Centre of Excellence for Sustainable Mining and Exploration (CESME)

Annual Report to the Office of Research Services

June 2021

Executive Summary

In the past year CESME has achieved the following:

- Hosted a successful virtual event associated with the PDAC meeting
- Provided scholarships to support graduate research
- Continued the development of an "Indigenous Certificate in Geological Studies" working closely with the Vice Provost Indigenous Initiatives
- Hosted to virtual presentations
- 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 our discussions with stakeholders about the development of the Indigenous Certificate in Geology, including First Nations educational organisations.

2. *Generate multidisciplinary research proposals and apply for external funding*

   Thanks to funding from NOHFC and Impala Canada we have been able to establish the NHFC Industrial Research Chair in Mineral Exploration. This Chair will support Dr. Hollings' research program for five years which will allow him to build a research team of

1 Postdoctoral Fellow and 5 MSc students. In addition, the Geology Department has been able to backfill Dr. Hollings position with a new tenure track hire. CESME has also supported the establishment of research partnerships with Clean Air Metals, Romios Gold, Enersoft, Generation Mining and Wesdome Gold Mines all of which have been supported through the NSERC Alliance program.

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 Postdoctoral Fellows (Mills) completed her term in the past year. Wang has completed his two year term and returned to China to take a teaching position.

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 have established a new partnership with the Mineral Deposit Research Unit at UBC which has led to the submission of a $4,050,000 NSER Alliance grant supported by 15 mining companies

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:

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

The service of these individuals is greatly appreciated and we look forward to working with them to strengthen CESME in the coming years.

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	Epp	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, there are two Post Doctoral Fellows (Wyatt Bain and Matt Brzozowski) affiliated with CESME.

Research Projects & Scholarly Activities

Indigenous Certificate in Geological Studies:

We have continued to work with Denise Baxter, Vice Provost Indigenous Initiatives to develop the Indigenous Certificate in Geological Studies. We received funding from eCampus Ontario to develop a microcertificate in Math which will form part of the Certificate. After some consultation the certificate has been renamed the Asim Certificate in Geology and is currently being prepared for Senate approval

Postdoctoral Fellow research activities

Dr. Brzozowski came to Lakehead late in 2020 and is working on the Thunder Bay North intrusions near Thunder Bay on a project funded by Clean Air Metals and an NSERC Alliance grant. Since his arrival Dr. Brzozowski developed a research partnership with Generation Mining and Enersoft which led to a successful application for an NSERC Alliance Grant.

Dr. Wyatt Bain joined Lakehead early in 2021 and is supported by the NOHFC IRC. He is working on the intrusive bodies around the Lac des Iles mine.

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 has led to the introduction of faculty from Business to Impala Canada and the development of a new relationship between Avalon Advance Materials Inc. and the Center for Innovation and Entrepreneurship Research.

Educational Activities

CESME sponsored two virtual guest speakers this year. Dr. Rachel Jekanowski gave a talk on ”Visual Culture and the Mining Industry: Popular Earth Science, Extraction, and Sustainability which was attended by 34 people. Dr. Matt Brzozowski gave a talk on “Applications of mineral chemistry to petrogenesis and exploration in conduit type Cu-PGE deposits” which was attended by 31 people.

Undergraduate and graduate training

We have supported two graduate students through the John R. Craig Memorial Scholarship and one through the Dr. Melville Bartley Memorial CESME Award.

Financial statement

CESME is in reasonable financial health. The statement provided below covers the 2019-2020 financial year.

Item	**Credit**	**Debit**
Carry Forward	$14,359.08	
Transfer from Research Support Fund	$2,609.51	
Donations		
Travel & Conferences		$0.00
PDAC booth rental		$0.00
Telecommunications		$768.60
Honorarium for Dr. Jekanowski		$350.00
Printing		$0.00
Curriculum development for ICGS		$6,385.66
PDAC breakfast videos		$2,259.51
Subtotal	*$16,968.59*	*$9,763.77*
Balance	**$7,204.82**	

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.

2020-2021 Budget*

Item	Cost
Attend PDAC meeting to promote CESME (2 x$2,000 people)	$4,000
Attend Roundup meeting to promote CESME (2 x$2,000 people)	$4,000
Conferences for CESME members	$4,000
Teaching relief for Director (1 x $7,800)	$7,800
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. Despite the Covid-19 pandemic the mining industry is very active in Northern Ontario and this has resulted in a number of industry funded collaborations. We anticipate that this will lead for demand to the training provided by the Asim Certificate in Geology and should lead to new research opportunities. We anticipate that CESME will be able to play a role in these activities and fulfill our goal to establish and strengthen links between community partners. The need for increased training to meet the growing economic development needs in Northern Ontario means that the ongoing development of the certificate will be increasingly critical.

Appendix 1

Media reports, posters and publications

CENTRE OF EXCELLENCE FOR
SUSTAINABLE MINING
& EXPLORATION

Lakehead UNIVERSITY

CENTRE OF EXCELLENCE FOR SUSTAINABLE MINING & EXPLORATION

Free Public Lecture

Presents Guest Speaker

Dr. Rachel Jekanowski

Banting Postdoctoral Fellow in the Department of English at Memorial University

Visual Culture and the Mining Industry: Popular Earth Science, Extraction, and Sustainability

As early as the 1940s, the National Film Board of Canada (NFB) produced industrial, scientific, and educational films about natural resource management, mining, and exploratory drilling. Many of these films were co-sponsored by government ministries with an interest in promoting the profitable development of Canada's natural resources. In this talk, I focus on a collection of popular science films produced by the NFB between the 1950s and the 1970s about geology, deep time, and the mining industry. Films like *Know Your Resources* (dir. David A. Smith, 1950), *The Face of the High Arctic* (dir. Dalton Muir, 1958), *Riches of the Earth (Revised)* (dir. Colin Low, 1966), and *The North Has Changed* (director uncredited, produced by David Bairstow, 1967) focused on the social dimensions of mining, alongside scientific narratives about Canada's physical geography and geological history. They were also created with different contexts and audiences in mind, from high school classrooms to Canada's centennial celebration in 1967. Turning to discourse analysis and archival research, I show how these films, as cultural responses to industrial development, express ideas of sustainability and extraction as economic and ecological practices. For contemporary viewers, these films also offer fertile grounds for reexamining the ways that science have been used to frame changing social attitudes towards environmental conservation and consultation with communities facing mining development.

Biography:
Dr. Rachel W. Jekanowski is an interdisciplinary scholar of Film and Media and the Environmental Humanities. Her research focuses on entanglements of visual culture, industry, and environments in North America, historically and in the times-to-come. Dr. Jekanowski is currently a Banting Postdoctoral Fellow in the Department of English at Memorial University, on the ancestral lands of the Mi'kmaq, Beothuk, Innu, and Inuit. Website: http://rjekanowski.ca/

Wednesday, April 14, 2021 at 11:00AM-12:30PM

For Zoom Link/Login & Password contact pnhollin@lakeheadu.ca

Sponsored by:
LU Research Chair in Environmental Humanities & CENTRE OF EXCELLENCE FOR SUSTAINABLE MINING & EXPLORATION

Canadian Institute of Mining and Metallurgy Thunder Bay Branch

CENTRE OF EXCELLENCE FOR SUSTAINABLE MINING & EXPLORATION

CIM Guest Lecturer

Dr. Matthew Brzozowski

(Post Doctoral Candidate; Centre of Excellence for SUSTAINABLE MINING & EXPLORATION (CESME); Lakehead University)

2:00 p.m., Monday, April 12th, 2021
Via Zoom

Applications of mineral chemistry to petrogenesis and exploration in conduit-type Cu-PGE deposits

Exploration for mineral deposits is becoming increasingly challenging as the industry shifts away from identifying shallow mineralized intrusions to identifying deep-seated intrusions. The success of mineral exploration, therefore, depends on the development of robust mineral deposit models and geochemical exploration tools. Development of such exploration criteria for magmatic Ni–Cu–PGE deposits has been challenging as these systems develop and are modified by a complex set of magmatic and post-magmatic processes. Using the Cu–PGE-mineralized Eastern Gabbro of the Coldwell Complex, Ontario, Canada as an example, we will explore the petrogenesis of the host rocks and the processes that generated and modified the conduit-type mineralization using Fe–Ti oxide and base-metal sulfide chemistry, and assess the applicability of Fe–Ti oxide and late-stage vein mineral chemistry to identifying and vectoring towards mineralization. This presentation will highlight the complexity of conduit-type Ni–Cu–PGE systems that arise from the combination of primary magmatic and late-stage hydrothermal processes, the challenges associated with the development of robust exploration tools, and the need to integrate detailed textural analysis with high-resolution mineral chemistry in the assessment of mineral deposit petrogenesis.

For further information, please contact:
Greg Paju 632-7035

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Petrogenesis of the Dog Lake Granite Chain, Quetico Basin, Superior Province, Canada: Implications for Neoarchean crustal growth

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ABSTRACT

The Neoarchean Dog Lake Granite Chain consists of six intrusions (Shabaqua, Silver Falls, Trout Lake, Barnum Lake, White Lily, and Penassen Lake), which parallel the tectonic boundary between the Abitibi-Wawa terrane to the south, and the Quetico Basin to the north. It is a single composite body at depth with derivative branches extending higher into the crust, and consists of three phases: monzodiorite, syenite/quartz monzonite and granite, emplaced at approximately 2.671 Ga, 2.663–2.669 Ga and 2.670 Ga, respectively.

The metaluminous monzodiorites with abundant angular igneous mafic xenoliths, enriched zircon $\varepsilon_{Hf}(t)$ values ranging from −0.52 to +4.20 and enriched $\varepsilon_{Nd}(t)$ (−0.37 to +1.74), were generated by assimilation fractional crystallization of a mafic magma generated by partial melting of enriched mantle metasomatized by melts of subducted oceanic sediments. The metaluminous syenite/quartz monzonite phase has similar mineral assemblages, trace element and Nd-Hf isotopic characteristics to the monzodiorite, and was probably produced by assimilation fractional crystallization of a monzodiorite magma. The granite-hosted zircons have prominent positive Ce anomalies, negative Eu anomalies and mostly positive zircon $\varepsilon_{Hf}(t)$ (−0.12 to +4.25) and enriched $\varepsilon_{Nd}(t)$ values (−1.70 to +0.71), suggesting a mixed source of immature sedimentary rocks and metasomatically enriched mantle-derived magma.

The subduction of oceanic lithosphere under the Abitibi-Wawa arc during the collision of the Abitibi-Wawa arc and the Wabigoon terrane before ~2.7 Ga, generated a metasomatically enriched mantle and associated volcanic rocks. The volcanic rocks underwent rapid weathering and erosion to form the immature sedimentary rocks of the Quetico accretionary prism. Lithospheric inversion caused partial melting of the metasomatically enriched mantle, generating a mafic magma. The mafic magma ascended and underwent assimilation fractional crystallization forming the monzodiorite and syenite/quartz monzonite. Mafic magma was emplaced at the base of the Archean immature sedimentary rocks, triggering melting to generate felsic magma. Mixing of these felsic and mafic magmas generated the DLGC granite in the shallow crust.

The Neoarchean arc-continent collision preserved in the Quetico Basin is similar to that in modern arc systems where intra-oceanic arc crust is added to continental margins, suggesting it was an important mechanism for recycling juvenile crust, generating compositional differentiation, and cratonization.

1. Introduction

The Archean Quetico Basin of the Superior Province is a metasedimentary subprovince located between the Abitibi-Wawa Terrane to the south and the Western Wabigoon, Winnipeg River, and Marmion terranes to the north (Fig. 1). Granitoids are the dominant plutonic rock within the Quetico Basin (Percival and Sullivan, 1988; Davis et al., 1990; Williams et al., 1991; Hattori and Percival, 1999; Lassen, 2004; Pettigrew and Hattori, 2006), and can be used to investigate the petrogenesis and formation of the subprovince (Sawyer, 2002). Neoarchean granitoid intrusions in the Quetico Basin comprise hornblende-biotite tonalite, metaluminous (A/CNK < 1.0) monzodiorite (-monzogabbro), -syenite, -monzonite, and peraluminous (A/CNK = 1.0–1.1) mica-bearing granites, but their genesis is still controversial (Day and Weiblen, 1986; Arth and Hanson, 1975; Southwick, 1991; Zayachkivsky, 1985; Williams et al., 1991; Percival and Sullivan, 1988; Percival, 1989). In addition, whether the source material for the Quetico Basin was derived from a *syn*-volcanic (i.e., the product of

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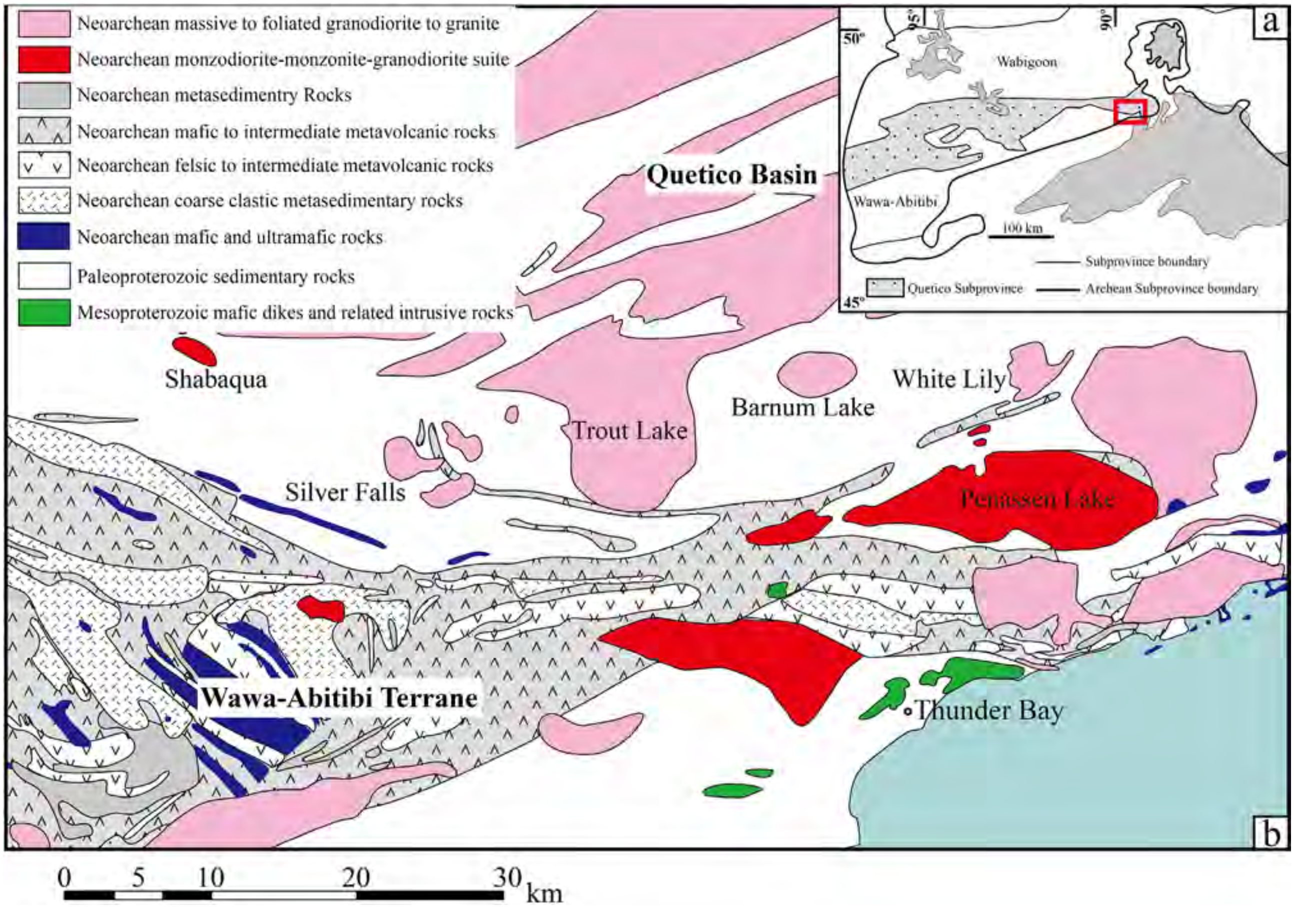

Fig. 1. Regional geology map showing the Quetico Basin with the Wabigoon terrane to the north and the Wawa-Abitibi terrane to the south (a) The key intrusions of the DLGC are shown within the Quetico Basin (b) (modified from (Ontario Geological Survey, 2006).

erosion of active felsic volcanic complexes), post-volcanic (the product of erosion from inactive volcanism), or syn- to post-tectonic material (erosion of a deformed, possibly mountainous region) is still uncertain (Devaney and Williams, 1989). Therefore, the petrogenesis of the granitoids in the Quetico Basin requires further study.

The Dog Lake Granite chain (DLGC) is a linear series of granitoid plutons, consisting of the Shabaqua, Silver Falls, Trout Lake, Barnum Lake, White Lily and Penassen Lake plutons, interpreted to represent a continuous region of magma generation, rather than discrete centers in Quetico Basin (Schwerdtner, 1978). Previous work has largely focused on the Barnum and Penassen Lake monzodioritic and dioritic intrusions, and suggested that they were part of the Neoarchean sanukitoid suite generated by the partial melting of sub-arc metasomatized lithospheric mantle (Stevenson et al., 1999; Laurent et al., 2014). However, little work has been completed on the other intrusions and rock types (e.g., syenite, granite) of the DLGC.

This paper presents whole rock, Sm-Nd isotope, zircon U-Pb, zircon trace element and Hf isotope data for granitoids from five representative intrusions of the DLGC. Detailed petrological and geochemical characterizations are compared with the Neoarchean mafic-ultramafic intrusions in the Quetico Basin and sanukitoids of the Superior Province to better understand the processes that generated the granitoid magmas in the DLGC and the implications for Neoarchean tectonic processes and crustal growth.

2. Regional geology

The Quetico Basin is a Neoarchean metasedimentary subprovince of the Superior Province located between the Abitibi-Wawa Terrane to the south and the Western Wabigoon, Winnipeg River, and Marmion terranes to the north (Fig. 1). It is a ~1200 km long and 100 km wide east-tending subprovince that is dominantly composed of greywackes, derived migmatites and granitic plutons (Williams et al., 1991). Detrital zircon ages from the northern part of the Quetico have been determined to be 2.70–2.97 Ga (Davis et al., 1990) whereas ages to the south are < 2.69 Ga (Zaleski et al., 1999). The structural geology of the Quetico Basin has been summarized by (Williams et al., 1991) who documented four distinct episodes of deformation. Deformation began with an early soft sediment deformation (D1) which caused minor slumping and recumbent folds, followed by a large-scale pervasive east-trending foliation and lineation (D2). The lithified sedimentary rocks then underwent upright folding (D3) and shearing (D4). Four major faults cut through the Quetico Basin including; the east-trending, dextral Quetico Fault which forms the northern contact with the Wabigoon terrane (Fumerton, 1982) with an estimated displacement of 120 km (Bau, 1979), the east-trending Rainy Lake-Seine River fault (Fumerton, 1982), the northeast-trending oblique sinistral Gravel River fault with an offset of at least 70 km (Williams, 1989), and the Kapuskasing Structural zone which has been interpreted to preserve 27 km of east–west shortening and ~50 km of dextral offset (Percival and West, 1994).

Seven suites of plutonic rocks have been recognized in the Quetico Basin (Williams et al., 1991): (1) early mafic-ultramafic intrusions (i.e., Quetico intrusions; Watkinson and Irvine, 1964; MacTavish, 1999; Pettigrew and Hattori, 2006), (2) tonalite and diorite with an age of ~2688-2687 Ma (Davis et al., 1990), (3) nepheline syenite and (4) carbonatitic intrusions ranging in age from 2683 to 2678 Ma (Lassen, 2004), 5) syenitic rocks intruded at 2680 ± 1 Ma (Hattori and

Percival, 1999), (6) voluminous, peraluminous granitic rocks with an age of ~2670 to 2653 Ma (Percival and Sullivan, 1988), and (7) a diorite-monzodiorite-granodiorite-syenite sanukitoid suite with an estimated age of 2670 Ma (Stern et al., 1989; Stevenson et al., 1999).

The DLGC is located due north of the City of Thunder Bay, Ontario, and consists of six ovoid magnetic highs visible on aeromagnetic maps within a predominantly metasedimentary host rock (Fig. 1; Ontario Geological Survey, 1999). Brown (1995) mapped the intrusions as syn- to late-tectonic porphyritic granites. The six intrusions occur over a distance of 65 km with individual intrusions ranging from a few hundreds of metres to 9 km in width. The intrusions are characterized by gravity and magnetic responses that are distinct from the surrounding batholiths consistent with them forming a distinct chain within the Quetico Basin (Kehlenbeck and Cheadle, 1990; Ontario Geological Survey, 1999). All of the intrusions, except the Shabaqua pluton, which is not well exposed, are cut by major roads and can be easily accessed. However, the interior of the intrusions and internal contact relationships are poorly exposed beyond the highways. Where described the intrusions generally consist of a massive, coarse-grained granitic core surrounded by marginal phases that are often more syenitic or trondjhemitic in composition and generally richer in xenoliths than the cores (Kehlenbeck, 1977; Scott, 1990; Metsaranta, 2015; Kuzmich, 2012). The contacts with the marginal phases are typically gradational with the xenoliths generally representing metasedimentary or metavolcanic country rocks (Scott, 1990).

Based on the petrology of five of the intrusions (Fig. 2; Appendix S1), we propose that the granitoid phases can be broadly correlated across multiple intrusions. Overall, the DLGC can be broadly subdivided into three distinct lithological phases: monzodiorite, syenite/quartz monzonite and granite (Table 1).

3. Analytical methods

Samples were selected to represent the various phases of individual intrusions and the DLGC as a whole. Thin sections were prepared at Lakehead University for transmitted light microscopy work, and corresponded to samples submitted for geochemical analysis. Whole rock major and trace element analyses were conducted at the Geoscience Laboratories (Geo Labs) of the Ministry of Northern Development and Mines in Sudbury, Ontario. Strontium-Nd isotope of the samples were determined at the Isotope Geochemistry and Geochronology Research Centre at Carleton University, Ottawa, Ontario. Zircon U-Pb dating work was conducted by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the University of Alberta, and zircon trace elements and Hf isotope analyses were conducted at the School of Resources and Environmental Engineering, Hefei University of Technology, Hefei, China, and Department of Geological Sciences, University of Manitoba, Canada. Detailed analytical methods are presented in Appendix Tables 1–5

4. Results

4.1. Whole rock geochemistry

Data from 37 major and trace element analyses and seven Sm-Nd isotopic analyses for DLGC granitoid samples are presented in Appendix Tables 1 and 2. On a TAS diagram, the monzodiorite phase has SiO_2 contents ranging from 49.9 to 56.9 wt%, and plots in the monzogabbro and monzodiorite field (Fig. 3a), whereas the syenite/quartz monzonite and granite phases plot in fields that are consistent with the petrological nomenclature. Except for three granite samples, most of the DLGC granitoid samples plot in the magnesian rocks series of Frost et al. (2001; Fig. 3b). The monzodiorite and syenite/quartz monzonite samples are metaluminous with A/NK values of 1.1–1.3 and 0.7–0.9, and A/CNK values of 0.8–1.0 and 1.3–1.9, respectively (Fig. 3c). The granite samples are mostly peraluminous with A/NK values of 1.0–1.2 and A/CNK values of 0.9–1.1 (Fig. 3c). The aluminum-saturation index (ASI) of the monzodiorite, and syenite/quartz monzonite phases are 0.7–1.0 and 0.8–1.0, plotting in the metaluminous field (Fig. 3d). The granite samples with ASI values of 1.0–1.1 mostly plot in the peraluminous field (Fig. 3d).

The Al_2O_3, MgO and Co contents of the DLGC granitoids decrease with increasing SiO_2 (Fig. 4a, b, d), and Cr and Ni contents correlate positively with MgO (Fig. 4e-f). The Th content of monzodiorite and syenite/quartz monzonite increase with increasing SiO_2, whereas that of granite decreases (Fig. 4c). The Dy/Yb values of the monzodiorite and syenite/quartz monzonite remain constant with increasing SiO_2 content, whereas they decrease in the granite (Fig. 5a). Light REE (La, Ce, Pr and Nd) contents increase with increasing SiO_2 content for the monzodiorite, but decrease in the granite (Fig. 5b). The HREE (Er, Tm, Yb and Lu) decrease with increasing SiO_2 in the monzodiorite, but increase in the granite (Fig. 5c).

All samples from the DLGC show similar trace element patterns characterized by enrichment of LREE relative to HREE with $(La/Yb)_N$ mostly from 10.4 to 88.3 and with no Eu anomalies (Fig. 5d). All the monzodiorite samples are characterized by positive large ion lithophile elements (LILE) anomalies, high REE and negative Nb, Ta, Sr, Zr, Hf, Ti and Rb anomalies (Fig. 5e-f). The syenite/quartz monzonite phase is broadly similar to the monzodiorite phase, but with negative Ba, Sr anomalies and positive Zr and Hf anomalies (Fig. 5e). The granite phase is similar to the syenite/quartz monzonite phase, but with positive Zr, Hf, and Ta anomalies (Fig. 5e). Compared with the monzodiorite and syenite/quartz monzonite phases, the trace element contents of the granite phase are lower and the patterns are less coherent (Fig. 5d, e).

Two monzodiorite samples were selected for Sm-Nd isotopic analysis, and their $^{143}Nd/^{144}Nd$ values range from 0.51087 to 0.51106 and $\varepsilon_{Nd}(t)$ from −0.37 to +1.74. The $^{143}Nd/^{144}Nd$ values of three syenite/quartz monzonite samples range from 0.51076 to 0.51095 with $\varepsilon_{Nd}(t)$ values of + 0.68 to + 1.09. The two granite samples have $^{143}Nd/^{144}Nd$ values of 0.51067 and 0.51138 with $\varepsilon_{Nd}(t)$ of −1.59 and +0.32 (Appendix Table 2).

4.2. Zircon U-Pb geochronology, trace elements and Hf isotopes

LA-ICP-MS U-Pb dating, trace elements and Hf isotopes of zircons separated from five DLGC samples (BK01, BK12, BK18, BK21 and SH04) are presented in Appendix Tables 3–5. Zircons from the monzodiorite (SH04 and BK12) are subhedral to anhedral, prismatic to sub-rounded crystals with homogeneous to weak oscillatory zoning, ranging from 80 to 200 μm in length with length/width ratios of approximately 1:1 to 1.5:1 (Appendix Fig. S1). The Th/U ratios of the monzodiorite zircons vary from 0.6 to 2.1, with an average value of 1.0. Sixteen $^{206}Pb/^{207}Pb$ ages were measured on the zircon grains from the Penassen Lake monzodiorite ranging from 2658 ± 18 Ma to 2684 ± 17 Ma. All of the sixteen ages lie along a discordia with the upper intercept age of 2671 ± 4 Ma (MSWD = 0.9; Fig. 6a). Fifteen $^{206}Pb/^{207}Pb$ ages were measured for the zircon grains from the Silver Falls monzodiorite ranging from 2668 ± 16 Ma to 2692 ± 19 Ma, and lie on a discordia with an upper intercept age of 2672 ± 4 Ma (MSWD = 0.4; Fig. 6b).

Zircons from the syenite/quartz monzonite phase (BK01 and BK21) are subhedral to anhedral, prismatic to sub-rounded crystals with weak oscillatory zoning ranging from 60 to 120 μm in length with length/width ratios of approximately 1:1 to 2:1 (Appendix Fig. S1). Some zircons from the Barnum Lake quartz monzonite have anhedral to subhedral cores, which occur as patches with oscillatory zoning (Appendix Fig. S1). The Th/U values of eleven zircon grains from the White Lily syenite vary from 0.6 to 1.8 with an average of 1.2, and their $^{206}Pb/^{207}Pb$ ages range from 2646 ± 19 Ma to 2683 ± 22 Ma. All eleven ages form a discordia with an upper intercept age of 2669.0 ± 10 Ma (MSWD = 2.2; Fig. 6c). The Th/U values of eight zircon rims from the Barnum Lake quartz monzonite range from 0.4 to 1.1 (average 0.8). Their $^{206}Pb/^{207}Pb$ ages vary from 2428 ± 17 Ma to

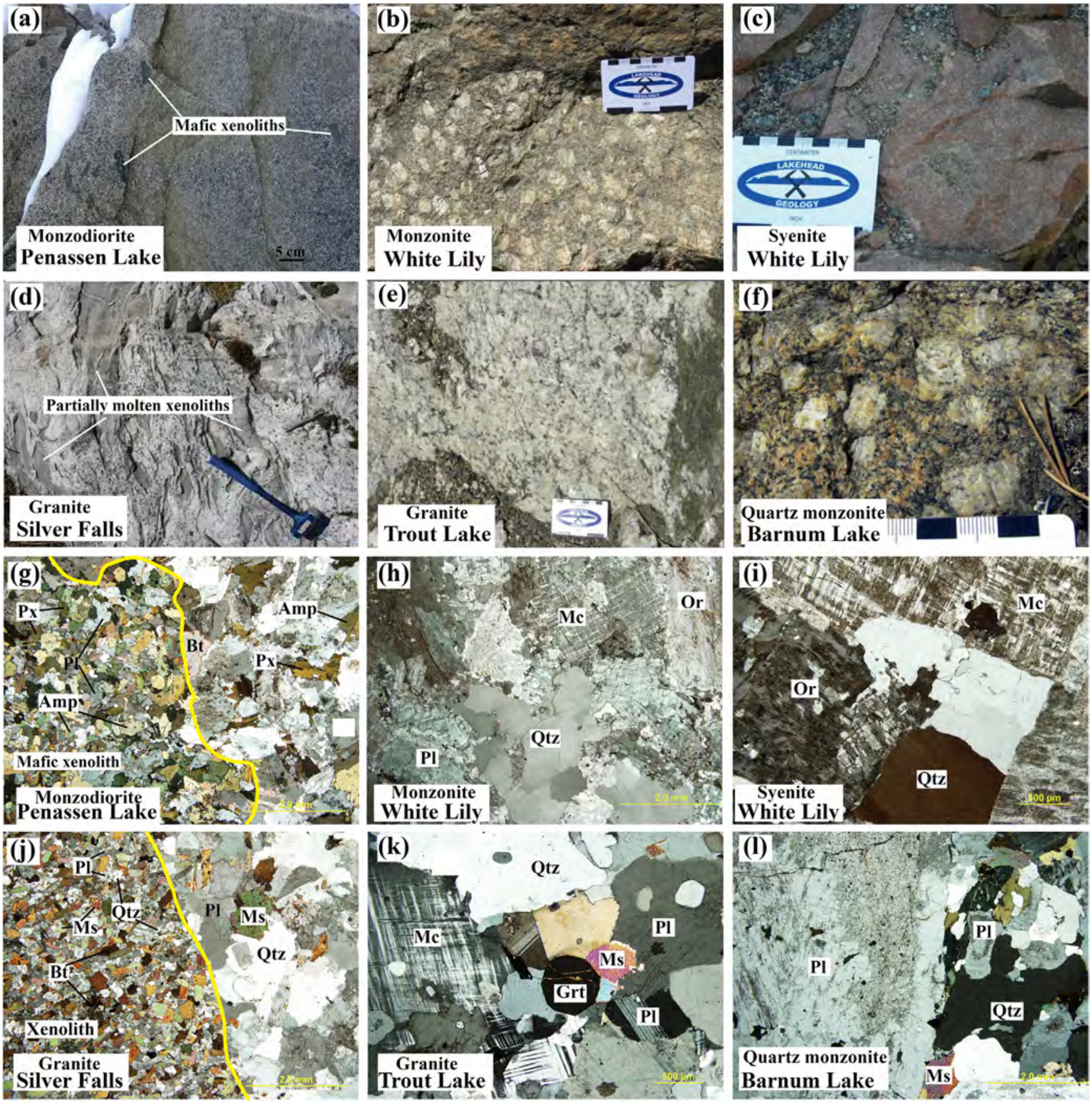

Fig. 2. Photographs of the granitoids from DLGC. (a) Typical exposure of the Penassen Lake Intrusion; (b) Coarse-grained monzonite/quartz monzonite phase; (c) Outcrop of the White Lily syenite phase; (d) Outcrop of the Silver Falls granite phase with abundant xenoliths; (e) Outcrop of the Trout Lake granite phase; (f) Typical outcrop of the Barnum Lake Intrusion (scale is in cm); (g) Photomicrograph of the typical monzodiorite containing mafic xenoliths from Penassen Lake. The monzodiorite contains sericitized Pl, Hbl, Px, Bt and Qtz, whereas the mafic xenolith consists of fine-grained Hbl, Px and minor Pl; (h) Photomicrograph of quartz monzodiorite consisting of medium-grained Qtz, Or, Pl and fine-grained Hbl; Pl and Hbl partial altered to Ser and Chl, respectively; Photomicrograph of a typical syenite phase from White Lily. The slide contains Or, Mc and Qtz; (j) Photomicrograph of the typical Silver Falls granite phase containing sedimentary rock xenolith. The monzogranite contains sericitized Pl, Ms and Qtz, and sedimentary rock xenolith mainly consists of Pl, Qtz, Ms and Bt; (k) Photomicrograph under plane polarized light of a Gt crystal; (l) Photomicrograph of a typical quartz monzonite contains sericitized and carbonate altered Pl megacryst, Ms and Qtz. Bt-biotite, Chl-chlorite, Gt-garnet, Hbl-hornblende, Mc-microcline, Ms-muscovite, Or-orthoclase, Pl-plagioclase, Px-pyroxene, Qtz-quartz, Ser-sericite.

2745 ± 16 Ma, and form a discordia with an upper intercept age of 2663 ± 23 Ma (MSWD = 2.0) and a lower intercept of 1561 ± 90 Ma (Fig. 6d). One zircon core yielded a $^{206}Pb/^{207}Pb$ age of 2806 ± 16 Ma with a Th/U value of 1.9 (Appendix Tables 3 and 4; Appendix Fig. S1).

Zircons from the granite phase (sample BK18 from the Trout Lake intrusion) are subhedral to anhedral prismatic crystals with oscillatory zoning, ranging from 80 to 300 μm in length (Appendix Fig. S1). The Th/U values of the zircons vary from 0.5 to 3.7 (mean 1.3), and yielded a concordant age of 2670 ± 9 Ma (MSWD = 2.9; Fig. 6e).

All the zircons have steep REE patterns with positive Ce anomalies (Fig. 7a-c). Zircons from the Penassen Lake and Silver Falls monzodiorites, as well as the White Lily and Barnum Lake syenite and quartz monzonite have variable Eu anomalies with δEu values ranging from 0.4 to 1.2, whereas the Trout Lake granite zircons exhibit a

Table 1
Petrology of the different phases in DLGC (see appendix S1 for detailed descriptions)

Unit	Crosscutting relationships	Mineral content (%)	Accessory minerals	Alteration	Distribution
Monzodiorite		plagioclase: 50–60 microcline: 2–15 orthoclase: 5–20 quartz: 0–5 hornblende: 10–25 biotite: 10–20 pyroxene: 5–10	Sphene, apatite, magnetic opaques, zircon	Weak chlorite, carbonate, muscovite alteration	Mainly within the Penassen Lake intrusion, less in Silver Falls and White Lily intrusions
Syenite/quartz monzonite	Gradational contact with monzodiorite (Kehlenbeck, 1977)	plagioclase: 45–60 (for syenite: 10–30) microcline: 5–15 (for syenite: 55–70) orthoclase: 10–15 quartz: 5–20 (for syenite: 0–10) biotite: 3–15 hornblende: 1–5	Monazite, apatite, sphene, opaque minerals, muscovite	Chlorite, muscovite, carbonate, epidote alteration	Mainly within Barnum Lake, less in Silver Falls and White Lily intrusions
Granite		plagioclase: 30–60 orthoclase: 8–25 microcline: 2–20 quartz: 20–40 hornblende: minor biotite: 1–10 muscovite: 1–8	Zircon, garnet, sphene	Chlorite, muscovite, carbonate alteration	In the Silver Falls, Trout Lake and White Lily intrusions

Notes: Mineral contents were estimated from least altered samples.

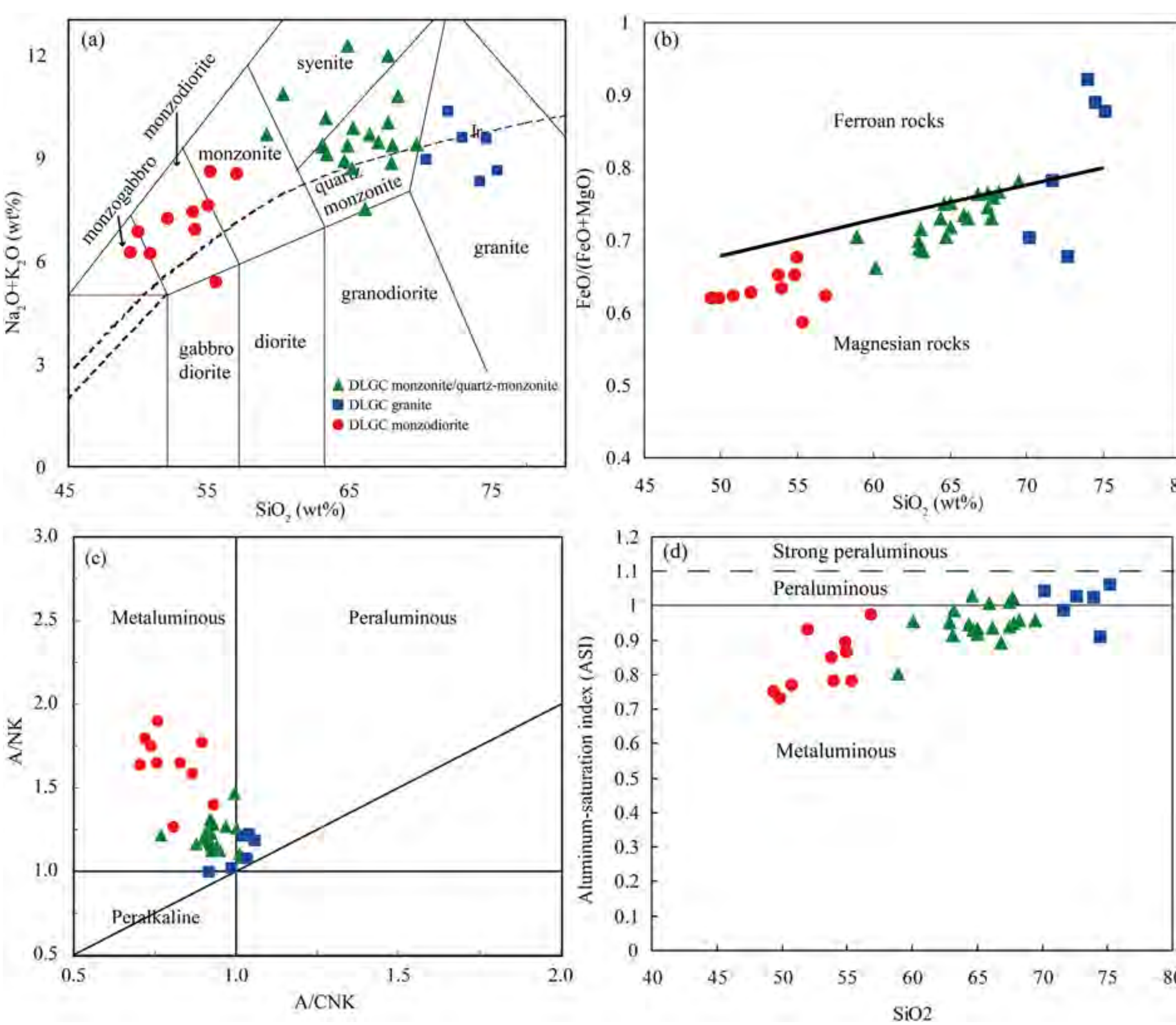

Fig. 3. Total alkali vs SiO_2 (a), (TAS; Middlemost, 1994), $FeO_T/(FeO_T + MgO)$ vs SiO_2 (b), (Frost et al., 2001), A/CNK vs A/NK (c) and ASI (Al/(Ca-1.67P + Na + K)) vs SiO_2 (d), (Frost and Frost, 2008) diagrams for DLGC and regional granitoids.

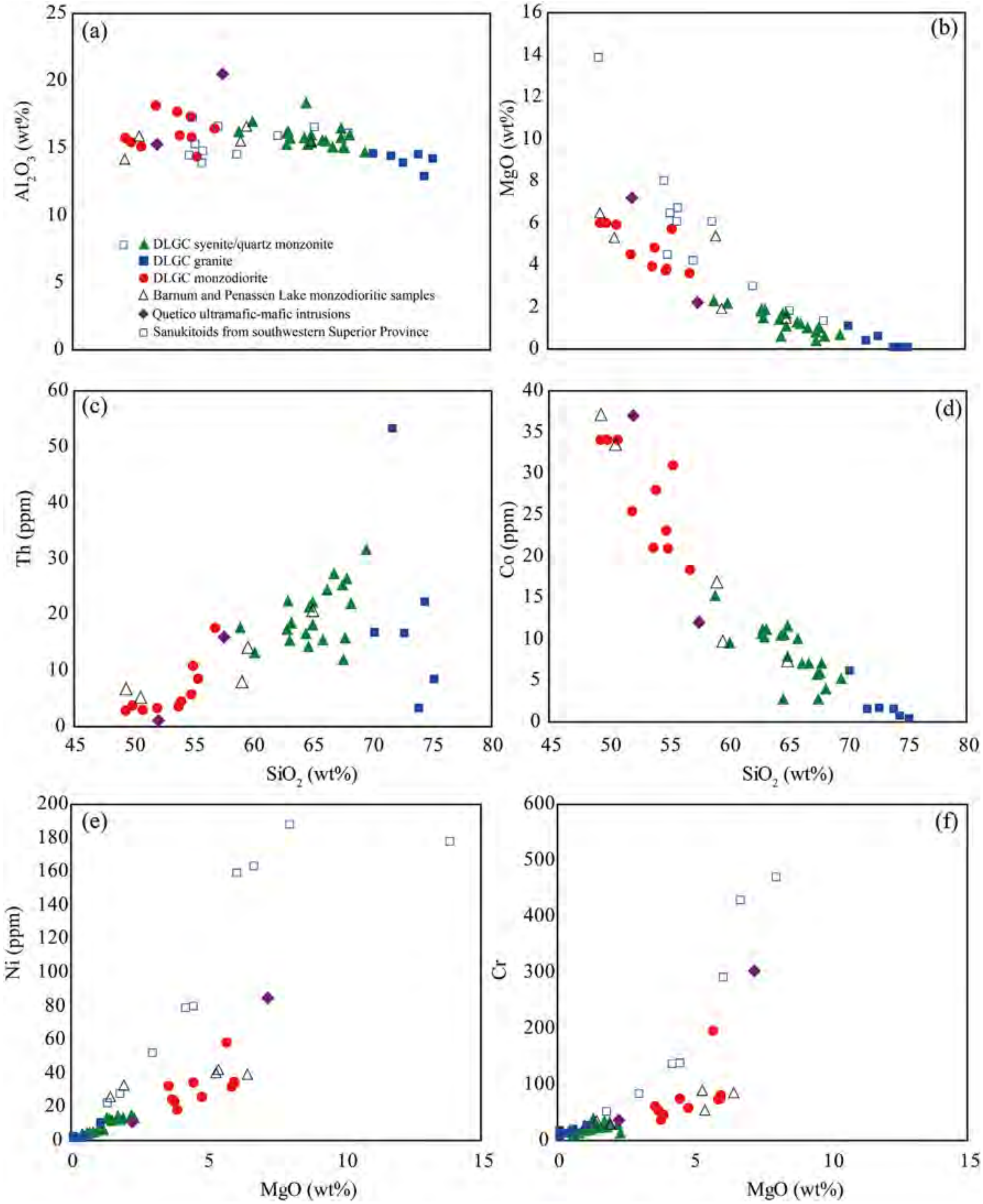

Fig. 4. Harker plots of major elements for the DLGC and regional granitoids. Data sources: Quetico ultramafic–mafic intrusions data from Pettigrew and Hattori (2006); Sanukitoids data from southwestern Superior Province from Shirey and Hanson (1986), Arth and Hanson (1975) and Stern et al. (1989); Barnum and Penassen Lake monzodioritic samples data from Stevenson et al. (1999).

pronounced negative Eu anomaly with the δEu (Eu/Eu*) value ranging from 0.1 to 0.3 (Fig. 7a-c). The U and Th contents of the Penassen Lake monzodiorite zircons show no correlation with increasing Hf contents (Fig. 7d-e). In contrast, the U and Th contents of zircons from the Silver Falls monzodiorite, the White Lily syenite and the Barnum Lake quartz monzonite decrease with increasing Hf content (Fig. 7d-e). There is a positive correlation between U, Th and Hf in the zircons from the Trout Lake granite (Fig. 7d-e). Rare earth elements are positively correlated with Th in the zircons from the DLGC, and the Th content of zircons from syenite/quartz monzonite phase is higher than in the granite phase (Fig. 7f).

In-situ zircon Hf isotopic analyses of DLGC granitoids are presented in Appendix Table 5. Sixteen spots from the Penassen Lake monzodiorite yielded initial $^{176}Hf/^{177}Hf$ values of 0.281094 to 0.281229 with $\varepsilon_{Hf}(t)$ values ranging from + 0.15 to + 4.20 (average = +2.01). The 15 spots from the Silver Falls monzodiorite zircons yielded initial $^{176}Hf/^{177}Hf$ values of 0.281094 to 0.281200 with $\varepsilon_{Hf}(t)$ values ranging from −0.52 to + 3.19 (average = 1.66). Eleven spots from the White Lily syenite and nine from the Barnum Lake quartz monzonite zircons yielded initial $^{176}Hf/^{177}Hf$ values of 0.281103 to 0.281262 and 0.281112 to 0.281099, with $\varepsilon_{Hf}(t)$ values ranging from +0.08 to +4.07 (average = +1.95) and +0.35 to +3.17 (average = +1.93),

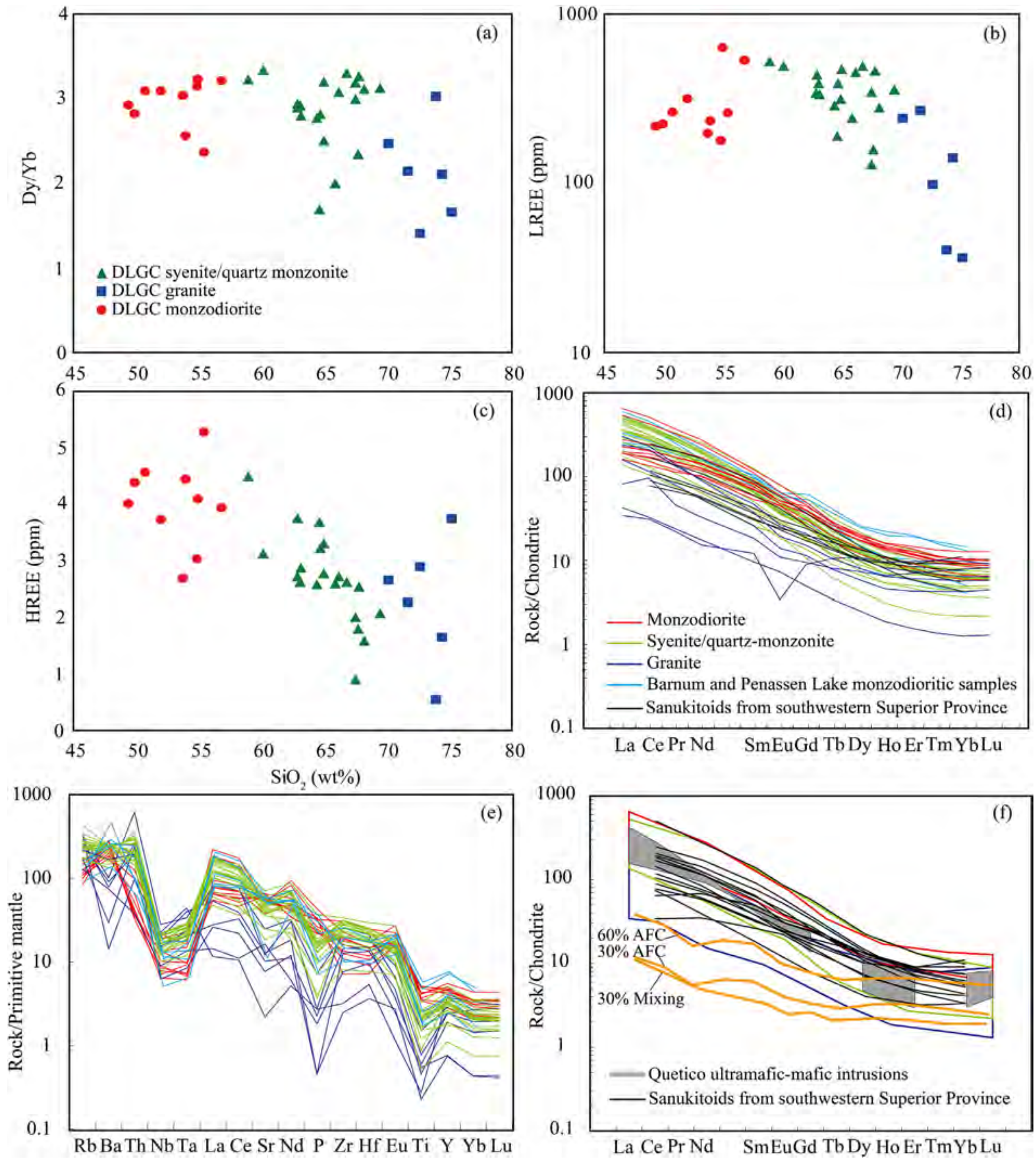

Fig. 5. Dy/Yb vs SiO_2 (a), LREE vs SiO_2 (b), HREE vs SiO_2 (c), chondrite-normalized REE (d), primitive mantle-normalized trace element patterns (e) for DLGC, comparison with regional granitoid and modelling results (f). Data sources same as Fig. 4. Normalization values are from Sun and McDonough (1989). Modelling data from Hollings and Kerrich (1999).

respectively. The 12 analyzed spots from the Trout Lake granite zircons have initial $^{176}Hf/^{177}Hf$ value of 0.281118 to 0.281243 with $\varepsilon_{Hf}(t)$ values ranging from −0.12 to +4.25 (average = 2.46).

5. Discussion

5.1. Hydrothermal modification of the DLGC

The rocks of the DLGC have undergone hydrothermal alteration and metamorphism, given the partial or complete replacement of primary minerals by chlorite, quartz, epidote, carbonate and clay (Fig. 1c, 3d and 4d in Appendix S1). It is critical, therefore, to take account of the effects of post-magmatic alteration on the geochemistry of each lithological phase in the DLGC. The alteration criteria of Polat et al. (2002) and Polat and Hofmann (2003) are adopted here to assess the effects of alteration. In the DLGC; all the samples have loss-on-ignition (LOI) values < 6 wt%, which suggests that secondary hydration or carbonation has been limited, consistent with our petrographic observations. Except for one granite sample from White Lily with an obvious Ce anomaly (Ce/Ce* = 1.5) on a primitive mantle-normalised diagram, all samples have minor to no Ce anomalies (Ce/Ce* = 1.0–1.1), indicating the absence of intense alteration that would have modified the geochemistry (Appendix Table 1).

The DLGC samples display a good correlation between TiO_2, Nb,

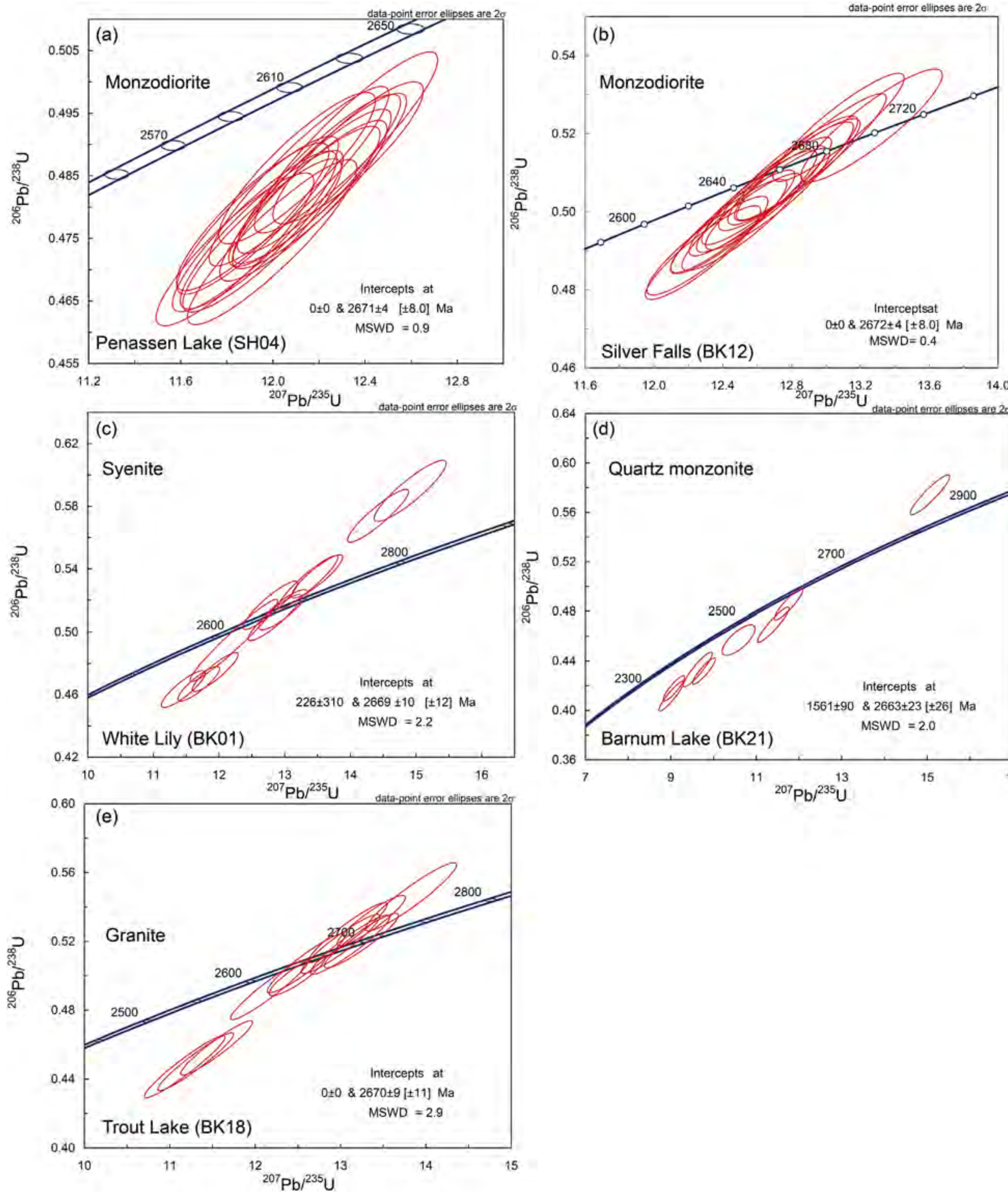

Fig. 6. Zircon U-Pb concordia diagrams and weighted mean $^{206}Pb/^{207Pb}$ ages diagram.

Sm, Nd and Zr (Fig. 8), but no correlation between K_2O and Zr (Fig. 8c), and only a weak correlation between Rb, Na and Zr. Hence it is inferred that Ti, Nb, Sm, Nd and Zr concentrations have not been significantly affected by post-magmatic alteration, whereas the Na, K and Rb may have been modified. Similarly, REE, HFSE (Ti, Nb, Zr, Y) in the DLGC samples display coherent patterns on primitive-mantle normalized diagrams (Fig. 5e), indicating that these elements were also relatively immobile during post-magmatic alteration.

5.2. Emplacement of DLGC granitoids

All the zircons from this study are subhedral to anhedral, and show clear oscillatory zoning in CL images. The Th/U ratios of the zircons are higher than 0.1, and they have steep REE patterns with obvious positive Ce anomalies consistent with magmatic zircons (Hoskin and Schaltegger, 2003). Therefore, the upper intercept ages are likely the magmatic crystallization age of the intrusions, yielding ages of 2671 ± 4 Ma (MSWD = 0.9) and 2672 ± 4 Ma (MSWD = 0.4) for the monzodiorite, 2669 ± 10 Ma (MSWD = 2.2) and 2663 ± 23 Ma

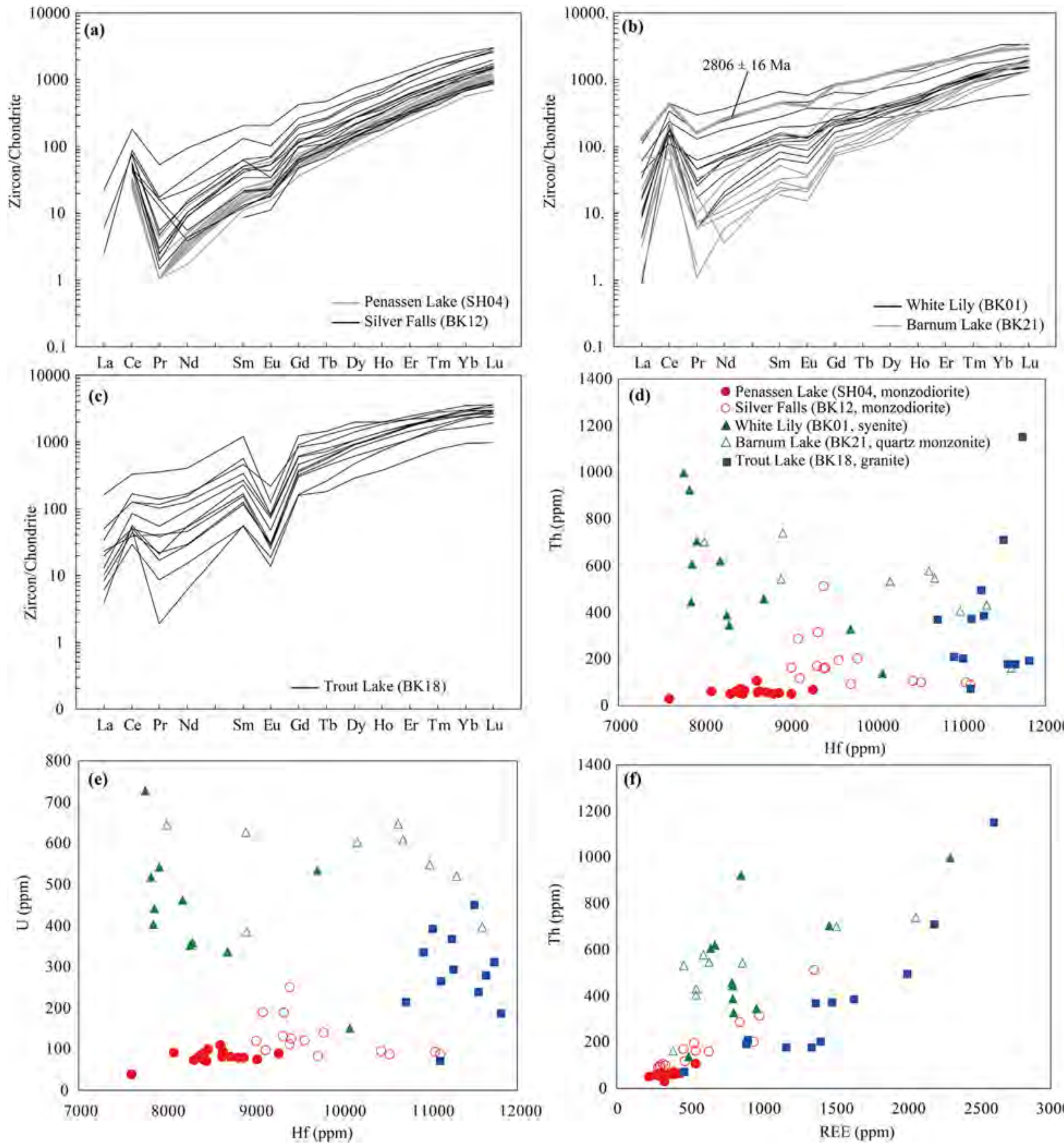

Fig. 7. Zircon chondrite-normalized REE pattern (a-c) Th vs Hf (d), U vs Hf (e) and Th vs REE diagram (f) of DLGC granitoids. Normalising values from Sun and McDonough (1989).

(MSWD = 2.0) for the syenite/quartz monzonite and 2670 ± 9 Ma (MSWD = 2.9) for the granite. Kehlenbeck (1977) noted that the quartz syenites and monzodiorites of the Barnum Lake intrusion had gradational contacts which suggests that the syenite, quartz monzonite and monzodiorite were broadly coeval. The zircons from the Barnum Lake quartz monzonite yielded an age of 2663 ± 23 Ma (MSWD = 2.0), slightly younger but within error of the monzodiorite samples (2671 ± 4 Ma to 2672 ± 4 Ma), White Lily syenite (2669 ± 10 Ma) and the Trout Lake granite (2670 ± 9 Ma). Kamo (2013) reported a TIMS zircon U-Pb age of 2679 ± 1.6 Ma (MSWD = 1.3) for a monzonite of the Trout Lake intrusion, and proposed that it was the best age estimate for the emplacement of the DLGC. This age is older than the ages reported in this study. The recognition of inherited cores in some of the zircon grains analysed in this study may explain the older TIMS age, which used whole crystals, and therefore may have included these cores to yield a mixed and apparently older age (Appendix Table 3, Appendix Fig. S1).

5.3. Magma sources

5.3.1. Monzodiorite phase

Stevenson et al. (1999) suggested that monzodioritic and dioritic rocks of the Barnum and Penassen Lake intrusions were part of the Neoarchean sanukitoid suite. Previous studies have suggested that sanukitoid magmas can be generated by 1) crustal contamination of komatiitic melts (Sparks, 1986); 2) melting of LILE-enriched mantle peridotite (Stern et al., 1989); 3) partial melting of sub-arc metasomatized lithospheric mantle (Stevenson et al., 1999; Beakhouse and

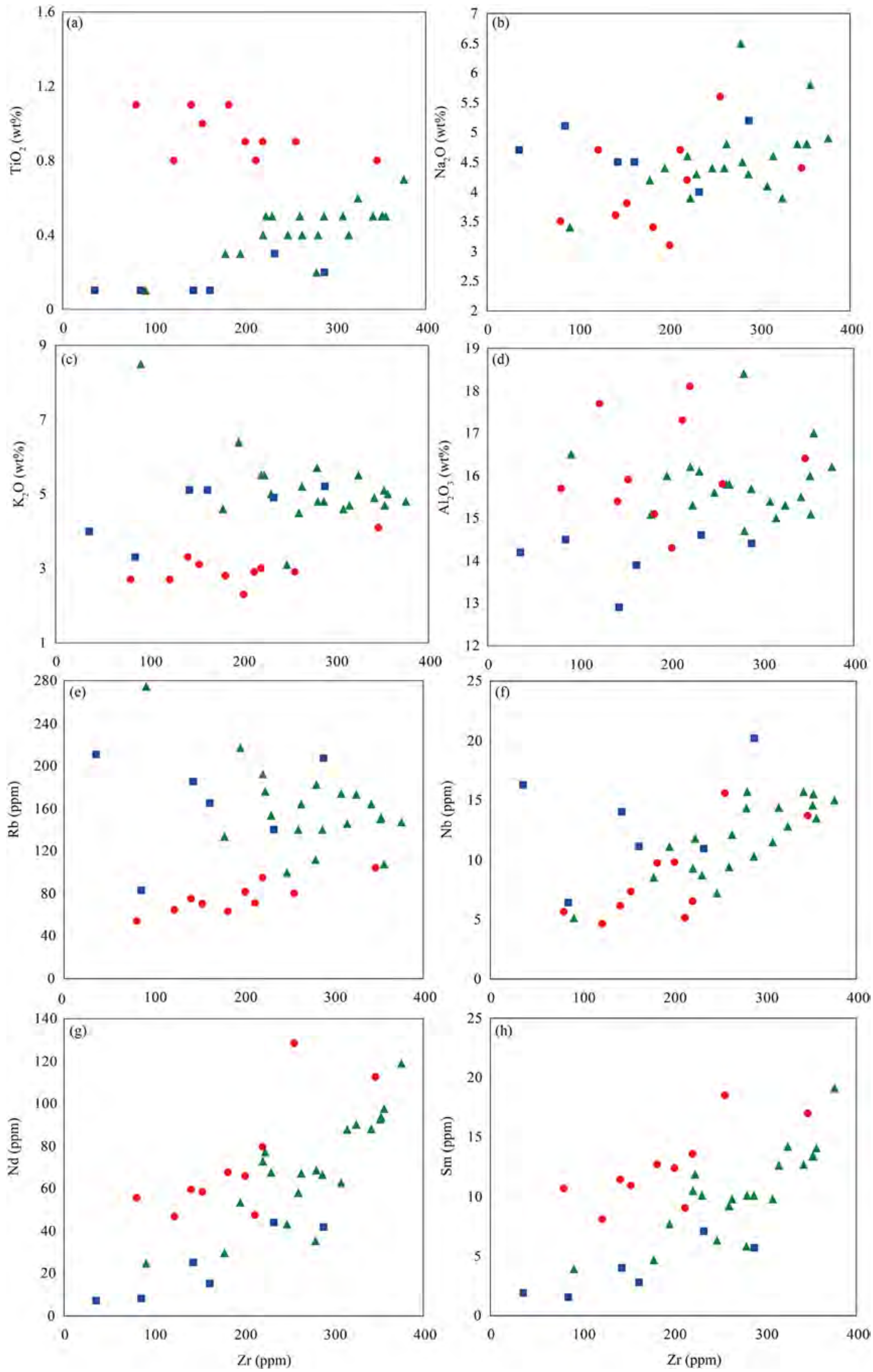

Fig. 8. Zr (ppm) vs TiO_2, Na_2O, K_2O, Al_2O_3, Rb, Nb (ppm), Sm (ppm), and Nd (ppm) variation diagrams for the DLGC granitoids.

Davis, 2005). The monzodiorites of the DLGC have Mg# of 47–56, higher than the maximum values that characterize the experimental compositions of partial melts generated from basalt (ca. 45; Evans et al., 1997). Similarly, modelling of mixing or AFC of a komatiitic protolith parental magma with upper-crust or average Archean felsic rock allowed Stern et al. (1989) to show that the abundances of Na_2O, K_2O, Sr and Ba are far too low in the contaminated melt to explain the compositions of sanukitoids from the southwestern Superior Province. Similarly, the Sr concentration of the melt generated by contaminating a komatiite range from 171 to 200 ppm, which is far lower than the Sr content of the monzodiorite from the DLGC suggesting it is not a likely source (800–1400 ppm). Hollings and Kerrich (1999) modelled the effects of AFC and binary mixing using typical Munro-type komatiite as a starting composition and both volcanic rocks and quartz-rich metasedimentary as a contaminant and showed that more than 60% AFC and 30% mixing could produce LREE-enriched andesite. However, the results of this modelling are not geochemically similar to the monzodiorite in DLGC (Fig. 5f). Given this, it is unlikely that the monzodiorites of the DLGC were formed by the contamination of plume derived melts, which is consistent with the absence of plume-derived komatiites in the immediate vicinity.

The monzodiorite phase of the DLGC shows an arc-like geochemical signature with enriched LILE, and negative Nb, Ta and Ti anomalies (Fig. 5e). Niobium and Ta behave in a similar way to Ti during melting in a subduction zone, and as a result, arc derived magmas have pronounced negative HFSE anomalies that can be generated by partial melting of either the downgoing slab or the metasomatically enriched mantle (Rudnick et al., 2000), during intracrustal differentiation (Tang et al., 2019) or fractional crystallization of amphibole during magmatic evolution (Li et al., 2017). The Dy/Yb ratios of the monzodiorite do not vary with increasing SiO_2 (Fig. 5a), which suggests that fractional crystallization of amphibole was negligible during the evolution of the magma. Therefore, the DLGC monozdiorite was likely generated by partial melting of metasomatically enriched mantle. Enriched mantle in subduction zones can be produced either by metasomatism of fluid derived from subducted plate or melts derived from subducted sediments. On plots of Pb/Ce vs Pb and U/Th vs Th, most of the monzodiorite samples plot in the subducted sediments field (Fig. 9). Therefore, we conclude that the DLGC monzodiorite magma was generated by partial melting of enriched lithospheric mantle metasomatized by melts derived from oceanic sediments.

The Th/Co ratio can serve as an efficient differentiation index with which to monitor the evolution of sanukitoid magmas (Stevenson et al., 1999). The $\varepsilon_{Nd}(t)$ values of the monzodiorite phase of the DLGC decrease with increasing differentiation (Th/Co) implying that crustal assimilation accompanied magmatic differentiation (AFC-assimilation fractional crystallization; Fig. 10). The monzodiorite contains abundant dark, angular microgranular and igneous-textured mafic xenoliths (Fig. 2a and g), which may be undigested fragments of basalt wall-rock assimilated during the magma's ascent. Therefore, we conclude that the monzodiorite of the DLGC was generated by assimilation fractional crystallization of the metasomatically enriched mantle-derived magma.

5.3.2. Syenite/quartz monzonite phase

The syenite/quartz monzonites likely formed by fractional crystallization of a monzodiorite magma. This is supported by 1) the similar mineral assemblages in the syenite/quartz monzonite and the monzodiorite; 2) fractionation trends between the monzodiorite and syenite/quartz monzonite (Fig. 4); 3) similar Nd-Hf isotopic systematics (Appendix Tables 2 and 5) similar REE patterns and incompatible element ratios (Fig. 5). The negative Ba, Sr and P anomalies in the syenite/quartz monzonite can be explained by fractional crystallization of feldspar and apatite during the evolution of the monzodiorite, consistent with the presence of apatite (Table 1).

One inherited zircon core yielded a $^{206}Pb/^{207}Pb$ age of 2806 ± 16 Ma in the Barnum Lake quartz monzonite (Appendix Table 3). The inherited zircon core has a Th/U value of 1.9 and a positive Ce anomaly suggesting it was derived from an igneous source (Fig. 7b). This implies that assimilation of igneous crust accompanied magmatic differentiation of syenite/quartz monzonite magma.

5.3.3. Granite phase

Stevenson et al. (1999) expanded the definition of sanukitoid to include granite (up to 71.0 wt% SiO_2) arguing that that the granites were derived by assimilation-fractional crystallization of Archean sanukitoids. They used the Th/Co value (always $<$ 4) as the efficient differentiation index, because the Th increases and Co decreases with increasing SiO_2. However, the Th content of the granite phase in DLGC with Th/Co values of 2.1–35.5 increases with increasing SiO_2 (Appendix Table 1), which suggests that they cannot be produced by the assimilation-fractional crystallization of DLGC monzodiorite and syenite/quartz monzonite magma with sanukitoid affinity.

Zircons crystallized from crustally derived magmas will have higher trace element contents (REE, Hf) than zircons from mantle-derived magma and will be Ce-enriched but Eu-depleted (Hoskin and Ireland, 2000; Belousova et al., 2002). The zircons from the DLGC granite have negative Eu anomalies (0.1–0.3), whereas those from the monzodiorite and syenite/quartz monzonite generally have smaller Eu anomalies

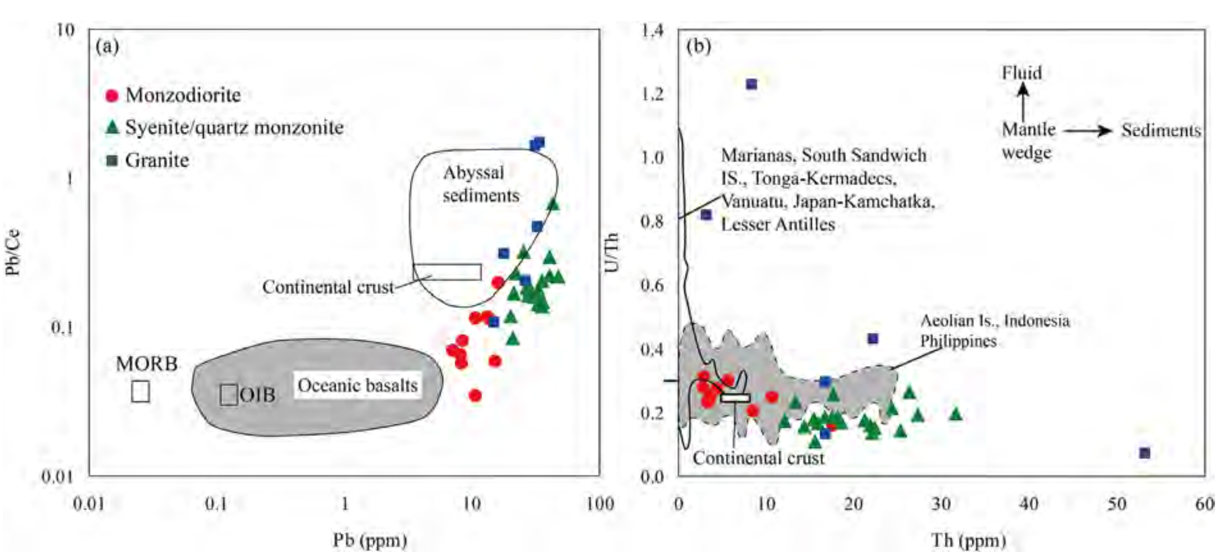

Fig. 9. Pb vs Pb/Ce ratios diagram (a), (Othman et al., 1989) and Th vs U/Th ratios diagram (b), (Hawkesworth et al., 1997).

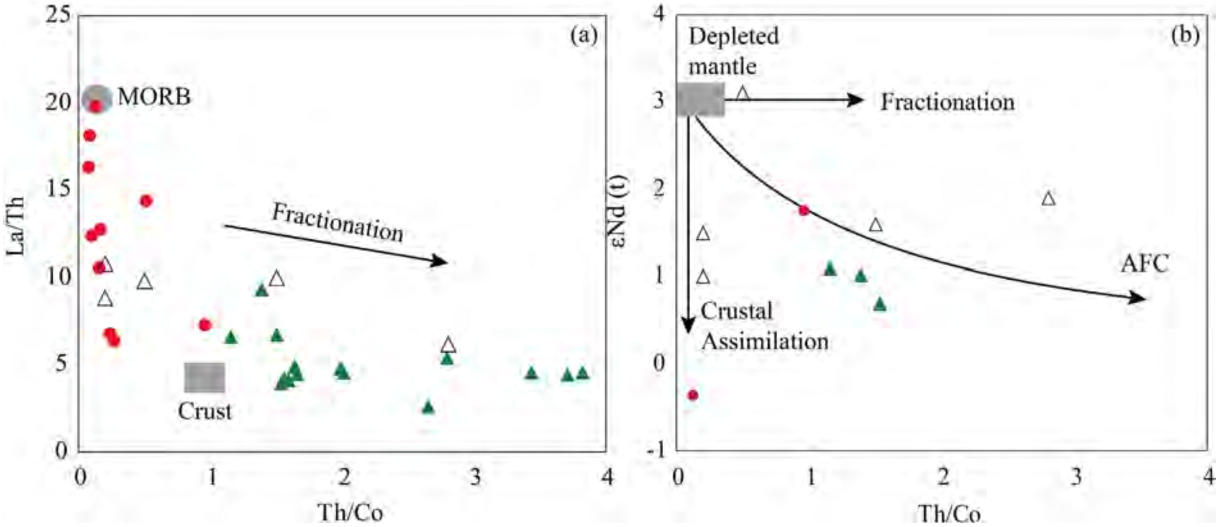

Fig. 10. Th/Co vs La/Th (a) and ε_{Nd}(t) (b) Diagram modified from Stevenson et al. (1999).

(0.4–1.2), implying that the granite phase was generated from a distinct crust-derived magma to the monzodiorite. Wang and Pupin (1992) showed that in zircons from crust-derived granites, Hf is positively correlated to other large ionic radius metal elements (such as Y, U, and Th). In contrast, in mantle-derived granites these elements are inversely correlated. The positive relations between Hf and Th, U contents in zircons from the DLGC granite phase, are therefore consistent with it being generated from a crust-derived magma. The presence of sedimentary xenoliths in the granite phase supports this model. In contrast, the negative correlations between Hf and the Th and U contents in zircons from the monzodiorite and syenite/quartz monzonite phases (except Penassen Lake sample) suggests that they were produced from a mantle-derived magma. The Th content of zircons from the syenite/quartz monzonite phase is higher than that of granite (Fig. 7f), and they have almost the same REE contents, also implying that the granite magma cannot have been generated by differentiation of the syenite/quartz monzonite magma.

The zircons from the granites of the DLGC have ε_{Hf}(t) values from −0.12 to +4.25, and can be divided into two groups (Fig. 11): −0.12 to +0.97 and + 2.12 to +4.25, implying two distinct sources. Their ε_{Nd}(t) isotopic values (−1.59 to +0.32, average −0.64) are slightly enriched, suggesting that they were derived from the mixing of crust- and mantle-derived magmas.

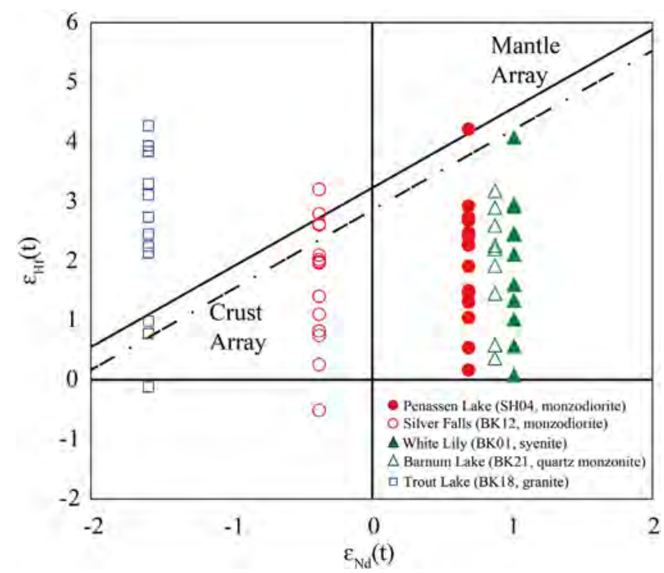

Fig. 11. Zircon ε_{Hf}(t) and whole-rock ε_{Nd}(t) (d) diagram. The whole-rock ε_{Nd}(t) values of sample SH04 and BK21 using the average ε_{Nd}(t) value of monzodiorite and quartz monzonite samples, respectively. Mantle and crust arrays are from Vervoort and Blichert-Toft (1999).

5.3.4. Hf-Nd isotope decoupling

The zircon ε_{Hf}(t) values for the DLGC deviate from the whole-rock ε_{Nd}(t) values with reference to the normal terrestrial arrays of mantle and crust Hf-Nd isotope evolution (Fig. 11; Vervoort and Blichert-Toft, 1999), suggesting that the Hf and Nd isotopes are decoupled in the DLGC. Three possible mechanisms can explain this decoupling: 1) melt-peridotite interaction in the magma source of mantle-derived rocks can cause Hf-Nd isotope decoupling in the oceanic lithosphere due to metasomatism of an ancient (e.g., ≥12 Ga) depleted peridotite protolith (Bizimis et al., 2003). This would produce significant deviations from the Terrestrial Array towards higher ε_{Hf} values relative to ε_{Nd} (Bayon et al., 2009; Vervoort et al., 2011); 2) the zircon (Vervoort and Blichert-Toft, 1999; Patchett et al., 2004; Vervoort et al., 2011) and garnet effect (Patchett et al., 2004; Schmitz et al., 2004), where the presence of both garnet and zircon in the source or crystallizing during the evolution of the magma will cause the Hf-Nd isotopes of the melts to deviate significantly from the Terrestrial Array towards lower ε_{Hf} values, caused by the preferential incorporation of Lu over Hf in garnet (Patchett et al., 2004; Schmitz et al., 2004); 3) the weathering effect where because zircon is a robust mineral phase resistant to both chemical and physical breakdown it retains Hf even during intense chemical weathering and is consequently a major repository of Hf on the continents (Vervoort et al., 2011). Weathering on the continents involves preferential breakdown and release of more radiogenic, higher Lu/Hf phases to the oceans, implying that melt extraction from a magmatic source with recycled oceanic sediments will result in Hf-Nd isotope decoupling towards higher ε_{Hf} values (Vervoort et al., 2011).

The Hf-Nd isotopes of the monzodiorite and syenite/quartz monzonite deviate significantly from the Terrestrial Array towards lower ε_{Hf} values which is most consistent with the zircon or garnet effect. The steep whole rock REE patterns may also suggest equilibration with garnet during melting in the peridotite source region (Fig. 5d), as shown by Stevenson et al. (1999) for the sanukitoid suites. In contrast, the Hf-Nd isotopes of the granites deviate significantly from the Terrestrial Array towards higher ε_{Hf}(t) values, which reflects either melt-peridotite interaction in the source region or the weathering effect. Given the evidence presented here for magma mixing to form the DLGC granites, melt-peridotite interaction in the source region is unlikely to have occurred. Zircons from igneous crustal rocks will retain their positive Hf isotopic character during chemical weathering and partial melting, whereas the whole-rock Sm-Nd system would readily equilibrate with the new granitic melt yielding lower $\varepsilon_{Nd}(t)$ values (Wu et al., 2006). Thus, we conclude that the felsic magma member of DLGC granites was generated by partial melting of immature sedimentary rocks, derived from the weathering of igneous rocks. This may also explain why the zircon Hf model ages of the DLGC granites are significantly younger than the whole-rock Nd model ages (Appendix Tables 2 and 5).

The Hf isotope model ages (T_{DM}) of the zircon rims from the granite phase samples in the DLGC range from 2796 ± 25 to 2962 ± 21 Ma (mostly 2796 ± 25 to 2865 ± 20 Ma; Appendix Table 5), which implies that the igneous crustal rocks eroded to form for the immature sedimentary rocks that were melted to form the DLGC granites formed between 2.77 and 2.88 Ga.

5.4. Geodynamic implications: Neoarchean subduction and continental collision

The DLGC forms a linear trend parallel to the tectonic boundary between the Abitibi-Wawa terrane to the south, and the Quetico Basin to the north (Fig. 1), which formed between 2663 and 2671 Ma after the collision between the Wabigoon terrane and Abitibi-Wawa arc (Percival and Williams, 1989). Several theories have been advanced to explain the occurrence of post-collisional (2670 to 2620 Ma) intrusive rocks, generally associated with the stabilization of cratons, including 1) continued subduction and tectonic underplating (Krogh, 1993), leading to episodic deformation and metamorphism; 2) magmatic underplating above a mantle plume, driving metamorphism through mafic magmatism (Zweng et al., 1993); 3) repeated delamination events (Moser et al., 1996) that would raise crustal temperatures through asthenospheric upwelling; 4) asthenospheric upwelling due to slab break-off following terrane collisions (Beakhouse and Davis, 2005); and 5) lithosphere inversion (Percival and Pysklywec, 2007). The deformation and metamorphism mechanism is inconsistent with the requirement for mantle-derived mafic magma in the source of the DLGC. Similarly, the absence of observed mafic magmatic rocks between 2663 and 2671 Ma, coupled with lower crustal seismic velocities in the 7 km/s range (Percival et al., 2012), does not support widespread mafic underplating and asthenospheric upwelling. Another possibility is that lower crustal rocks were subsequently delaminated, however, Archean cratons generally have buoyant lithospheric keels (e.g., Poudjom Djomani et al., 2001) that may have been present since the time of crust formation (e.g., Griffin et al., 2003). Moreover, the long-term buoyancy of Archean mantle lithosphere (Poudjom Djomani et al., 2001; Kelly et al., 2003) and absence of widespread mafic magmatism does not support the asthenospheric upwelling model (Percival and Pysklywec, 2007). Therefore, lithosphere inversion (Percival and Pysklywec, 2007) caused by a density instability associated with a low-density depleted mantle lithosphere and a lower crust that became eclogitic following the 2720–2680 Ma Superior Province orogenies (Percival et al., 2012) is likely the main mechanism for the generation of DLGC granites.

We propose that three distinct stages are required for the formation of the DLGC: 1) ~2.8 to 2.7 Ga, subduction of oceanic lithosphere under the Abitibi-Wawa arc before the collision of the Abitibi-Wawa arc and the Wabigoon terrane, which produced a metasomatically enriched mantle and related volcanic rocks; 2) before ~2.7 Ga, the volcanic rocks underwent rapid weathering, erosion and deposition forming immature sedimentary rocks in the Quetico accretionary prism (Percival and Williams, 1989; 3) The lower crust became eclogitic following the collision of the Abitibi-Wawa arc and the Wabigoon terrane, creating a density instability with respect to the low-density depleted mantle lithosphere that, acting with basal tractive forces, caused inversion of the lithosphere (Percival et al., 2012). This resulted in partial melting of metasomatically- enriched mantle to generate mafic magmas that ascended along lithospheric scale faults and underwent assimilation fractional crystallization forming the DLGC monzodiorite and syenite/quartz monzonite. The pulse of mafic magmatism resulted in the emplacement and accumulation of magma at the base of the Archean immature sedimentary rocks, causing melting and generation of the felsic magma. Mixing between this felsic magma and the original mafic one generated the DLGC granite in the shallow crust.

6. Conclusions

On the basis of new petrographic, U-Pb zircon age, whole-rock major and trace element, and zircon trace element and Hf isotope data, three phases can be identified in the DLGC consisting of monzodiorite (2671 ± 4 Ma to 2672 ± 4 Ma), syenite/quartz monzonite (2669 ± 10 Ma to 2663 ± 23 Ma) and granite (2670 ± 9 Ma). The monzodiorite and syenite/quartz monzonite are similar to sanukitoids, produced by assimilation fractional crystallization of mafic magma generated by partial melting of the enriched arc mantle that had been metasomatized by melts of oceanic sediments. The DLGC granites were derived from felsic magma mixing with mafic magma, and the felsic magma member was generated by partial melting of immature sedimentary rocks, produced by the chemical weathering of juvenile crustal rocks.

In the Neoarchean, a variety of processes occurred between the Abitibi-Wawa arc and Wabigoon terrane, including subduction of oceanic crust, arc-continent collision and juvenile crust melting, uplift-erosion and sedimentation, and post-collisional anatexis. While growth of juvenile crust is assumed to occur through arc magmatism from ~2.8 to 2.7 Ga, reworking of juvenile crust took place due to post-collisional lithosphere inversion at 2663–2671 Ma. The reworking of juvenile crust by post-collisional magmatism drives the bulk crust composition toward a more continental one. Consequently, arc-collision is not only a crucial step of the Wilson cycle by which intra-oceanic arc crust (Abitibi-Wawa arc) is added to continental margins, but also is an important mechanism for continental crustal growth, differentiation and cratonic stabilization during the Neoarchean.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Appendix 2

Membership forms

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: __Matthew Boyd___________________

Department: ___Anthropology______________

Email: ____matthew.boyd@lakeheadu.ca_____

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  ____

  _____CESME____

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: ______ _________________________

Date: ____June 17, 2021____________________

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: Dr. Andrew Conly

Department: Geology

Email: andrew.conly@lakeheadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows: ____

  Centre for Sustainable Mining and Exploration (CSEME)

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: Andrew Conly

Digitally signed by Andrew Conly
Date: 2021.06.24 10:44:26 -04'00'

Date: June 24, 2021

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: ___Jian Deng________________

Department: ____Civil Engineering__________

Email: jdeng2@lakeheadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows: ____

  ___Centre of Excellence for Sustainable Mining and Exploration__________

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Centre of Excellence for Sustainable Mining and Exploration	100%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: Jian Deng Digitally signed by Jian Deng DN: cn=Jian Deng, o=Lakehead University, ou=Civil Engineering, email=jdeng2@lakeheadu.ca, c=CA Date: 2021.06.29 09:44:34 -04'00' ________________

Date: June 29, 2021 ________________

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: Amanda Diochon

Department: Geology

Email: adiochon@lakeheadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:

  CESME (as member)

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: Amanda Diochon Digitally signed by Amanda Diochon
DN: cn=Amanda Diochon, o=Lakehead University, ou, email=adiochon@lakeheadu.ca, c=US
Date: 2021.06.23 09:53:21 -04'00'

Date: June 23, 2021

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: _____Martha Dowsley_____________________________

Department: ______Anthropology and Geography and the Environment_____________

Email: __mdowsley@lakeheadu.ca________________________________

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows: ____

  __CESME and CRANHR____

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%
CRANHR	50%
CESME	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: __ MDowsley **______________________________**

Date: _______June 14 2021________________________

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: _**Dr. Ernie Epp**________________________________

Department: _ **History**__________________________

Email: _**eepp@lakeheadu.ca**________________________________

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  _Centre of Excellence for Mining Sustainabilty and Exploration
  ____
  ____
- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);
- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and
- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: ____________________

Date: 15 June 2021

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: _Dr Philip Fralick________________________________

Department: __Geology___________________________

Email: philip.fralick@lakeheadu.ca_________________________________

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  ____

  ___CESME____

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: _____Dr Philip Fralick________________________

**Date: ___June 14/ 2021___________________________

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: ___Scott Hamilton________________________________

Department: ______Anthropology_______________________

Email: ____shamilto@lakeheadu.ca______________________________

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  ____
  Centre of Excellence for Sustainable Mining and Exploration
  ____

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: ___ ______________________________

Date: ___June 21, 2021______________________________

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: Rachel W. Jekanowski

Department: Dept. of English, Memorial University

Email: rjekanowski@mun.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  Centre of Excellence for Sustainable Mining and Exploration
  ____
- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);
- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and
- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: ______________________________

Date: June 14, 2021

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: **<u>Peter Lee</u>**

Department: **<u>Biology</u>**

Email: pflee@lakeheadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows: ____

  <u>CESME</u>

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Peter Lee

Signature: ________________________________

Date: June 29, 2021

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: ___Baoqiang Liao______________________________

Department: __Chemical Engineering__________________________

Email: __bliao@lakeheadu.ca_______________________________

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  ____
  Centre of Excellence for Sustainable Mining and Exploration (CESME)
  ____

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
CESME	50%
Advanced Green Chemical and Processes Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: ________ ______________________

Date: ______June 14, 2021________________________

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: Kam Tin Leung

Department: Department of Biology

Email: ktleung@lakehaeadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  Centre of Excellence for Sustainable Mining and Exploration
- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);
- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and
- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%
Centre of Excellence for Sustainable Mining and Exploration	100%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: ______________________________

Date: June 15, 2021

Office of Research Services
955 Oliver Road
Thunder Bay, ON
P7B 5E1
Tel. 807-343-8223

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: **Nancy Luckai**
Department: **Faculty of Natural Resources Management**
Email: **nluckai@lakeheadu.ca**

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:

  CESME
  ____

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: CESME Centre	100%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: _nluckai

Date: 21 June 2021

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: ___Robert Petrunia___________________

Department: __Economics__________________

Email: __rpetruni@lakeheadu.ca_______________

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:

  Centre of Excellence for Sustainable Mining and Exploration______________
  ____

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: __________________________________

Date: ____21/6/2021__________________

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: Michael Rennie

Department: Biology

Email: mrennie@lakeheadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:

  CESME

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);

- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and

- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: Michael Rennie Digitally signed by Michael Rennie Date: 2021.06.16 15:05:50 -04'00'

Date: CESME

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: Karl Skogstad

Department: Economics

Email: kaskogst@lakeheadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:

  Current member of CESME

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);
- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and
- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature: Karl Skogstad

Date: June 14th, 2021

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: __**Robert Stewart**_____________

Department: **Geography and the Environment**

Email: **rob.stewart@lakeheadu.ca**

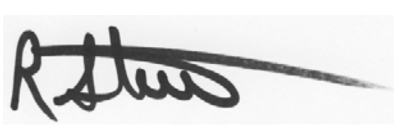
By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:
  _____CESME____

  ____
- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);
- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and
- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: CESME	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature:  ____

Date: **June 30 2021**

Appendix A:

Centre/Institute Researcher Affiliation Approval Form (due June 30)

This form must be completed by each individual researcher who is affiliated with a Research Centre(s)/Institute(s) and attached to Centre/Institute Annual Reports due June 30 each year to the Office of the Associate Vice-President Research and Graduate Studies.

Name: Shannon Zurevinski

Department: Geology

Email: shay@lakeheadu.ca

By affixing my signature below, I confirm that:

- I am affiliated with the following Research Centre(s)/Institute(s) as follows:

  CESME

- My affiliation, including name, department and research activities may be included in the Research Centre/Institute's Annual Report and Website (if applicable);
- I acknowledge that the Research Centre(s)/Institute(s) I am affiliated with, are eligible to receive a Centre-Initiated Research Support Fund (RSF) overhead allocation which is generated as a result of my tri-agency grants (if applicable); and
- I am a member of more than one research centre/institute and I wish to allocate my tri-agency grant funding and generated Centre-initiated RSF as follows (if applicable):

Name of Affiliated Centre/Institute	RSF Percentage Share (must equal 100%)
Example: ABC Centre	50%
XYZ Centre	50%

**Note that researchers who wish to allocate overhead from other government (non-tri-agency), municipal, private sector, not-for-profit organizations, etc) research grants/contracts, must use the Research Proposal Approval Form to authorize overhead allocations to affiliated research centres/institutes.*

Signature:

Date: June 22/2021