a mixing line between pure Quetico metasedimentary rock and pyroxenite (clinopyroxene and orthopyroxene in 3:2 proportions; T2). The T1 and T2 mixing lines account for the end-member compositional variability observed in most of the unmineralized lithologies outside of the Northwestern Border Zone. Moreover, the area between T1 and T2 represents the variability in abundance and composition of plagioclase (between andesine and albite), and the relative abundance of metasedimentary material either as an assimilated component, xenolithic fragments, or a component of the heterolithic breccias.

Data points from the stratigraphic bottoms of cyclic units containing the mineralized leucogabbro and gabbro of the Northwestern Border Zone are closely bracketed by the low MgO ends of mixing lines T1 and T2. In contrast, data points from the stratigraphic middles and tops of mineralized cyclic units are closely bracketed in Fig. 10b and d by mixing lines representing combinations of pure labradorite and orthopyroxene (T3), and labradorite, orthopyroxene, and a constant 40 wt% contribution of Quetico metasedimentary rock (T4). The 40 wt% fraction of Quetico metasedimentary rock represents a maximum contribution of assimilated material in the mineralized cyclic units. It must be noted that data points between T3 and T4 in Fig. 10b and d are derived from samples in which Quetico metasedimentary rock assimilation is evident in hand sample and no discernible orthopyroxene is evident in thin section. A key point here is that the major-element chemistry of these samples is difficult to explain without a significantly larger input of assimilated metasedimentary material and a larger localized volume of orthopyroxene (up to ~ 19 wt%). A similar statement can be made about the LLC in general, with the caveat that the input of Ouetico metasedimentary rock and the corresponding orthopyroxene abundance are lower outside of the Northwestern Border Zone. Moreover, the clear association between assimilated metasedimentary rock, and the occurrence of abundant orthopyroxene, and intergranular biotite and quartz in the middle parts and tops of the cyclic units suggests that assimilation of this material caused an increase in SiO₂ activity. This resulted in a localized shift toward a more orthopyroxene-dominated mineral assemblage as entrained metasedimentary material was progressively assimilated by fractionating silicate melt at the site of emplacement during the formation of the cyclic units (Campbell 1985). This localized effect accounts for the trend toward a more pyroxene-dominated (clinopyroxene-orthopyroxene) composition with decreasing depth in individual cyclic units in the LLC that is the opposite of the more typical trend toward higher modal plagioclase abundance with decreasing depth observed in cyclic units elsewhere.

The fact that orthopyroxene was not directly observed in any lithology other than the biotite-leucogabbro is likely due to the alteration of primary orthopyroxene to hornblende-actinolite-chlorite-epidote-talc. However, its occurrence implies that the LLC is dominantly gabbronoritic in composition rather than gabbroic as previously thought (Pettigrew and Hattori 2002). Similarly, olivine was not observed in any of the sampled lithologies. As with orthopyroxene, this does not preclude its occurrence. However, modeling of the whole-rock data provides clear evidence for an almost complete lack of olivine across all LLC lithologies, except for volumetrically minor zones of dunite encountered during drilling. This is consistent with the generally Ni-poor nature of all lithologies in the LLC and suggests that significant olivine crystallization occurred prior to emplacement.

Parental magma trace-element composition, tectonic setting, and magmatic evolution

The trace-element composition of cumulate rocks is not entirely representative of the composition of their parental melts (Barnes 1986; Godel et al. 2011). To account for this, we have applied the equilibrium distribution method (EDM; Bédard 1994, 2001, 2006) to model the composition of the parental melt of LLC cumulate rocks. Specific considerations used are described in detail in Tables 8 and 9 in ESM2. Whole-rock geochemical data used to model the parental melt compositions are from the least contaminated samples of leucogabbro, gabbro, and biotite-leucogabbro (LL10-005-47, LL10-005-117, LL-21-80, and LL-21-84a), with Hf/Zr and Y/Ho ratios near 1 (ESM1, Fig. 3), and minimal evidence of hydrothermal alteration. The contribution of trace elements from the trapped melt faction (TMF), which comprised the initial modal abundance of intergranular phases (2.8-13 vol.%; ESM2, Table 8) and variable proportions of mineral overgrowths on the primary cumulus phases, was subtracted using a non-modal melting approach ("backstripping"; Bédard 1994, 2001). A maximum final TMF of 20% was determined for mineralized leucogabbro based on the average abundance of intergranular minerals in samples from each lithology and the variability of model trace-element profiles produced with this value (Fig. 11). A maximum final TMF of 13% was determined for the biotiteleucogabbro and gabbro.

The calculated trace-element composition of parental melts for leucogabbro (CU1), gabbro (CU2 and surface sample), and biotite-leucogabbro (surface) are provided in Table 10 of ESM2 and illustrated in Fig. 11. The modeled parental melts for leucogabbro and gabbro closely overlap one another, and are characterized by fractionated LREE and HREE (La/Sm_{pm} = 1.71-2.17; Gd/Yb_{pm} = 1.41-2.86), uniform LILE enrichment, and negative Zr/Zr* (0.2-0.32), Eu/Eu* (0.39-0.51), Sr/Sr* (0.57-0.82), and Nb/Nb* (0.40–0.48) anomalies (Fig. 11). In contrast, the modeled parental magma for the biotite-leucogabbro is significantly more evolved, and features more negative Eu/Eu* (0.27), Sr/Sr* (0.14), Nb/Nb* (0.23), and Zr/Zr* (0.48) anomalies, and a greater degree of LREE (La/Sm_{pm} = 2.72) and HREE fractionation (Gd/Yb_{pm}=4.77; Fig. 11). The modeled primitive mantle-normalized trace-element profiles of the mineralized leucogabbro and gabbro strongly resemble those of igneous rocks formed in modern arc settings, such as the Sierran continental arc (Fig. 11; Irvine and Baragar 1971; Pearce 1983; Barnes et al. 1993; Saccani et al. 2008). These similarities seem to support a model for the initial formation of the LLC involving discrete injections of a single parental magma formed via partial melting of metasomatized, LILE-enriched mantle in an arc setting in all but the very last stage of formation of the LLC. This interpretation is also in good agreement with data from the coeval LDI complex (Brügmann et al. 1997; Barnes and Gomwe 2011) and is suggestive of an arc setting for the LDI intrusive suite more broadly.

The more evolved composition of the calculated parental melt for the paragenetically late biotite-leucogabbro (Fig. 1b; Pettigrew and Hattori 2001) suggests that the parental melt reservoir feeding the system became more fractionated over time. This effect is likely due to the pervasive assimilation of Archean crustal material given the uniform enrichment in Th, and the resulting high Th/Yb, Th/Nb, and Th/La ratios of the calculated parental melts for biotite-leucogabbro (3.57, 0.49, and 0.11, respectively) relative to those for the calculated parental melts for mineralized leucogabbro (0.28, 0.11, and 0.03, respectively) and gabbro (0.11-0.63, 0.13-0.23, and 0.03-0.08, respectively). One effect of this assimilation would be the introduction of significant external SiO₂ to the melt prior to emplacement, and early crystallization and segregation of plagioclase and ferromagnesium minerals, such as orthopyroxene and olivine (Campbell 1985; Brügmann et al. 1997; Mungall 2014), which would have generated the negative Sr/Sr* and Eu/Eu* anomalies observed in all of the modeled parental melts, and the Ni-depleted character of the LLC. This process likely occurred throughout the evolution of the LLC and became more pervasive at later stages of evolution, leading to the more evolved composition of the biotite-leucogabbro. A key implication of this is that the parental magmas to the LLC resided at depth for some period of time prior to final emplacement, and crystallized a plagioclase-, orthopyroxene-, and olivine-bearing noritic cumulate pile either below the LLC or in the conduit system connecting the deep and shallow expressions of this system. This interpretation agrees with similar models for the LDI system in which noritic magmas were derived from a sub-plutonic reservoir (i.e., a staging chamber) where it interacted with additional compositionally distinct melts (Hinchey et al. 2005; Barnes and Gomwe 2011; Djon et al. 2017a, b).

Formation of the Legris Lake mafic-ultramafic complex

The data presented here indicate that the parental magmas to the LLC were likely initially extracted from a metasomatized mantle source in an arc setting. Following extraction, a single parental magma coalesced in a staging chamber where it assimilated external SiO_2 (Fig. 12) from tonalitic country rock, as suggested by the Sm–Nd isotope signature of the LLC. Introduction of external SiO_2 drove crystallization of olivine, orthopyroxene, and plagioclase prior to emplacement. This resulted in a bulk chemical change in the residual melt, producing a slightly more evolved composition with strongly negative Eu/Eu* and Sr/Sr* anomalies,



Fig. 12 Schematic diagram showing the formation of cyclic units in the Northwestern Border Zone (shown in blue) via injections of silicate melt that has assimilated SiO_2 and S from tonalitic country rock (pink) and evolved via crystallization of orthopyroxene (green rectangles), plagioclase (blue squares), and olivine (ol; brown triangles). Sulfide saturation occurred at depth or during emplacement and immiscible sulfide melt (yellow circles) was variably retained at the site of emplacement due to its high density. See text for details

highly fractionated REE profiles, and generally low Ni. This interpretation is similar to the genetic model for the LLC previously proposed by Pettigrew and Hattori (2001, 2002).

The sulfur isotope composition of the sulfide mineralization and whole-rock S/Se ratios suggest that addition of external S was a driver of sulfide liquid immiscibility in the LLC, likely due to the assimilation of tonalitic country rock. The segregation of sulfide liquid at the base of mineralized cyclic units (Fig. 4; CU1 and CU5) indicates that the intruding magmas were saturated with sulfide liquid at the time of emplacement. This early formed liquid would have efficiently stripped PGE from the coexisting silicate melt, but would have been difficult to mobilize in the intruding melts and retain at the site of emplacement due to its high density (4200–4500 kg/m³; Dobson et al. 2000; Lesher 2019). As a result, the entrainment of PGE-rich sulfide liquid in individual magma pulses and its retention at the site of emplacement was variable, with some cyclic units having abundant PGE-bearing sulfide mineralization (CU1, CU5) and others having very little (CU2-CU4). Accordingly, the silicate melt that crystallized to form the latter group of cyclic units would have been relatively depleted in PGEs as a result of the loss of early formed sulfide liquid, resulting in elevated whole-rock Cu/Pd ratios (Fig. 7e, f).

Significant assimilation of Quetico metasedimentary rock at shallow levels drove a localized shift in melt composition, promoting orthopyroxene crystallization. This resulted in the more noritic composition of the stratigraphic middles and tops of cyclic units, and partial equilibration of the traceelement signatures of the silicate melt and metasedimentary rock. This also produced the observed compositional trend in cyclic units wherein they become more mafic and pyroxenedominated with decreasing depth in response to the progressive assimilation of SiO₂ from abundant Quetico metasedimentary rock fragments entrained in intruding melts during the formation of individual cyclic units. However, this interaction was apparently unrelated to sulfur saturation.

The lack of trace-element variability between individual cyclic units suggests that the source and compositions of silicate melt pluses feeding the LLC remained relatively constant through most of its formation. However, over time assimilation of Quetico metasedimentary rock appears to have become more pervasive, resulting in a more Eu- and Sr- depleted, and LREE/HREE fractionated melt, with more evolved trace-element profiles similar to that of the metasediment. This is reflected in the mantle-normalized trace-element signature of the late-stage biotite-leucogabbro.

Comparison between the LDI Mine Block Intrusion and the LLC

In addition to the clear spatial and temporal association between the LLC and LDI, several other key similarities suggest a petrogenetic relationship between these systems, and perhaps a similar degree of PGE prospectivity.

- The occurrence of large zones of brecciated and stratiform mineralization, with locally pervasive hydrothermal alteration (Barnes and Gomwe 2011).
- Similar degrees of LILE enrichment and the occurrence of pegmatitic/varitextured rocks containing primary hydrous minerals (e.g., biotite, hornblende) indicative of melt extraction from a hydrous, metasomatized mantle source (Djon et al. 2018).
- Similar trends of trace-element depletion and enrichment consistent with an arc setting (Brügmann et al. 1997; Barnes and Gomwe 2011; Djon et al. 2017a, b, 2018).
- 4) Similar ranges in S/Se ratios, and 34 S and ϵ Nd_T values in mineralized lithologies (Brügmann et al. 1997; Duran et al. 2015), and similar evidence of S and SiO₂ addition from Wabigoon tonalite.
- 5) Similar noritic composition and genetic models involving melt fractionation/crystallization at depth.

However, a key difference between LDI and the LLC is the role magma mixing played during the formation of each. In the LDI system, there is evidence for interactions between two compositionally distinct magmas involving the assimilation of early formed Pd-enriched sulfide mineralization by a secondary pulse of sulfide undersaturated melt. This likely drove sulfide saturation in the secondary melt and resulted in a sulfide liquid with unusually high Pd/Pt ratios (Barnes and Gomwe 2011; Djon et al. 2017a, b, 2018). This sulfide liquid was subsequently emplacement and retained in the LDI Mine Block Intrusion. In contrast, magma mixing does not appear to have occurred during the magmatic evolution of the LLC and the early formed sulfide melt was only variably retained at the site of emplacement. This resulted in the more discrete volume of PGE-rich sulfide mineralization observed in the LLC relative to LDI.

Conclusion

Based on bulk-rock trace-element geochemistry and calculated parental melt compositions, the magmatic evolution of the LLC began with the partial melting of a metasomatized mantle source in an arc setting. Following the accumulation of this melt in a staging chamber, extensive assimilation of SiO₂ and S from tonalitic country rocks drove the crystallization of olivine, plagioclase, and orthopyroxene, and saturation of the melt in sulfide liquid. This, in turn, resulted in the formation of a more evolved, sulfide-saturated residual melt, with a tonalite-like εNd_T signature that was emplaced at shallow levels and crystallized the plagioclasedominated cumulate lithologies of the LLC. Though not observed directly, orthopyroxene was a major part of the cumulate assemblage, indicating that the LLC is dominantly gabbronoritic rather than gabbroic in composition.

Mineralization in the LLC is primarily hosted in layered cyclic units that represent discrete pulses of a single parental melt. During their formation, entrainment of sulfide liquid during magma emplacement and its retention at shallow levels was variable due to the high density of the sulfide liquid. This led to variable degrees of PGE-rich sulfide mineralization among the cyclic units.

Variable assimilation of Quetico metasedimentary rock had a strong influence on the trace-element geochemistry of the LLC and resulted in a variable spread in the εNd_T signature of the cyclic units. This process drove a highly localized increase in the abundance of orthopyroxene, quartz, and biotite where metasedimentary rock was assimilated, and was most prevalent in the mineralized zones in the northwestern part of the LLC. However, the lack of correlation between metasedimentary rock assimilation and sulfide mineralization indicates that this was not an important factor in promoting sulfide saturation. Later in the evolution of the magmatic system, metasedimentary rock assimilation at depth became more widespread and exerted a stronger control on the trace-element geochemistry of this system.

The LLC and world-class LDI deposit share a clear temporal and geochemical association. Together with the Tib Lake Complex, they form a single intrusive suite that likely includes several other nearby PGE-bearing mafic–ultramafic complexes to the west and south (i.e., Wakinoo Lake, Demars Lake, Buck Lake, and Tamin Lake). Based on the model presented here, future studies should focus on the magmatic evolution of these systems and the processes driving sulfide saturation in each. Moreover, a detailed structural assessment to identify potential feeder conduits connecting the shallow and deeper level portions of these systems could provide key vectors to mineralization.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00126-023-01183-x.

Acknowledgements We thank Wolfgang Maier, Bernd Lehmann, Chris Jenkins, and an anonymous reviewer for their detailed critiques that greatly improved the final version of this manuscript. We also offer special thanks to Kristi Tavener and Jonas Valiunas for their help with sample preparation, Justin Jonsson and Tianna Groeneveld for the assistance in the field, and Devin Jackson and Jami Brown for the assistance in core sampling and mine site activities at LDI. We also thank Guosheng Wu, Shuangquan Zhang, Richard Stern, and Mike Hamilton for their assistance with analytical work and data collection.

Author contribution This manuscript and the data and interpretations presented herein were written by Dr. Wyatt M Bain. Dr. Peter Hollings oversaw this work and together with Dr. Matthew Brzozowski and Dr. Lionnel Djon provided assistance with field work and data presentation and interpretation and provided editorial support. Dr. Daniel Layton-Matthews and Dr. Agatha Dobosz carried out detailed MLA analysis of samples for this study and provided editorial support.

Funding This work was supported by Impala Canada Ltd., an NSERC Alliance grant (ALLRP 556281–20) and the NOHFC Industrial Research Chair to Hollings.

Declarations

Conflict of interest Author Lionnel Djon is currently an employee of Impala Canada Ltd. All other authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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ARTICLE



Characterizing the supra- and subsolidus processes that generated the Current PGE–Cu–Ni deposit, Thunder Bay North Intrusive Complex, Canada: insights from trace elements and multiple S isotopes of sulfides

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Received: 26 September 2022 / Accepted: 6 July 2023 $\ensuremath{\mathbb{C}}$ The Author(s) 2023

Abstract

The Current deposit is hosted by serpentinized peridotite that intruded rocks of the Quetico Subprovince in the Midcontinent Rift, and is subdivided into three morphologically distinct regions — the shallow and thin Current–Bridge Zone in the northwest, the deep and thick 437–Southeast Anomaly (SEA) Zone in the southeast, and the thick Beaver–Cloud Zone in the middle. The magma parental to the Current deposit became saturated in sulfide as a result of the addition of external S from at least two sources — a deep source characterized by high $\Delta^{33}S$ (< 3‰) values, and a shallow source, potentially the Archean metasedimentary country rocks, characterized by low $\Delta^{33}S$ (<0.3‰). Variations in $\Delta^{33}S$ –S/Se–Cu/Pd values indicate that the contamination signatures were largely destroyed by interaction of the sulfide liquid with large volumes of uncontaminated silicate melt. The intrusion crystallized sequentially, with the Current–Bridge Zone crystallizing first, followed by the Beaver–Cloud Zone, and lastly by the 437–SEA Zone. This, along with the elevated Cu/Pd ratios in the 437–SEA Zone, which formed as a result of sulfide segregation during an earlier saturation event, and development of igneous layering in this zone, suggests that it represents the feeder channel to the Current deposit. After the intrusion crystallized, the base-metal sulfide mineralogy was modified by circulation of late-stage hydrothermal fluids, with pyrrhotite and pentlandite being replaced by pyrite and millerite, respectively. This fluid activity mobilized metals and semi-metals, including Fe, Ni, S, Se, Co, Cu, Ag, and As, but did not affect the PGE. This contribution highlights the importance of the interplay between magma dynamics and magmatic–hydrothermal processes in the formation of Ni–Cu–PGE-mineralized deposits.

Keywords Current deposit · Ni-Cu-PGE · Base-metal sulfide chemistry · S isotopes

Editorial handling: W. D. Maier

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Introduction

Magmatic Ni–Cu–platinum-group element (PGE) sulfide deposits form through a series of suprasolidus processes that have been relatively well constrained and which can largely be summarized by four major events — i) generation of a mafic–ultramafic magma via partial melting of the mantle, ii) saturation of a mantle-derived magma in sulfide and segregation of an immiscible sulfide liquid, iii) interaction of the sulfide liquid with the silicate melt and enrichment of metals in the former based, and iv) concentration of the metal-enriched sulfide liquid to form an ore body (Naldrett 2010). While these fundamental processes are commonplace in magmatic Ni–Cu–PGE deposit, the mechanism by which sulfide saturation occurs varies between deposits. Although several mechanisms have been proposed, including closed-system fractional crystallization, magma mixing, increasing magma fO_2 , and addition of externally derived Si or S (Robertson et al. 2015b), most of these, apart from direct addition of S, were deemed incapable of generating economic concentrations of Ni-Cu-PGE mineralization (Ripley and Li 2013). Notable examples of conduit-type Ni-Cu-PGE sulfide deposits that formed via assimilation of distinct contaminants include Norilsk, which was contaminated by anhydrite (e.g., Ripley et al. 2010), Voisey's Bay, which was contaminated by paragneiss (e.g., Ripley et al. 2002), and Jinchuan, which was contaminated by carbonate rock (e.g., Lehmann et al. 2007). Additionally, contamination by geochemically distinct assimilants within a single conduit system has been described in the Eastern Gabbro of the Coldwell Complex (Midcontinent Rift System), in which the Marathon deposit assimilated Archean sedimentary rock and the northern deposits likely assimilated metamorphosed igneous rock (Shahabi Far et al. 2018; Brzozowski et al. 2020). Regardless of how these fundamental processes operate, the sulfide liquid that results eventually crystallizes to the commonly observed assemblage of pyrrhotite-pentlandite-chalcopyrite (Craig and Kullerud 1969; Kullerud et al. 1969).

It is well understood, however, that subsolidus processes have the potential to modify the mineralogy of the basemetal sulfide (BMS) assemblage, as well as the grade and tonnage of the mineralized system (Prichard et al. 2013; Holwell et al. 2017; Brzozowski et al. 2020; Lawley et al. 2020; Wang et al. 2021). These processes, therefore, have the potential to affect the economic value of a mineralized system (Holwell et al. 2017). An example of a mineralized system whose economic potential is believed to have been improved via subsolidus processes is the Roby Zone of the Lac des Iles deposit in northern Ontario, Canada. Although the mineralization at Lac des Iles is unequivocally magmatic (Barnes and Gomwe 2011; Djon and Barnes 2012; Duran et al. 2016), it has been demonstrated that the Pd enrichment in the Roby Zone was the result of upgrading by magmatic-hydrothermal fluids (Watkinson and Dunning 1979; Hinchey and Hattori 2005). Accordingly, the success of mineral exploration and eventual metal extraction depends on having a strong understanding of these supra- and subsolidus processes and a robust mineral deposit model.

The Thunder Bay North Intrusive Complex (TBNIC) of the Midcontinent Rift System contains a series of mafic–ultramafic intrusions, including the $1,106.6\pm1.6$ Ma Ni–Cu–PGE-mineralized Current and Escape intrusions (Fig. 1B) (Bleeker et al. 2020; Kuntz et al. 2022). Although exploration of these two systems has been ongoing since 2005, limited work has been done to characterize the suprasolidus processes that generated the base- and preciousmetal mineralization or the subsolidus processes that modified the mineralization. Accordingly, this contribution

focuses on characterizing the suprasolidus processes that generated the BMS mineralization along the length of the Current conduit, as well as the subsolidus processes that modified the initial mineralization, with the ultimate goal of developing a robust mineral deposit model. This is accomplished by integrating detailed petrography, whole-rock and BMS chemistry, and multiple S isotopes (³²S, ³³S, ³⁴S, ³⁶S). This contribution represents one of the first studies to develop a holistic model for a BMS deposit in the Thunder Bay–Nipigon Embayment region. It, therefore, not only has broad implications for the formation of, and exploration for, Ni–Cu–PGE deposits globally, but also lays the foundation for our understanding of deposits in this portion of the Midcontinent Rift System.

Geological setting of the Thunder Bay North Intrusive Complex

The TBNIC is located in the Quetico Subprovice of the Superior Province in northern Ontario, Canada and represents one of several magmatic Ni–Cu–PGE-mineralized complexes that formed as part of the North American Midcontinent rifting event ca. 1.1 Ga (Fig. 1A) (Bleeker et al. 2020; Kuntz et al. 2022). It comprises several mafic–ultramafic chonoliths that straddle the east–west trending Quetico Fault System (Fig. 1B) (Bleeker et al. 2020). From east to west, these intrusions are the Current, 025, Steepledge, and Lone Island intrusions that are connected by dykes–sills of the East–West Corridor (Fig. 1B) (Kuntz et al. 2022).

The 1,106.6 \pm 1.6 Ma Current intrusion has been drilled extensively since 2006 (730 drill holes totaling 162,997 m as of 2020) (Kuntz et al. 2022). It defines a ~ 3.4-km-long northwest–southeast-trending chonolith (Figs. 1B and 2) with a "tadpole-shaped" aeromagnetic anomaly that suggests it extends for up to 6 km towards the southeast (Bleeker et al. 2020); this has been verified by drilling. The chonolith comprises undeformed and unmetamorphosed olivine melagabbro, feldspathic lherzolite, and lherzolite, as well as quartzbearing gabbro/monzonite (Chaffee 2015; Kuntz et al. 2022).

The Current chonolith has been subdivided into i) the Current–Bridge Zone to the north, ii) the 437 Zone–Southeast Anomaly (SEA) to the south, and iii) the Beaver–Cloud Zone in between (Fig. 2a). The Current–Bridge Zone is hosted by granite, whereas the Beaver–Cloud and 437–SEA zones are hosted by metasedimentary country rock (Fig. 2) (Kuntz et al. 2022). The lithology of the Current–Bridge and Beaver–Cloud zones largely comprises peridotite (Fig. 3A–C), whereas the 437–SEA Zone is layered from a lower peridotite to melagabbro to an upper oxide gabbro and capped with a quartz-bearing gabbro/monzonite (Figs. 3D, ESM 1 S1) (Heggie et al. 2015). Northwest of the Quetico Fault in the Current Zone, the chonolith is thin (<70 m), sinuous, tubular, shallow (<60 m to its

Fig. 1 (A) Simplified geologic map of the North American Midcontinent Rift illustrating the distribution of rock types and highlighting the location of several Ni-Cu-PGE-mineralized intrusions and complexes, including the Thunder Bay North Intrusive Complex (modified from Good et al. 2015). (B) Simplified geologic map showing the locations of maficultramafic intrusions of the Thunder Bay North Intrusive Complex, including the Ni-Cu-PGE-mineralized Current and Escape intrusions (modified from Thomas et al. 2011)



base), and relatively flat lying (Figs. 2B and 3A) (Kuntz et al. 2022). Straddling the Quetico Fault in the Bridge Zone, the chonolith changes to a more stubby, tabular morphology with a gentle southeast plunge to a depth of <150 m (Figs. 2B and 3B). From the Beaver Zone to the SEA, the chonolith progressively thickens from ~150–500 m, is tabular in shape, and extends to progressively greater depths of up to ~1,000 m at the base of the SEA (Figs. 2B and 3C, D).

The BMS mineralization in the Current deposit is hosted within the lherzolite and olivine melagabbro (Fig. 3) (Kuntz et al. 2022). This mineralization largely occurs as disseminated pyrrhotite, pentlandite, chalcopyrite, pyrite, and cubanite, with overall abundances ranging from a few percent to > 25%; small bodies of semi-massive to massive sulfide occur at the base of the Bridge and Beaver zones (Fig. 3B, C) (Bleeker et al. 2020; Kuntz et al. 2022). Base-metal sulfides are distributed throughout the chonolith in the Current Zone and the northwest portion of the Bridge Zone, but become bottom loaded in the southeast portion of the Bridge Zone where it meets the Beaver Zone (Fig. 3A–C). Southeast of the Beaver Zone, the majority of BMSs are bottom loaded. The SEA and Cloud Zone are exceptions to these general characteristics, the former containing only minor BMS, and the latter comprising <1% finely disseminated and irregularly dispersed chalcopyrite \pm pyrrhotite at the roof of the chonolith (Fig. 2B).

Samples and methods

The mineralogy and texture of BMS were characterized in 284 thin sections collected along the length of 36 drill holes that intersected the Current, Bridge, Beaver, Cloud, and 437

Fiq. 2 (A) Simplified geologic map illustrating the morphology of the Current intrusion (grey) crosscutting the Archean metasedimentary rocks of the **Ouetico Subprovince (south** of Quetico Fault Zone) and Archean granite (north of the Quetico Fault Zone) in plan view, highlighting the relative locations of the five mineralized zones and the Southeast Anomaly (modified from Chaffee 2015). The yellow circles represent the locations of drill holes from which samples were characterized in this study. The grey dashed lines are the UTM locations where the intrusion has been subdivided into the Current-Bridge, Beaver-Cloud, and 437-SEA zones. (B) Schematic cross section of the Current intrusion illustrating the change in morphology of the conduit with depth and the relative location of sulfide mineralization in the five zones (modified from Thomas et al. 2011)



zones, as well as the SEA (Fig. 2A). Five samples of the granite country rock and two samples of the metasedimentary country rock were also characterized (Fig. 2A). Mineral Liberation Analysis (MLA) was conducted on ten thin sections at the CREAIT facility at Memorial University of Newfoundland using an FEI Quanta 400 scanning electron microscope (SEM) equipped with a Bruker XFlash energy dispersive X-ray (EDX) detector and mineral liberation analysis software. Operation conditions of the instrument are provided in the Electronic Supplementary Material (ESM 1).

Bulk-rock geochemical data comprise assays for base metals (Cu), precious metals (Pd, Pt, Ir), and S that were used by Clean Air Metals to define the Current deposit. The vast majority of the assay data were determined at ALS (~98% of the database), with the remaining $\sim 2\%$ determined at Accurassay Laboratories.

Quality assurance and control for these analyses were performed throughout the exploration process to meet the requirements of the National Instrument 43–101. All bulk-rock data utilized herein represent rocks with Pd>0.01 ppm. Details regarding the analytical methods used to collect the bulk-rock data are provided in the Electronic Supplementary Material (ESM 1)

The trace-element contents of BMS from 65 polished thin sections and pucks from 31 drill holes were determined at the Element and Heavy Isotope Analytical Laboratory at the University of Windsor using an Agilent 7900 ICP–MS coupled with a 193-nm excimer laser. The accuracy of the measured concentrations was assessed by comparing the measured values of sulfide reference UQAC FeS-1 (University du Québec à Chicoutimi, Canada) and MASS-1 to the working values; the measured values are in good agreement with the working values (ESM 2

Fig. 3 Schematic cross sections of the (A) Current Zone, (B) Bridge Zone, (C) Beaver Zone, and (D) Southeast Anomaly illustrating the relationships of the main rock units in the conduit, the change in conduit morphology from northwest to southeast along the intrusion, and the change in location of mineralization that accompanies this change in morphology (modified from Thomas et al. 2011; Bleeker et al. 2020)



Table S1). Details regarding instrument operating conditions, standardization, correction of metal argide interferences, and signal processing are provided in ESM 1.

The S isotope composition (³²S, ³³S, ³⁴S, ³⁶S) of BMS was determined in situ using a CAMECA IMS 1280 secondary ion mass spectrometer at the Centre for Microscopy, Characterisation and Analysis, University of Western Australia. Details regarding instrument operating conditions, standardization, and data processing are provided in ESM 1. Sulfur isotope values are reported in delta notation as permil deviations from Vienna Canyon Diablo troilite. Mass-independent fractionation was assessed by calculating the deviation of the measured values from mass-dependant fractionation ($\Delta^{33}S = \delta^{33}S - 1,000 \times [(1 - \delta^{34}S)^{1.91} - 1]$).

Accuracy of the sample measurements was assessed by measuring the isotopic composition of the Nifty-b chalcopyrite, VMSO pentlandite, Alexo pyrrhotite, and Sierra pyrite standards. Their measured compositions are in excellent agreement with the reference values provided by LaFlamme et al. (2016) (ESM 2 Table S2).

Results

Bulk-rock geochemistry

In metal–S space, Cu and PGE generally correlate positively with S concentrations, but there is a subgroup within which chalcophile elements exhibit no discernable correlation with S (Fig. 4A, B). Similarly, when comparing the Pt-group PGE (PPGE) and Ir-group PGE (IPGE), Pd correlates positively with both Pt (Pd/Pt= 0.9 ± 0.4 , average ± 2 SD; Fig. 4C) and Ir (Pd/Ir= 21 ± 131 ; Fig. 4D).

Base-metal sulfide mineralogy

The samples that were characterized for this study comprise variably mineralized mafic–ultramafic rocks from the chonolith, granitic country rocks, and samples where the two have mingled (Fig. 5A). Base-metal sulfides are largely disseminated (Fig. 5B), but can be net-textured (Fig. 5C) and blebby (Fig. 5D). The latter sulfide variety can be mineralogically segregated, with a portion comprising pyrrhotite–pentlandite and portion comprising chalcopyrite (Fig. 5D); a finegrained assemblage of silicate minerals commonly surrounds the chalcopyrite (Fig. 5D).

The BMS assemblages throughout the Current intrusion comprise variable proportions of pyrrhotite, pentlandite, chalcopyrite, and pyrite, with lesser cubanite, millerite, violarite, and rare troilite and gersdorffite. Chalcopyrite, pyrrhotite, and pentlandite largely occur as equilibrium assemblages with sharp, curved contacts (Fig. 5E). Pyrrhotite can occur as single large (mm-sized) crystals (Fig. 5E, F) or as aggregates of numerous fine-grained (tens of microns) crystals that share ~ 120° angles; these textural varieties of pyrrhotite can occur within the same thin section (Fig. 5F). Troilite occurs as wavy intergrowths in pyrrhotite. Pentlandite can occur as large (hundreds of microns) crystals associated with chalcopyrite–pyrrhotite assemblages (sometimes at the contact between the two), as flames within pyrrhotite (Fig. 5E), and in veinlets that crosscut pyrite (similar to pyrrhotite in Fig. 5G). Cubanite occurs as laths within chalcopyrite (Fig. 5E, F).

Pyrite generally occurs in disequilibrium with pyrrhotite (Fig. 5H), as large (mm-sized) crystals either associated with chalcopyrite–pentlandite–cubanite or isolated from other BMS, and as wormy intergrowths in chalcopyrite (Fig. 5I). Rarely, chalcopyrite associated with pyrite can occur isolated within alteration patches (Fig. 5J). Locally, pyrite can occur as blocky intergrowths with pentlandite (Fig. 5K). Millerite occurs as aggregates of irregular crystals in chalcopyrite; it is most common in samples that contain pyrite (Fig. 5L). Violarite occurs as anhedral–euhedral grains within chalcopyrite, pyrite, and silicates (Fig. 5N).

The visual proportion of pyrite to other BMS varies significantly within the sample population, with some samples having no pyrite, others being composed entirely of chalcopyrite–pyrite, and no pyrrhotite, and others comprising pyrrhotite–pentlandite–chalcopyrite–pyrite–millerite. Mineral abundance data obtained via MLA on ten samples confirm this thin section-scale variability in sulfide mineralogy (Fig. 6). Of note is that the abundances of pyrrhotite and pyrite exhibit a clear negative and non-linear correlation (Fig. 6D). This mineralogical variability matches that

Fig. 4 Binary diagrams illustrating the variation in bulk-rock (A) Cu–S, (B) Pd–S, (C) Pd–Pt, and (D) Pd–Ir. The red arrow highlights data that exhibits a positive trend on these diagrams, whereas the green field highlights data that falls off this trend. Dashed lines represent constant Pd/Pt and Pd/Ir ratios. DL = detection limits



obtained on a larger sample population by Clean Air Metals (grey squares in Fig. 6). Within this larger sample set, it is also evident that a similar negative and non-linear correlation exists between pentlandite and millerite (Fig. 6E).

Base-metal sulfide trace-element chemistry

Distribution among BMS

The trace-element chemistry of the six most common BMS throughout the Current deposit is provided in ESM 2 Table S3 and illustrated in Fig. 7. In the Current deposit, the order of decreasing Co contents is pentlandite = millerite > pyrite > pyrrhotite > chalcopyrite-cubanite (Fig. 7A).Iron-rich BMS consistently have lower Zn concentrations than Cu-rich BMS (Fig. 7A). Palladium, Pt, and Au exhibit similar ranges of concentration (up to three orders of magnitude) that are generally indistinguishable among the BMS, apart from pentlandite, which has consistently elevated Pd contents (up to 208 ppm), and some pyrite that extend to elevated Pd values similar to pentlandite (Fig. 7B-D). The concentrations of the IPGE (Os, Ir, Ru) among the BMS are indistinguishable and exhibit similar ranges (e.g., four orders of magnitude for Ir; Fig. 7E-G). Silver and Sn exhibit similar distributions among the BMS, with their concentrations generally decreasing in the order chalcopyrite > pyrrhotite-pentlandite-millerite > pyrite (Fig. 7H, I). The concentration of As typically extends to higher values in pyrite compared to chalcopyrite-pyrrhotite-pentlandite; Bi exhibits a mirrored distribution (Fig. 7J, K). The concentration of Se in chalcopyrite, pyrrhotite, pentlandite, and millerite is similar and exhibits relatively limited variability, whereas its concentration in pyrite extends to notably lower values than in the other BMS (Fig. 7L).

Cu/Pd and S/Se values

Bulk-rock Cu/Pd ratios of samples from the Current–Bridge (1,892–3,275) and Beaver–Cloud (1,902–4,100) zones are largely indistinguishable, exhibit limited variability, and fall entirely within the range of mantle values (Fig. 8). The 437–SEA Zone has consistently higher and more variable Cu/Pd ratios (3,166–42,444, Fig. 8).

The S/Se values of chalcopyrite (942–8,480), pyrrhotite (1,731–7,158), and pentlandite (1,597–4,076) are indistinguishable and will be considered together (Fig. 8A). Pyrite and millerite are considered separately as they are secondary BMS. Based on the primary BMS assemblage, the S/Se values of the Current–Bridge (942–5,880), Beaver–Cloud (1,706–15,023), and 437–SEA (1,597–6,180) zones overlap and are generally indistinguishable (Fig. 8A). These S/ Se values extend to lower and higher values than those of the mantle (Fig. 8A). Pyrite and millerite in the Current deposit are characterized by S/Se values that are notably more variable than the primary BMS assemblage, ranging from 979 to 23,091, and extend to values notably lower and higher than the mantle range (Fig. 8B). Pyrite from a granite country rock sample with Cu/Pd of 4,500 has S/Se values of 30,066–64,426 (Fig. 8). Pyrite from two metasedimentary country rock samples with Cu/Pd of 34,000–59,000 have S/ Se values of 12,848–82,249 (Fig. 8).

Multiple sulfur isotopes

The overall S isotope composition of the Current deposit (-0.06% to 0.36% $\Delta^{33}S$ and -2.4% to 2.30% $\delta^{34}S,$ ESM 2 Table S4) largely falls within the range of mantle values, although several samples have Δ^{33} S values that are distinctly higher than mantle (Fig. 9A). The overall S isotope compositions of the BMS, both primary and secondary, are indistinguishable (Fig. 9A, B). Similarly, the S isotope compositions of BMS in the Current-Bridge and Beaver-Cloud zones are also largely indistinguishable (Fig. 9A, B). Notably, there is no significant difference in the S isotope composition of texturally distinct BMS (Fig. 5B-D) or those associated with mafic magma-granite magma mingling (Fig. 5A) (ESM 2 Table S4). In Δ^{33} S–Cu/Pd–S/Se space, BMS generally exhibit horizontal trends, with large variability in isotope composition and limited variability in Cu/Pd and S/Se values, apart from a few samples from the 437-SEA Zone with elevated Cu/Pd, and pyrite with elevated S/Se values (ESM 1 Figs. S3A, B).

Discussion

Origin of the pyrite-millerite assemblage in the Current deposit

Although pyrite and millerite can form via magmatic processes by recrystallization from monosulfide solid solution (MSS), this only occurs in sulfide liquids characterized by elevated S/metal ratios (approximately 40 wt. % S at 600 °C) (Naldrett et al. 1967; Kullerud et al. 1969; Craig 1973). Most sulfide liquids, however, do not achieve such high S/metal ratios, and so primary pyrite in magmatic sulfide deposits is quite rare (Piña et al. 2016). Formation of magmatic millerite is largely restricted to Ni-rich komatiitic ores, whereas those that occur in mafic-ultramafic systems are largely the result of low-temperature alteration of pentlandite (Barnes et al. 2011; Duran et al. 2015). Given these physicochemical constraints, the occurrence of pyrite as anhedral, pitted grains (Fig. 5H–L) rather than the euhedral grains expected for primary pyrite (e.g., Dare et al. 2011; Duran et al. 2015; Piña et al. 2016), the disequilibrium textures exhibited in pyrite-pyrrhotite (Fig. 5H) and pentlandite-millerite assemblages, the patchy chemical zonation in pyrite (ESM 1 Fig. S2E), and the



inverse correlation between the abundance of pyrrhotite–pyrite and pentlandite–millerite (Fig. 6D, E), it is likely that the pyrite and millerite in the Current deposit are not magmatic in origin, but rather formed by the low-temperature (<230 °C; Naldrett and

Kellurud 1967; Naldrett et al. 1967; Craig 1973; Misra and Fleet 1974) alteration of pyrrhotite and pentlandite, respectively. This characterization will be used throughout the discussion when characterizing magmatic and hydrothermal processes.

◄Fig. 5 Images of drill core samples (A–D) and reflected–light photomicrographs (E-N) illustrating representative examples of base-metal sulfides and textures in the Current deposit. (A) Mingling between the mafic Current magma and a felsic melt. Note the occurrence of basemetal sulfides where the two magmas mingled. (B) Disseminated, (C) net-textured, and (D) blebby base-metal sulfide mineralization. (E) An equilibrium (magmatic) assemblage comprising pyrrhotite-pentlandite-chalcopyrite-cubanite. (F) Cross-polarized, reflected-light photomicrograph illustrating pyrrhotite occurring as a single crystal and as an aggregate of multiple crystals. Note the 120° dihedral angles between crystals in the latter. (G) Pyrite partially replaced by pyrrhotite. (H) Pyrrhotite partially replaced by pyrite. (I) An assemblage comprising chalcopyrite-pentlandite-pyrite. (J) Chalcopyrite restricted to an alteration patch and physically associated with pyrite. (K) An assemblage of chalcopyrite-pentlandite-pyrite in which the pyrite was partially replaced by pentlandite. (L) An assemblage of chalcopyrite-millerite-pyrite. (M) An assemblage comprising largely chalcopyrite-pentlandite, with violarite occurring along fractures in pentlandite. (N) An assemblage of chalcopyrite-pyrite-gersdorffite. Po=pyrrhotite, Pn=pentlandite, Ccp=chalcopyrite, Cbn=cubanite, Py=pyrite, Mill=millerite, Viol=violarite, Gdf=gersdorffite

Sulfide saturation and metal enrichment-depletion

Many primary BMS in the Current deposit are characterized by mantle S/Se values (2850-4350; Eckstrand and Hulbert 1987; Palme and O'Neil 2014), but significant variability towards values greater and lower than mantle is also observed (Fig. 8A). Likewise, although BMS at Current are characterized by $\Delta^{33}S - \delta^{34}S$ values that are largely within range of mantle values (Δ^{33} S = 0 ± 0.1‰, δ^{34} S = 0 ± 2‰; Lesher and Burnham 2001; Farquhar 2002; Ripley and Li 2003; Bekker et al. 2009), several BMS have Δ^{33} S that are distinctly higher than the mantle (Fig. 9A, D, F). Although variations in R factor alone can explain the lower-than-mantle S/Se and mantle-like Δ^{33} S values (ESM 1 Fig. S4), it cannot explain the elevated S/Se and Δ^{33} S values. These elevated values must, therefore, represent the addition of S from an external source. Given the mantlelike δ^{34} S for all of the BMS and elevated Δ^{33} S (Fig. 9), it seems likely that the contaminant was Archean in age as these isotopic signatures are diagnostic of Archean sedimentary reservoirs (Farquhar and Wing 2003, 2005).

The country rocks provide a potential local source of S as they comprise Archean metasedimentary, and granitic rocks of the Quetico Subprovince (Hart and MacDonald 2007). Although there is limited S isotopic data on these country rocks, the data that are available for the Archean Quetico metasedimentary rocks demonstrate that it is heterogeneous, with δ^{34} S values in the range of -3.03% to 0.61% and Δ^{33} S values in the range of 0.01% to 0.29% (Caglioti 2023). Considering this heterogeneity, the fact that the Quetico Subprovince represents a mixture of crustal sources (Williams 1991), and the significant variability of Δ^{33} S during the Archean (Farquhar et al. 2010), it is possible that the Quetico metasedimentary rocks contain S with highly variable and positive Δ^{33} S values. Similarly, there is no isotopic data available for the Archean granitic country rocks into which the northern portion of the Current intrusion intruded, but the lack of deviation of δ^{34} S– Δ^{33} S from mantle values of sulfides hosted within a mixture of mafic magma and felsic country rock melt (Fig. 5A, ESM 2 Table S3) suggests that the granitic country rocks do not contain a significant mass independent fractionation (MIF) signal. Lastly, it is also possible that S was sourced from Archean rocks at depth, which has been suggested for other Ni–Cu–PGE-mineralized intrusions in the Midcontinent Rift System, including the Marathon deposit (Shahabi Far et al. 2018; Brzozowski et al. 2020, 2021) and Duluth Complex (Ripley et al. 2007).

It has been well documented that contamination signatures recorded by S isotopes and S/Se values can be diluted by interaction of the contaminated sulfide liquid with uncontaminated pulses of silicate melt (Lesher and Burnham 2001; Ripley and Li 2003; Hiebert et al. 2013, 2016; Oueffurus and Barnes 2015; Smith et al. 2016, 2021; Shahabi Far et al. 2018; Brzozowski et al. 2020, 2021), with complete destruction of the geochemical-isotopic signatures at R factors > 1,000 (ESM 1 Fig. S4). Considering the importance of R factor to the enrichment of sulfide liquids in metals in Ni-Cu-PGE deposits, particularly volumetrically small, conduit-type, PGE-rich systems like Current (Figs. 2 and 3), it is possible that the largely mantle-like S isotope and S/Se values of BMS that extend towards non-mantle values may be the product of dilution caused by variably high R factors of < 10,000. To assess this, the S isotope and S/Se values of BMS, and bulk-rock Cu/Pd values are compared to compositions modeled using the R factor equations of Ripley and Li (2003).

Copper, Pd, and Se concentrations are modelled following the closed-system R factor equation of Ripley and Li (2003) and employing sequential steps of batch equilibration:

$$C_{sul_f}^{metal} = \frac{C_{sul_i}^{metal} + (R * C_{sil_i}^{metal})}{1 + \frac{R}{D_{sul-sil}^{metal}}}$$
(1)

The parameters $C_{sul_i}^{metal}$ and $C_{sul_f}^{metal}$ are the initial and final concentrations of a metal in the sulfide liquid, respectively, $C_{sil_i}^{metal}$ is the initial concentration of a metal in the silicate melt, *R* is the incremental R factor (i.e., the R factor of each individual pulse of magma), and $D_{sul-sil}^{metal}$ is the sulfide liquid–silicate melt partition coefficient for a given metal. Sulfur isotopes are modeled using the open-system R factor equation (Ripley and Li 2003):

$$dS_{sul_f} = \frac{dS_{sul_i} + R^o(dS_{sil_i} + \Delta S_{sul-sil})}{1 + R^o}, where R^o = \frac{C_{sil}^S}{C_{sul}^S} * R$$
(2)

Fig. 6 Binary diagrams illustrating the variation in abundances of (A) chalcopyrite-pyrrhotite, (B) pentlandite-pyrrhotite, (C) chalcopyrite-pyrite, (D) pyrrhotite-pyrite, (E) pentlandite-millerite obtained by mineral liberation analysis. Note the strong negative, nonlinear correlation between the abundances of pyrrhotite-pyrite and pentlandite-millerite. The grey squares are data from an unpublished metallurgical study by Clean Air Metals Inc



The parameters dS_{sul_i} and dS_{sul_i} correspond to the initial and final (after sulfide liquid-silicate melt interaction) S isotope compositions of the sulfide liquid, respectively, dS_{sil} is the initial S isotope composition of the incoming silicate melt, $\Delta S_{sul-sil}$ is the S isotope fractionation factor between sulfide liquid and silicate melt, and C_{sil}^S and C_{sil}^S are the concentrations of S in the silicate melt and sulfide liquid, respectively. Values used for the model parameters are provided in Table 1, along with an explanation of why the values were chosen. Given the likelihood that the contaminant was Archean in age and the overall mantle-like δ^{34} S values of the samples (Fig. 9), modeling focused on Δ^{33} S–S/Se–Cu/Pd. Because the nature of the Archean contaminant is not known, modeling was done using several contaminant starting compositions representing assimilation of S with a range of Δ^{33} S values from mantle-like (0.1%), to those similar to metasedimentary pyrite in the Quetico Subprovince (up to 0.3%; Caglioti 2023), to those notably higher than mantle (1%, 3%, and 10%); these values are within the range of Δ^{33} S values of Archean sedimentary reservoirs (Farquhar and Wing 2003, 2005; Farquhar et al. 2010).

According to the model, as R factor increases from 100 to ~ 10,000, the S/Se value of the sulfide liquid decreases more rapidly than the Cu/Pd ratio, whereas at R factors > 10,000, the opposite is observed, with S/Se being essentially invariable and Cu/Pd decreasing significantly (Fig. 10A). The Cu/Pd–S/Se data from the Current deposit generally follows the model trend at R factors < 10,000, exhibiting limited variability in Cu/Pd values, but significant variability in S/Se values (Fig. 10A). This suggests that i) the sulfide liquid at Current experienced R factors < 10,000, consistent with R factors estimated from bulk-rock Cu and Pd (Fig. 11), and ii) the silicate melt assimilated material that was characterized by elevated S/Se values. Based on the modeling, the minimum S/Se value of the contaminant was likely in the range of 36,000, which is within the



Fig. 7 Binary diagrams illustrating the variation in metal (A-H) and semi-metal (I-L) concentrations in base-metal sulfides as a function of Co concentration. All concentrations are in ppm

range of values of pyrite in the Archean Quetico granitic (30,066–64,426, ESM 2 Table S3) and metasedimentary country rocks (12,848–82,249; Caglioti 2023).

The modeled variations in Cu/Pd- Δ^{33} S exhibit similar trends for all of the hypothetical contaminants, with significant variability in Δ^{33} S at R factors < 10,000, and essentially

no variability in Δ^{33} S at R factors > 10,000 (Fig. 10B), similar to S/Se. The model curves for the various contaminants in S/Se– Δ^{33} S space exhibit distinct trends based on how positive the Δ^{33} S value of the contaminant is, with the overall slope of the curves increasing with isotopically lighter contaminants (Fig. 10C). Two things are evident

Fig. 8 Binary diagrams illustrating the variation in bulk-rock Cu/Pd and sulfide S/Se in (A) the primary chalcopyritecubanite-pyrrhotite-pentlandite assemblage and (B) the secondary pyrite-millerite assemblage. The red, dashed field outlines the range of bulk-rock Cu/Pd and S/Se values. The purple and pink dashed fields represents the bulk-rock Cu/Pd ratio of Archean granitic and metasedimentary country rock and S/Se of its pyrite $(n_{Py}=2 \text{ and } n_{Py}=4)$, respectively); data for metasedimentary pyrite is from Caglioti (2023). The mantle ranges for Cu/Pd (1,000-10,000) and S/ Se (2,632-4,350) are from Barnes et al. (1993, 2015b), and Eckstrand and Hulbert (1987) and Palme and O'Neil (2014), respectively

Fig. 9 Binary diagrams illustrating the variation in (A) Δ^{33} S- $\delta^{3\overline{4}}$ S and (B) Δ^{33} S- Δ^{36} S of base-metal sulfides. The mantle range for Δ^{33} S is from Farquhar (2002) and Bekker et al. (2009), and for $\delta^{34}S$ is from Lesher and Burnham (2001) and Ripley and Li (2003). The mantle ranges for Cu/Pd (1,000-10,000) and S/Se (2,632-4,350) are the same as in Fig. 8. The pink, dashed field highlights the composition of pyrite from Quetico metasedimentary rocks from Caglioti (2023). Error bars for S isotopes are 2σ



Table 1 Parameters for numerical modeling

	Value	Note	Reference
Silicate melt			
Cu _{sil.i}	100	Similar to the values of the theoretical parental melt	Heggie (2012)
Pd _{sil.i}	0.01	to the Current deposit.	
Cu/Pd _{sil.i}	10000		
S _{sil}	400	Similar to the median S content of unmineralized dikes and volcanic rocks in the Midcontinent Rift north of Lake Superior.	Cundari et al. (2021)
Se _{sil.i}	0.10	Calculated by maintaining a mantle S/Se ratio of 4,000.	Brzozowski et al. (2021)
S/Se _{sil.i}	4000	Within the range of mantle values (2,632-4,350).	Eckstrand and Hulbert (1987), Palme and O'Neil (2014)
$\Delta^{33}S_{sil,i}$	0	Within the range of mantle S isotope values.	
Sulfide liquid			
Cu _{sul.i}	80000	Within the range of metal tenors in the Current	Kerr (2003)
Pd _{sul.i}	25	deposit. Calculated using assay data and the method of Kerr (2003).	
S _{sul}	360000	Sulfur content similar to pyrrhotite-pentlandite- chalcopyrite.	
Se _{sul.i}	10	Within the range of bulk-rock values of other Ni–Cu– PGE deposits globally. Minimum value required to generate the high S/Se ratios observed in the Cur- rent sulfides. Does not significantly affect the model at high R factors (>1,000).	Queffurus and Barnes (2015)
S/Se _{sul.i}	36000	Serves as the starting contaminated composition.	
$\Delta^{33}S_{sul.i}$ (Model 1)	0.1	Model in which the contaminant has a mantle-like Δ^{33} S value.	
$\Delta^{33}S_{sul.i}$ (Model 2)	0.3	Model in which the contaminant has a Δ^{33} S value similar to sedimentary pyrite of the Archean Quetico Subprovince.	Caglioti, unpublished MSc thesis
$\Delta^{33}S_{sul.i}$ (Model 3)	1	Models in which the contaminant has Δ^{33} S values	Farquhar and Wing (2003, 2005), Farquhar et al. (2010)
$\Delta^{33}S_{sul.i}$ (Model 4)	3	heavier than mantle.	
$\Delta^{33}S_{sul.i}$ (Model 5)	10		
Other parameters			
R	100		
R ^o	0.11		
$\Delta S_{sul-sil}$	0.00		Ripley and Li (2003)
D ^{Cu} _{sul-sil}	2130	Maximum sulfide liquid-silicate melt partition coef-	Barnes and Ripley (2016)
D ^{Pd} _{sul-sil}	536000	ficients.	
D ^{Se} _{sul-sil}	2339		

All concentrations are in ppm. S isotopes are in permille

from the model curves and distribution of Current data. First, it seems unlikely that the contaminant(s) had Δ^{33} S values greater than 3‰ as the Current data have S/Se values notably higher than those predicted by models using such contaminants (Fig. 10C). Second, none of the contaminant models individually can explain the distribution of BMS compositions at Current, with some BMS having mantle-like Δ^{33} S, but elevated S/Se values, and others having high Δ^{33} S, but mantle-like S/Se values (Fig. 10C). The elevated Cu/Pd values of the 437–SEA Zone (Fig. 10A, B) indicate that the silicate melt(s) from which they crystallized must have lost < 0.1% of their sulfide liquid prior to or during intrusion (Fig. 10A, B). It is possible that the elevated S/Se values in this zone are also the result of sulfide removal rather than contamination. This scenario seems unlikely, however, as generating S/Se values in the range of 6,000 would require removal of > 10% sulfide liquid from the melt, which would have severely depleted the melt in Pd (Fig. 10). Rather, the distribution of data suggests that the Current magma(s) assimilated externally derived S from isotopically distinct reservoirs, some of which had mantle-like Δ^{33} S and others that had high Δ^{33} S values of up to 3‰ (Fig. 10C).



Fig. 10 Binary diagrams illustrating the modeled variations in (**A**) S/ Se–bulk-rock Cu/Pd, (**B**) Δ^{33} S–bulk-rock Cu/Pd, and (**C**) Δ^{33} S–S/Se as a function of variable R factor and contamination by rocks with different Δ^{33} S values (colored, solid lines). The green, dashed line represents modeled compositional variations as a function of sulfide liquid removal. The colored fields represent the S/Se ratio of primary chalcopyrite–cubanite–pyrrhotite–pentlandite in the different mineral-

ized zones and bulk-rock Cu/Pd. References for the mantle ranges are the same as those in Fig. 9. The purple and pink dashed fields represents the bulk-rock Cu/Pd ratio of Archean granitic and metasedimentary country rock and S/Se of its pyrite; data for metasedimentary pyrite is from Caglioti (2023). The numbers on the model curves represent R factor and the degree of sulfide liquid removal



Fig. 11 Binary diagram illustrating the variation in bulk-rock Cu/Pd and Pd in the Current deposit. The colored fields represent the distribution of data for the Current–Bridge and Beaver–Cloud zones, whereas the data points represent the 437–SEA Zone. The solid curves represent modeled variations as a function of R factor and sulfide abundance. The dashed curve represents modeled variations

as a function of sulfide liquid removal. The Cu–Pd contents of the starting melt and the sulfide liquid–silicate melt partition coefficients are provided in Table 1. The numbers on the curve represent sulfide percent, either as the amount present in the rock (in the case of the R factor models) or the amount of sulfide liquid removed (in the case of the sulfide segregation model)

The MIF signal recorded by some BMS in the Current-Bridge and Beaver-Cloud zones (Fig. 10C), therefore, likely originated from the addition of S with elevated Δ^{33} S from Archean rocks at depth. In contrast, the mantle-like Δ^{33} S and elevated S/Se values that largely characterize BMS in the 437-SEA Zone likely record assimilation of S from the local metasedimentary country rocks, which exhibit similar geochemical-isotopic signatures (Fig. 10C). This is consistent with the fact that the 437-SEA Zone was one of the final zones to have remained magmatically active in the Current intrusion, as evidenced by the lithologic layering in this zone that could only have been developed as a result of relatively closed-system fractional crystallization when the magmatic system was waning (ESM 1 Fig. S1) (Heggie et al. 2015). This portion of the conduit would, therefore, have experienced the greatest contact time with the metasedimentary country rocks, increasing the amount of metasedimentary S that was added to the magma.

An implication of this interpretation is that the sulfide liquid formed at depth and was carried upwards, the possibility of which has long been questioned (Lesher 2019). Recent numerical simulations and textural evidence, however, demonstrate that dense sulfide liquids may be transported upwards by attachment to vapor bubbles in shallow, degassing magmas (Yao et al. 2019; Yao and Mungall 2020). Barnes et al. (2019) demonstrated this concept for the Norilsk ores, where they identified segregated sulfide globules capped by highly fractionated, residual silicate melt (i.e., sulfide liquid + vapor bubble). A similar textural variety of sulfide occurs at Current (Fig. 5D), suggesting that the Current magma(s) were degassing during transport, which may have supported the upward movement of sulfide liquid.

Remobilization of metals

The peridotite host rocks of the Current deposit are pervasively serpentinized. This, along with several lines of mineralogical and geochemical evidence, support the idea that late-stage hydrothermal fluids circulated through the host rocks of the deposit. This evidence includes i) the ubiquity of secondary pyrite and millerite after pyrrhotite and pentlandite, respectively (Fig. 5H-J, L), ii) the occurrence of pyrrhotite and pentlandite veinlets that crosscut secondary pyrite (Fig. 5G), iii) the presence of chalcopyrite restricted to patches of late-stage hydrous minerals (Fig. 5J), iv) the lack of correlation between bulk-rock S and base-precious metals (e.g., Cu and Pd) for a subpopulation of samples from the deposit (Fig. 4A, B), and v) the occurrence of gersdorffite with pyrite (Fig. 5N). Although gersdorffite can crystallize from sulfide liquids (Hem and Makovicky 2004), the generally low As content of the primary BMS at Current (Fig. 7J, ESM 2 Table S3) suggests that the As content of the original sulfide liquid was low, precluding the possibility of gersdorffite being a magmatic phase. Such a low As content in BMS is consistent with the fact that As is often undersaturated in sulfide liquid unless it was added to the silicate magma via assimilation of an As-rich contaminant (Smith et al. 2021).

Given the presence of pyrite after pyrrhotite (Fig. 5H) and millerite after pentlandite (Fig. 5L), it is clear that at least some amount of Fe and Ni must have been remobilized since pyrrhotite has a higher Fe content than pyrite (~62 wt. % vs.~47 wt. %), and pentlandite has a lower Ni and higher Fe content than millerite (~ 34 wt. % vs. ~ 65 wt. % Ni and ~ 33 wt. % vs. 0 wt. % Fe). The replacement of pyrrhotite by pyrite and pentlandite by millerite would, therefore, release Fe to the fluid, whereas the latter reaction would sequester Ni from the fluid; although the source of this additional Ni is uncertain, it could have originated from the olivine that was pervasively serpentinized, as has been demonstrated in the serpentinized Huangshandong Ni-Cu sulfide deposit in northwestern China (Wang et al. 2021). Mobilization of Fe and Ni is also consistent with the occurrence of pyrrhotite and pentlandite veinlets that crosscut pyrite (Fig. 5G), implying that this textural variety of pyrrhotite and pentlandite must have crystallized from fluids that circulated after the replacement of primary pyrrhotite by pyrite, as well as the occurrence of gersdorffite (Fig. 5N). Although removal of Fe can sufficiently explain the replacement of pyrrhotite by pyrite, it is likely that S was also added during this reaction. This is evident by the lack of correlation between bulkrock S and metals in some samples from the Current deposit (Fig. 4A, B), indicating that S was likely mobile.

Considering that pyrite has a relatively invariable S content of ~ 53 wt. % and the Se content of pyrrhotite exhibits relatively limited variability (50-223 ppm), the large range in S/Se values exhibited by pyrite (Fig. 8B) cannot be entirely the result of S addition during pyrrhotite replacement as this would result in a maximum S/Se value in pyrite of 10,600 (530,000 ppm S / 50 ppm Se), whereas pyrite in the Current deposit exhibits values as high as 64,000 (Fig. 8B). Accordingly, some Se must have been released from pyrrhotite to the fluid as it was replaced by pyrite; this is consistent with the greater range in Se content of pyrite that extends to notably lower values (as low as 23 ppm) than the majority of pyrrhotite (Fig. 7L). Given that Se is thought to be most mobile in acidic, saline, and oxidizing fluids (Prichard et al. 2013), this implies that the fluids that reacted with and replaced pyrrhotite and pentlandite by pyrite and millerite, respectively, had low pH, high salinity, and high fO_2 . Importantly, these are also conditions under which several metals may be mobilized, including some of the PGE (Mountain and Wood 1988; Pan and Wood 1994; Wood 2002; Hanley et al. 2005; Liu and McPhail 2005),

although recent studies suggest these strict conditions may not be a requirement for metal mobilization (Sullivan et al. 2022).

Despite favorable fluid conditions for the mobility of the PPGE, the range of concentrations of Pd and Pt, as well as Au, in pyrrhotite and pyrite are largely indistinguishable, implying that the replacement reaction did not add or remobilize these metals (Fig. 7B–D). This is consistent with the positive correlations between bulk-rock Pd-Pt (Fig. 4C) and Pd-Ir (Fig. 4D). The IPGE (Ir, Os, and Ru) extend to lower concentrations in pyrite compared to pyrrhotite (Fig. 7E-G). Although these lower concentrations may result from IPGE remobilization by a hydrothermal fluid, large-scale remobilization seems unlikely given that the IPGE are generally considered immobile relative to, for example, Pd (Xiong and Wood 2000; Wood 2002; Sullivan et al. 2022). Given the lower concentrations of Sn and Bi in pyrite compared to pyrrhotite, it is likely that the lower IPGE content in pyrite relates to the formation of IPGE-Sn-Bi-Pb-bearing PGM, which are heterogeneously distributed throughout pyrite, as well as other BMS (ESM 1 Fig. S2) and were excluded from integration regions when processing laser ablation spectra. The higher As content of pyrite relative to pyrrhotite (Fig. 7J) suggests that As was added to the system by the hydrothermal fluid that replaced pyrrhotite by pyrite. This is consistent with the presence of gersdorffite (Fig. 5N) and the mobility of As in Ni-Cu-PGE deposits (Gervilla and Kojonen 2002; Le Vaillant et al. 2015, 2016). Similarly, the concentration of Co extends to notably higher values in pyrite relative to pyrrhotite, suggesting that it was also added to the mineralizing system (Fig. 7A). Given that Ag does not generally occur as an independent mineral (apart from electrum), its lower concentration in pyrite relative to pyrrhotite (Fig. 7H) suggests that it was remobilized from the BMS assemblage during replacement of pyrrhotite by pyrite.

Although not related to the replacement of pyrrhotite by pyrite, Cu was also likely remobilized given i) the occurrence of some chalcopyrite within hydrous mineral assemblages (Fig. 5J) (cf. Brzozowski et al. 2020) and ii) the lack of correlation between bulk-rock Cu and S in a subpopulation of samples from the Current deposit (Fig. 4A). This Cu could not have been added to the system, however, as such a process would generate a vertical trend in bulk-rock Cu/ Pd vs. Pd space, which is not observed (Fig. 11). Rather, it must have been remobilized within the system.

These results have important implications for the Current deposit because they demonstrate that metals were variably mobilized by late-stage hydrothermal processes. At the deposit scale, the tenors of Cu and Pd were not affected by this event, as is evident by their coherent behavior in Cu/Pd vs. Pd space (Fig. 11). The IPGE tenors were also unaffected by this event, but their hosts were modified, with As-bearing IPGM becoming a host as a result late-stage As addition. The Ni and Co tenors of the deposit were likely improved during hydrothermal circulation given the presence of millerite after pentlandite, the latter of which has a higher Ni content, and the higher concentration of Co in pyrite after pyrrhotite. In contrast, the Ag tenor of the deposit was likely reduced by removal from the mineralizing system as evidenced by its lower concentration in pyrite after pyrrhotite.

Feeder zone and direction of magma flow

The direction of magma flow, and hence the location of the magma feeder zone, remain topics of contention in the Current deposit, with both SE to NW magma flow and NW to SE magma flow both being suggested (Bleeker et al. 2020). Three physicochemically distinct features of the SEA point towards a model whereby magma flow in the Current intrusion was from SE to NW, suggesting that the SEA could have been the feeder zone to the intrusion.

Loss of sulfide liquid

The SEA is the only zone in the Current intrusion to be characterized by Cu/Pd values that are elevated relative to mantle values (Fig. 10A, B), indicating that it is the only zone to have crystallized from Pd-depleted magma that lost sulfide liquid after it had equilibrated with the silicate magma and scavenged metals (Figs. 10 and 11). Given this, and the fact that bulk-rock Cu/Pd ratios throughout the Current deposit show relatively limited variability (Fig. 11), this loss of sulfide liquid was likely a local event, which we suggest is the removal of sulfide liquid via drainage down towards deeper portions of the intrusive system below the SEA. This suggestion is consistent with the lower Pd contents of pentlandite in this zone compared to pentlandite in the other zones of the deposit (ESM 2 Table S3). Such backflow of sulfide liquid towards deeper portions of an intrusive system has been described by Barnes et al. (2015a). Additionally, Pd depletion is also a feature of the feeder zone to the Marathon conduit-type magmatic sulfide deposit (Good et al. 2015). Loss of sulfide liquid requires this region of the deposit to have experienced a period of decreased magmatic activity, otherwise the sulfide liquid would likely have remained in suspension, resulting in mineralization that was similar to the other portions of the Current deposit, with no Pd depletion, but this is not observed. A decrease in magmatic activity would have allowed for more efficient settling of sulfide liquid droplets or percolation of sulfide liquid through pore spaces between silicate minerals, promoting the removal of sulfide liquid from the SEA. In the case of percolation, it was demonstrated by Mungall and Su (2005) that a sulfide liquid would not be capable of percolating through a cumulate pile by capillary forces, but could be forced through pore spaces by the flow of the enclosing silicate melt. Accordingly, if magmatic activity in the SEA decreased, backflow of the magma could have forced the sulfide liquid through grain boundaries, allowing it to percolate through the cumulate pile and to be removed from the SEA. Additionally, maintaining this Pd-depleted signature in the magma from which the SEA crystallized suggests that, after sulfide loss, the metal content of the mineralizing system was not replenished by significant influx of more primitive magma. Together, these metal characteristics require that the Current deposit crystallized in stages, with the SEA crystallizing last. In such a scenario, the SEA would have acted as a relatively independent system in its final stages prior to crystallization, allowing the magma and sulfide liquid in this zone to acquire distinct geochemical signatures resulting from loss of sulfide liquid via gravity drainage, potentially down the feeder zone. An alternative possibility to explain the Pd depletion in the SEA is retention of sulfide liquid in traps at depth. This scenario seems unlikely, however, because these traps would have been upstream of the deposit, resulting in Pd depletion in all of the zones of the Current deposit, which is not observed (Figs. 10 and 11).

Progressive crystallization from northwest to southeast could explain the recrystallized pyrrhotite observed throughout the Current intrusion (Fig. 5F). Deformation could not have caused this recrystallization because the intrusion is undeformed (Kuntz et al. 2022). An alternative explanation for the recrystallization is thermal metamorphism (Good et al. 2015). This would have required two features — i) some portions of the Current intrusion would need to have been significantly crystallized as pyrrhotite must have already been present and it recrystallizes from MSS at temperatures of < 650 °C (Kullerud et al. 1969; Kelly and Vaughan 1983; Ebel and Naldrett 1996; Lusk and Bray 2002), and ii) there must have been a sustained source of heat. Both of these requirements would have been satisfied in the progressive crystallization scenario, with the still magmatically active 437-SEA Zone providing the necessary heat. This direction of progressive crystallization is also consistent with changes in the morphology of the intrusion, with the shallower and thinner Current-Bridge Zone likely having begun crystallizing prior to the deeper and thicker Beaver-Cloud and 437-SEA zones (Figs. 2 and 3).

An alternative possibility to explain the Pd-depleted nature of the SEA is equilibration of the Current magma, flowing from northwest to southeast, with sulfide liquid. If such a scenario were true, then one would expect a systematic depletion in Pd from Current–Bridge to Beaver–Cloud to SEA, but this is not observed (Figs. 10 and 11). Additionally, it is difficult to conceive of a scenario whereby the Current pluton would have intruded from shallower depths (in the northwest) to greater depths (in the southeast). Although magma may migrate along weaknesses in the crust and be emplaced laterally, magma flow is principally upwards, driven by buoyancy and pressure forces (Longo et al. 2023). Given that the Southeast Anomaly occurs at a depth of ~ 1000 m and the Current–Bridge Zone occurs at a depth of ~ 50 m (Fig. 2b), it seems more likely for magma to have flowed from southeast upwards towards the northwest.

Local source of S

Base-metal sulfides in the SEA record distinct S isotope signatures compared to BMS in the other zones of the deposit, having Δ^{33} S values that are largely within the range of mantle values compared to the Δ^{33} S values that are higher than mantle in the other zones (Fig. 10). This indicates that the sources of S that contributed to sulfide saturation in the SEA were different than those which contributed to saturation in the Current-Bridge and Beaver-Cloud zones. Specifically, the magmas from which the latter zones crystallized likely became sulfide saturated by addition of S from a source at depth, whereas S from the local metasedimentary country rocks was also added to the magma from which the SEA crystallized (Fig. 10c). Addition of local S to the magma from which the SEA crystallized, and the lack of evidence for this addition elsewhere in the Current intrusion, can be explained by increased contact time between the SEA magma and the country rock, which would have allowed for greater diffusive transfer of S into the SEA magma (Robertson et al. 2015a; Barnes and Robertson 2019). Although local S addition could also have occurred via bulk assimilation as a result of, for example, erosion of the conduit floor, this seems unlikely as there is no evidence of bulk-rock contamination: i) partially assimilated xenoliths of country rock material are not observed in the SEA, ii) addition of significant amounts of siliceous country rock material would have resulted in the crystallization of orthopyroxene, but orthopyroxene is rare at Current, and iii) rocks throughout the Current intrusion, including the SEA, have Th/La ratios that are systematically lower than mantle values (0.07–0.1; Chaffee 2015; Yahia et al. 2022). Local addition of S only in the SEA implies that the flow of the SEA magma was restricted to the southeast portion of the Current intrusion, which is hosted by metasedimentary country rock, and/or that the magma was relatively stagnant in this area. It is likely that both scenarios occurred for two reasons. First, sequential crystallization of the Current intrusion from northwest to southeast would have progressively isolated the SEA from the other portions of the conduit, restricting magma flow to portions of the conduit hosted by metasedimentary country rock. Second, the Pd-depleted nature of the SEA (i.e., high Cu/Pd ratios) requires that the magma from which it crystallized lost sulfide liquid, which requires the SEA to have experienced a period of decreased magmatic activity that would have promoted gravitational settling. This decreased magmatic activity would have allowed the SEA magma to stagnate in contact with the metasedimentary country rock. Considering that the Pd content of pentlandite is lower in the SEA compared to the other zones in the Current deposit (ESM 2 Table S3), it is likely that this local addition of S triggered a separate sulfide saturation event in the SEA magma during and/or after the removal of earlier-formed sulfide liquid. The removal of earlier-formed sulfide liquid would have depleted the magma in Pd, as well as other metals, as demonstrated by the Rayleigh fractionation model in Figs. 10 and 11, such that the locally formed sulfide liquid was depleted in Pd, now recorded as Pd-depleted pentlandite.

Lithological layering

The above geochemical-isotopic characteristics that are unique to the SEA (elevated bulk-rock Cu/Pd, elevated S/Se ratios in sulfides, and mantle-like Δ^{33} S values in sulfides) suggest that this zone was potentially the final portion of the Current conduit to have crystallized. This interpretation is supported by the lithologic layering and accompanied changes in major-minor-element chemistry along drillhole that is observed only in this zone (Heggie et al. 2015). From base to top, this layering comprises peridotite, melagabbro, upper oxide gabbro, and quartz-bearing gabbro/monzonite, and is accompanied by systematic decreases in MgO-Cr and increases in Al₂O₃ up drillhole (ESM 1 Fig. S1). Such layering in the SEA, which is also observed in other conduit-type systems (e.g., Kabanga, Uitkomst, Eastern Gabbro; Gauert et al. 1995; Li et al. 2002; Maier et al. 2011; Cao et al. 2019), could have formed via closed-system fractional crystallization (Heggie et al. 2015) or open-system processes, such as slumping and saltation. Although it is difficult to distinguish between closed- vs. open-system processes with the available data, we suggest that the layering was the result of essentially closed-system processes for three reasons. First, the systematic changes in major-minor-element chemistry from the peridotite to the quartz-bearing gabbro/monzonite mimic the geochemical variation expected during fractionation of a magma. Second, there is a lack of rhythmic layering in the SEA, which may be expected if the layering formed by repeated magma replenishment followed by crystallization on the wall rock and collapse (Shaw 1997). Lastly, there is no evidence in drill core for folding of the lithologic layers, which may be expected if the layering formed as a result of slumping (Shaw 1997). We, therefore, suggest that the series of rock types that make up the SEA were the result of magmatic fractionation. This process occurred once the energy of the magmatic system waned and the conduit was no longer being replenished by magma.

Taken together, i) the Pd-depleted nature of the magma from which the SEA crystallized, ii) the distinct source of S that contributed to sulfide saturation in this zone, and iii) the lithological layering observed in this zone indicate that the SEA was the final zone to have crystallized and is, therefore, the feeder to the Current intrusion. This indicates that magma flow in the Current intrusion was from southeast to northwest.

Deposit model for the Current Ni-Cu-PGE system

We have developed a holistic mineral deposit model for the Current Ni-Cu-PGE deposit that incorporates the mineralogical-geochemical-isotopic features characterized here with the physical features of the intrusion. This model highlights the key mineralizing processes that operated throughout the intrusion to generate the mineralization, as well as how these processes changed as the mineralizing system evolved. Consider a shallow-dipping conduit that was emplaced at shallow levels into Archean metasedimentary and granitic country rocks. During the early, high-energy stage of system development, the conduit was charged with multiple pulses of olivine- and sulfide-laden magma (Fig. 12A). The sulfide liquid carried into the conduit formed at depth by the addition of S from Archean rocks and was entrained upwards, perhaps facilitated by the presence of vapor bubbles (Fig. 5C), and was initially characterized by elevated S/Se and Δ^{33} S (up to 3%) values. During intervals of magmatic quiescence, the magma flowed down the conduit, carrying with it some of the olivine and sulfide liquid that it introduced (Fig. 12A). This process of influx and backflow could have generated eddy currents, aiding the entrained sulfide liquid in interacting with silicate melt (Fig. 12A). The high R factors (>1,000) achieved would have largely diluted the geochemical (S/Se)–isotopic (Δ^{33} S) signatures of the assimilated Archean S, such that most of the sulfide liquid would have been characterized by mantlelike signatures, apart from those that interacted with lower volumes of silicate melt.

During the low-energy stage of conduit development when the magmatic system was beginning to wane, the thinner morphology and/or shallow emplacement of the Current–Bridge and Beaver–Cloud zones promoted their early and rapid crystallization, closing them off to further magmatic activity (Fig. 12B). These regions of the conduit are characterized by high R factor, Pd-rich sulfides. The SEA was still magmatically active during this stage, allowing the composition of the resident magma and sulfide liquid to be further modified by magmatic processes. Restriction of magma flow to the portion of the conduit hosted by metasedimentary country rock, and its eventual stagnation in this area, allowed local S to be added to the magma,



Fig. 12 Two-stage schematic model illustrating the processes that led to the formation of sulfide liquid and its subsequent enrichment in metals in the Current deposit — (A) high-energy stage and (B) waning stage of magmatic activity

generating additional sulfide liquid with distinct S isotope compositions. During periods of magmatic quiescence, olivine, clinopyroxene, and sulfide liquid drained down the conduit and, potentially, accumulated in the feeder zone, decreasing the sulfide abundance and Pd content of the SEA (Fig. 12B). The eventual cessation of the magmatic system allowed the magma in the SEA to evolve via essentially closed-system fractional crystallization, generating the systematic change in lithology from primitive to more evolved rocks up stratigraphy (Fig. 12B). After crystallization, circulation of hydrothermal fluids altered the host rocks and mineralization, which remobilized some of the metals.

Comparison to the architecture of other Ni-Cu-PGE deposits

Intrusions can exhibit a range of geometries, including channelized subvolcanic sills (e.g., Norilsk, Russia and Uitkomst, South Africa; Gauert et al. 1995; Naldrett and Lightfoot 1999; Maier et al. 2004), tube-like conduits (e.g., Nebo Babel, Australia and Limoiera, Brazil; Seat et al. 2007; Mota-e-Silva et al. 2013), and feeder dikes that link vertically separated sills (e.g., Voisey's Bay, Canada; Evans-Lamswood et al. 2000). Although the Current deposit is classified as a conduit-type intrusion, its architecture falls into multiple of the aforementioned intrusion geometries depending on the location within the mineralized system. Specifically, the granite-hosted Current-Bridge Zone is characterized by a tube-like geometry similar to Nebo Babel, Limoiera, and Uitkomst, whereas the sedimentary-hosted Beaver-Cloud and 437-SEA zones have more ribbon-like geometries, being notably wider than they are thick, similar to Norilsk (Figs. 2 and 3). This change in geometry occurs abruptly at the contact between the rheologically distinct granite and sedimentary country rocks (Figs. 2 and 3). Although it is known that crustal-scale weaknesses exhibit fundamental controls on magma migration and intrusion geometry, the Current intrusion is one of few magmatic systems in which this is unambiguously demonstrated. This contrasts with Nebo Babel, Limoiera, and Uitkomst, which intruded into either intrusive or sedimentary country rock and exhibit comparatively invariable geometries along their lengths (Maier et al. 2004; Seat et al. 2007; Mota-e-Silva et al. 2013). One peculiarity of the geometry of the Current intrusion is that, unlike most magmatic intrusions, it thickens towards the feeder zone (Fig. 2). Considering that both the Beaver-Cloud Zone and SEA coincide with the Quetico and Escape Lake fault zones, respectively, and both zones are thick relative to the Current-Bridge Zone (Fig. 2), it is suggested that this thickening resulted from exploitation of a crustal weakness. The Current intrusion, therefore, serves as a prime example of how country rock rheology and crustal weakness control intrusion architecture.

Conclusions

The Current deposit represents one of the best examples of a conduit-type Ni–Cu–PGE sulfide deposit. This tube-shaped intrusion was emplaced into Archean metasedimentary and granitic rocks, and records a variety of magmatic and post-magmatic processes in the texture, and trace-element and S isotope composition of its diverse BMS assemblage.

- 1. Saturation of the Current magmas in sulfide and generation of a sulfide liquid resulted from addition of external S from at least two sources, one located at depth $(\Delta^{33}S < 3\%)$ and the other being the local Archean metasedimentary country rocks $(\Delta^{33}S < 0.3\%)$.
- 2. The Current intrusion crystallized sequentially, from the Current–Bridge Zone towards the 437–SEA Zone. This, along with the elevated Cu/Pd ratios, distinct source of S, and igneous layering in the 437–SEA

Zone, suggests that it represents the feeder channel to the Current deposit.

3. The BMS mineralogy was modified by the circulation of hydrothermal fluids through the rocks, with pyrrhotite being replaced by pyrite and pentlandite being replaced by millerite. This fluid activity mobilized several metals and semi-metals, including Fe, Ni, S, Se, Co, Cu, As, and Ag, but did not affect the PGE.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00126-023-01193-9.

Acknowledgements The authors would like to thank Clean Air Metals Inc. for providing access to their geochemical database and core yard for sampling, and for allowing us to publish this study. The authors would also like to thank Georges Beaudoin, Wolfgang Maier, William Smith, and David Holwell for their constructive comments that helped fine-tune and strengthen the manuscript. We would like to thank J. C. Barrette (University of Windsor), Dr. Guosheng Wu (Lakehead University), and Dr. Laure Martin and Matvei Aleshin (University of Western Australia) for their contributions in obtaining analytical data. Lastly, we would like to acknowledge Connor Caglioti, Khalid Yahia, and Andrea Corredor Bravo (Lakehead University) for their continued discussions on the petrogenesis of the Thunder Bay North Intrusive Complex.

Funding This project was funded by a NSERC Alliance Grant (Grant No. ALLRP 551989—20) to Dr. Peter Hollings, and supported with in-kind contributions from Clean Air Metals Inc.

Declarations

Conflicts of interest There are no conflicts of interest associated with this study.

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