Targeted Geoscience Initiative 5, Gold Project: A summary of contributions to the understanding of Canadian gold systems

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ABSTRACT

The discovery of new mineral deposits is essential to maintain a stable supply of mineral commodities, however, new mineral discoveries are in ever more remote, deeper, and/or covered geological environments, which presents significant challenges. The fifth phase of the Targeted Geoscience Initiative (TGI-5) was developed to address these challenges and to advance our understanding of ore-forming processes at various spatial scales and across geological time. Here we present a selection of highlights from research activities comprising the Gold Project. These research activities, all of which included significant field components, focused on different aspects of the gold mineral systems and included gold districts with variable metal endowment (e.g. southern and northern Neoarchean Abitibi greenstone belt), geological setting (e.g. pre-, syn-, and post-orogenic processes), and geological age (e.g. Paleoproterozoic Trans-Hudson, and Phanerozoic Appalachian orogenic belts).

The southern Abitibi is host to many different types of giant gold deposits (e.g. synvolcanic and orogenic gold ore systems), although the sources of ore-components for these mineral systems remained unclear. New TGI research addressed this knowledge gap and demonstrate that (1) diagenetic sulphides (pyrite nodules) and their host sedimentary sequences within the Superior Province are pre-enriched in gold; (2) Archean calc-alkaline felsic volcanic centres associated with large synvolcanic gold deposits further suggest that igneous differentiation in the lower crust may be associated with the generation of synvolcanic gold-rich magmatic-hydrothermal systems; and (3) undocumented upper mantle pathways existed, which were revealed by anomalous ore-forming element concentrations within cratonic mantle samples from the southern Superior Province. Together these research activities provide new insights into the upgrading of ore components from the mantle to the upper crust, although the role of these pre-enriched source rocks to gold ore systems remains unclear.

Other research activities focused on the complete source-to-ore pathways of gold-bearing fluids for multiple gold districts across Canada. The similar pacing of events and timing of auriferous vein development within the overall tectonic evolution for several of these gold districts likely reflects a common driver (e.g. upwelling asthenosphere) and/or tectonic triggers (e.g. crustal extension and associated magmatism). However, the contrasting metal endowment of areas with otherwise similar histories (e.g. southern versus northern Abitibi belt) suggests that the prospectivity of gold districts is not entirely related to the large-scale drivers and triggers of ore-forming fluids. Moreover, long-term preservation is another critical factor in gold ore systems, which is promoted by rapid burial; limited post-ore remobilization during hydrothermal and metamorphic overprinting; and long-term craton stability. Indications of preferential preservation, such as the occurrence of synorogenic polymict conglomerate, constitute key exploration criteria.

New analytical methods that were developed as part of TGI-5 are also providing new tools (e.g. rapid in situ element mapping and data interrogation approaches; new geochronological methods; clumped isotope thermometers) for recognizing ore-proximal depositional controls from the rock record. An improved understanding of these controls and efficient vectoring tools are increasingly important for mineral exploration targeting.

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INTRODUCTION

This volume summarizes the research conducted between April 2015 and March 2020 by the Geological Survey of Canada (GSC) and its collaborators as part of the Gold Project of Natural Resources Canada's Targeted Geoscience Initiative Program (Phase 5). This synthesis volume contains 20 individual papers, including this contribution, that discuss regional- to deposit-scale characteristics of auriferous deposits across Canada.

The primary goal of Phase 5 of the TGI program ("Source-to-ore geoscience for effective exploration") was to generate new knowledge, models, and methodologies to enhance the exploration industry's ability to detect mineral deposits. Each of these research activities is integrated into a source-to-ore processes-based framework. Other important objectives of the Gold Project were to adopt collaborative approaches in research activities, to publicly disseminate the results in a timely manner, and to contribute to replenishing the pool of highly qualified personnel (HQP) in geosciences. Progress on each of the Gold Project objectives is discussed below.

A general introduction to the Gold Project synthesis volume and background information about the project are given here. We also summarize a subset of the main contributions to the understanding of Canadian gold mineral systems made through the various activities of the project. Readers are referred to the original contributions for further details on the scientific highlights specific to each research activity. It is important to note that this synthesis volume can only provide a snapshot of the state of research and data analysis at the end of March, 2020; however, product delivery will continue for some time, with longer term outcomes in preparation or planned for the future.

The Targeted Geoscience Initiative

The *Resources and Technical Surveys Act* of 1985 mandates that the Minister of Natural Resources "shall make detailed investigations of mining camps and areas containing economic minerals or deposits of other economic substances, for the purpose of determining the mode of occurrence and the extent and character of ore-bodies and deposits" (R.S., 1985, c. R-7, s. 31994, c. 41, s. 3b). In the late 1990s, following various phases of restructuring at Natural Resources Canada, the GSC asked the Canadian Geoscience Council (CGC) to provide advice on the Minerals Geoscience Program. The CGC recommended that scientific leadership should be fostered at the national level and that regional, field-based metallogenic studies should represent important components of future mineral programs (Cathro et al., 2000). The GSC responded with a revised strategy built around newly funded, integrated, multidisciplinary and partnered national programs of thematic research (Duke, 2000). In 2000, this led to the development and implementation of the TGI Program, comprising a budget of $15 million over three years (2000–2002) to fund deposit- to district-scale mineral research projects throughout Canada. TGI was renewed for two years (Phase 2: 2003–2004) and comprised research projects focused on energy resources. A third phase followed, with a total budget of $25 million over five years (2005–2010), primarily for research promoting exploration for Cu resources in and around major base metal mining camps with operational smelters. A fourth phase was announced in mid-2010 with an initial budget of $10 million for two years, which was extended to $25 million for five years (2010–2015) in late 2010. Phase 4 marked a change from site-specific to ore system-based thematic research. TGI was renewed in 2015 for 5 years (Phase 5: 2015–2020) with a total budget of $22 million.

TGI-5 used a thematic, ore-system approach to define research projects (Fig. 1) that was guided by an internal review of the TGI-4 program and recommendations for future thematic research (Bleeker et al., 2014), while building on the research conducted on key Canadian ore systems during Phase 4 (2010–2015) of the program. In this context, an "ore system" can be defined as "*a mineralized system, across a range of scales, which culminated in one, or more typically a group of related deposits that share common genetic and geologic characteristics. At the large scale, the ore system is defined by the geodynamic and tectonic setting that created the set of conditions which, at the smaller scale, resulted in ore deposition. Ore deposits comprising an ore system can differ in style and position in the crust, and in timing, but share common causative ore-forming processes and controlling parameters*." This definition is a slight modification of the original definition of "mineral systems" proposed by Wyborn et al. (1994), which followed the perspective of "petroleum systems" used by the hydrocarbon exploration industry. The revised definition adopted here considers the entire process chain (Fig. 1) and resembles the definition of metallogeny, as initially proposed by De Launay (1913), and which is a largely overlapping concept: "*the study of the genesis of mineral deposits, with emphasis on their relationship in space and time to regional petrographic and tectonic features of the Earth's crust*" (American Geosciences Institute's Glossary of Geology: Neuendorf et al., 2005).

The Gold Project – Rationale, Objectives, and Approaches

Exploration for gold has historically represented a significant part of global and Canadian mineral exploration expenditures with an increasingly important proportion

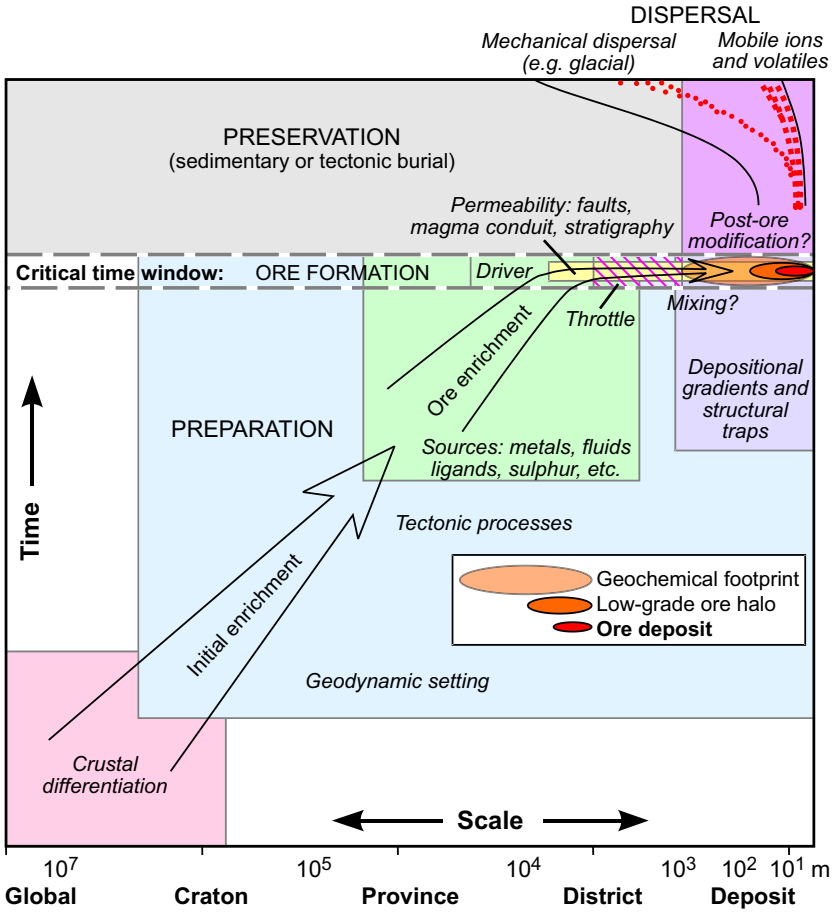

Figure 1. Schematic diagram of time versus scale illustrating the concept of complex mineral systems culminating in an economic ore deposit (small red ellipse). Ore deposits typically require an initial preparatory processes ("ground preparation") that pre-dates ore formation, several critically linked ore-forming processes that overlap in space and time, preservation of orebodies, and dispersion of spent fluids and/or metals. These processes typically operate across a vast range of scales. Initially, large-scale geodynamic and tectonic processes concentrate elements of interest into a regional- to district-scale source region, from which they are stripped by hydrothermal fluids or magmas. Faults or other permeable zones then focus ore-forming fluids or magmas into depositional environments where chemical, physical, or thermal gradients cause ore deposition. After passing through the depositional environment, spent fluids disperse into the environment. Many of these processes leave forensic evidence, such as hydrothermal alteration, that can be used to locate mineral deposits and their larger geochemical "footprints". Post-depositional dispersal of ore constituents or "pathfinder" elements, whether by chemical or mechanical means (e.g. erosion), may increase the scale of the exploration target. *From* Bleeker et al. (2014) as *adapted from* Huston et al. (2012).

in the last decade (Fig. 2a,b). Since 2017, between 55% and 65% of the total exploration expenditures in Canada were spent on gold (Fig. 2b,c). The increasing proportion of exploration budgets being spent on gold exploration is not only due to the higher costs associated with exploring for more remote or deeper deposits but is also due to the increased interest in gold due to its favourable market price, which is, in turn, largely influenced by global events (Fig. 2d,e). To mitigate increasing costs and risks, exploration efforts and spending in Canada are focused on the most favourable geological settings, including the southern parts of the Archean Superior Province in Quebec and Ontario (i.e. over half of exploration expenditures), the Cordillera (British Columbia and Yukon) and emerging districts in Nunavut (Natural Resources Canada, Canadian Mineral Exploration Information Bulletin, 2019).

Many gaps remain in our knowledge of gold mineral systems, including the source(s) of gold, transportation mechanisms, and final concentration processes (source-to-ore framework) result in significant limitations to developing improved exploration and genetic models. National databases that map the overall distribution of deposits, even within historical Canadian gold districts, are outdated and are missing some significant new discoveries. The objective of the Gold Project, as defined in 2015, was to improve our understanding of the mechanisms that control or influence the heterogeneous distribution of gold resources through space and time, to study fundamental aspects of ore genesis and optimize exploration models by improving our knowledge of their predictive features (Mercier-Langevin et al., 2017). The Gold Project took a multi-scale (craton/orogen to ore zone), multi-disciplinary, and collaborative approach to tackle these gaps in our understanding of ore-forming processes.

Two complementary research themes defined the Gold Project: 1) system controls on gold through space and time (source, concentrating mechanisms, and depositional controls); and 2) tectonic influences on gold (tectonic drivers and conduits). These two subprojects are complementary and comprised a series of thematic and/or regional to site-specific activities (Fig. 3) in many of the gold-bearing Canadian geological provinces (Fig. 4). Importantly, most components of the Gold Project were field-based with scientists and students carrying out significant field work and data acquisition in areas of interest across Canada.

Subproject G-1: System Controls on Gold through Space and Time (Source to Ore)

The formation and localization of major gold deposits and districts are linked to the secular evolution of the Earth through time, including the periods of continen-

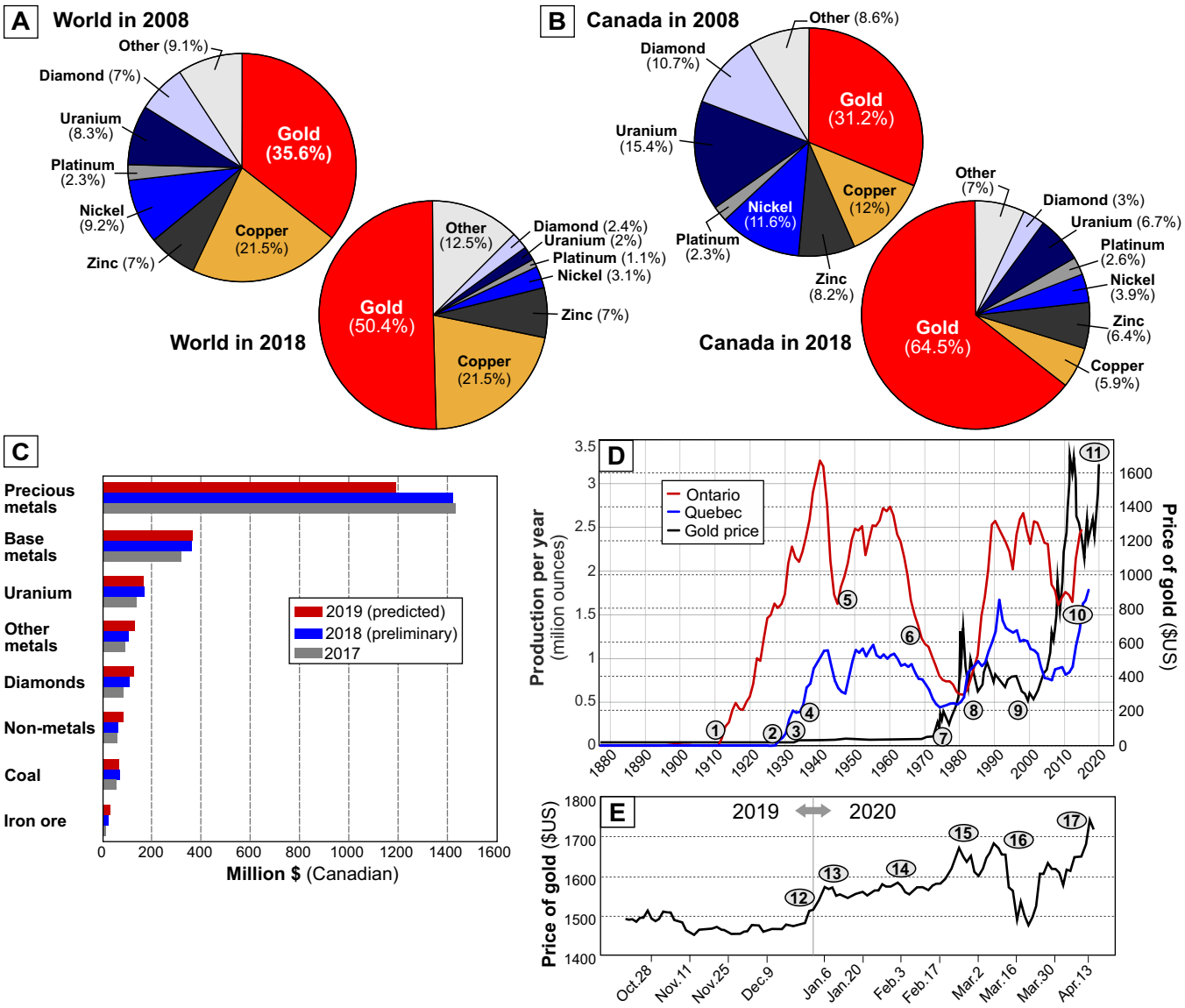

Figure 2. a, b) Global (a) and in Canada (b) exploration expenditures in 2008 and 2018. *From* Prospectors and Developers Association of Canada, State of Mineral Finance 2019: At the Crossroads online report. **c)** Exploration and deposit appraisal expenditures in Canada by mineral commodity for the years 2017 to 2019. Data for 2018 are preliminary, whereas data for 2019 are predicted. Precious metals, which includes gold, maintains a sizeable lead over all other commodity groups throughout the entire period. From Natural Resources Canada, Canadian mineral exploration information bulletin 2019. **d)** Historical gold production in Quebec and Ontario and gold price evolution from 1877 to 2017, *from* Dubé and Mercier-Langevin (2019, 2020). Numbers refer to specific events: 1 = onset of production from large gold deposits in Ontario (Dome, Hollinger, and McIntyre mines; onset of major gold production in Canada coincides with the major decline of gold production in the United States in the first few decades of the twentieth century (Lindgren, 1933)); 2 = onset of production from large gold deposits in Quebec (Horne mine); 3 = gold price raised from US$ 20.74 to US$ 35 per troy ounce by the Roosevelt administration in 1934 following the passage of the Gold Reserve Act; 4 = Sigma and Lamaque mine enters production in Quebec; 5 = World War II; 6 = closure of several major gold-producing mines (e.g. Hollinger, Wright-Hargreaves, Teck-Hughes, and Horne); 7 = price of gold decoupled from the United States dollar under President Nixon's administration; 8 = Large gold producers enter production (e.g. Hemlo, Doyon, and Bousquet mines); 9 = Bre-X scandal; 10 = large tonnage open pit mining starts at the Canadian Malartic and Detour Lake mines; 11 = surge in gold price due to geopolitical risks and economic uncertainty. **e)** Variations in the price of gold between October 2019 and April 2020 due to the coronavirus disease 2019 (COVID-19) pandemic: 12 = China's authorities report cases of a severe pneumonia in Wuhan; 13 = Word Health Organization (WHO) announces identification of a new coronavirus with the first deaths reported in China and the first cases reported outside of China in mid-January. WHO declares global public health emergency on March 30th, 2020; 14 = first deaths due to the new virus outside of China, WHO names new coronavirus COVID-19; 15 = global stock market volatility and major plunge on February 24, 2020 due to heightened coronavirus fears, first major measures (lockdowns and travel bans); 16 = WHO confirms COVID-19 as a pandemic, lockdowns and quarantines become global, stock markets plunge causing trading to be halted on a few occasions, massive gold reserves are liquidated to raise cash, and supply chains are disrupted; 17 = Rise in the price of gold in response to continued stock markets instability.

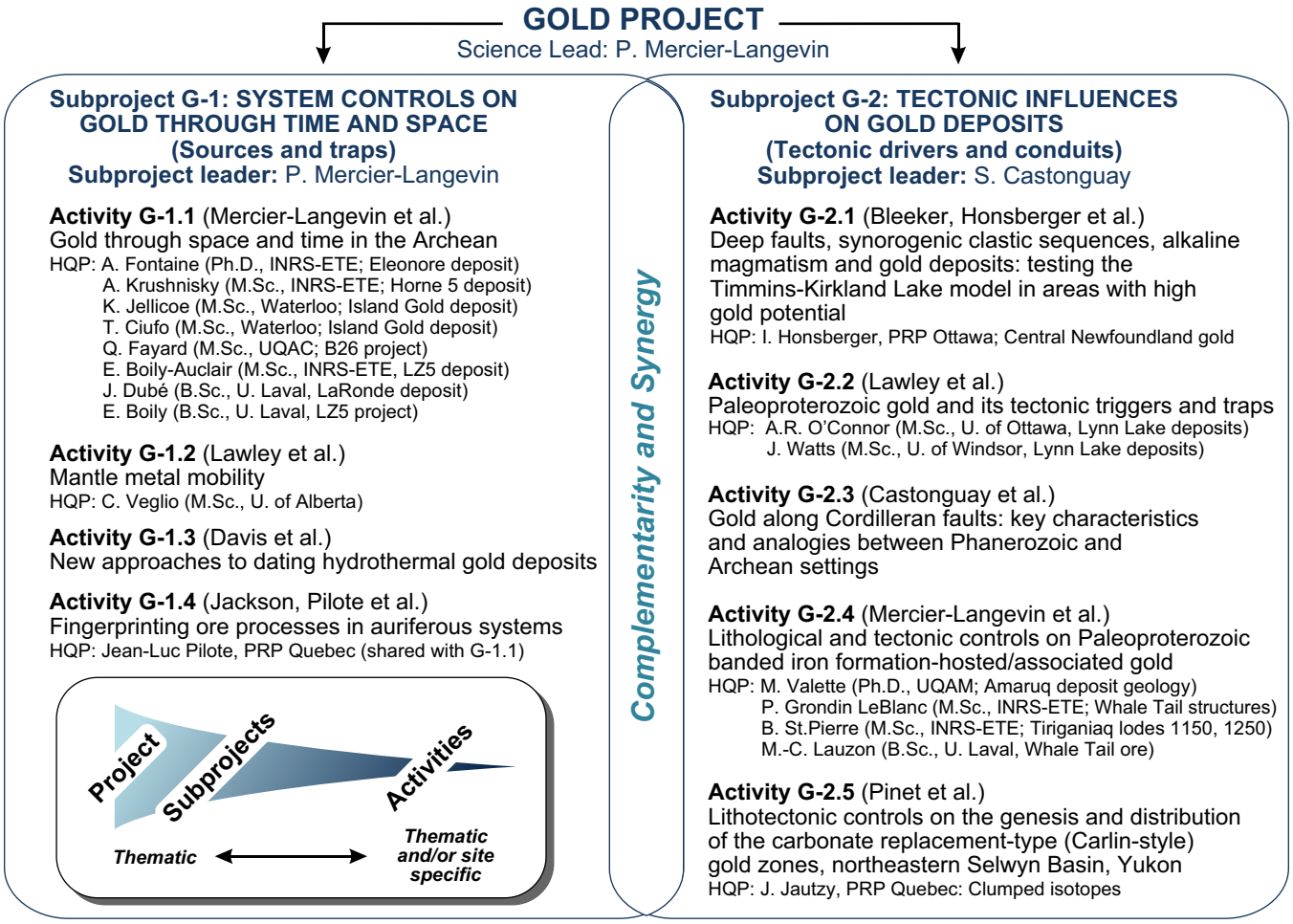

Figure 3. Schematic diagram showing the structure of the Gold Project with its two subprojects and nine activities. *See* Figure 4 for a map of the location of the pojects. *Modified from* Mercier-Langevin et al. (2017). Abbreviations: HQP = highly qualified personnel, PRP = postdoctoral research program.

tal amalgamation and breakup that occur during supercontinent cycles (Barley and Groves, 1992). Archean cratons, particularly Neoarchean parts, are amongst the best gold-endowed regions of the world. Numerous world-class orogenic gold deposits were formed during that era, in addition to several major gold deposits of other types, with some containing polyphase mineralization (e.g. Dubé et al., 2015, and references therein). The precise reasons for such a major "temporal" peak in gold endowment are still not completely understood. Among the proposed controls of gold deposition in the Neoarchean are fertile upper mantle to lower crustal source(s), enriched upper crustal units and peak felsic crust formation, onset of plate tectonics, terrane collisions, the presence of large-scale fault systems that were able to channel large-scale fluid flow and repeated tapping of the same enriched source regions, and/or particularly efficient depositional mechanisms (e.g. Barley and Groves, 1992; Sillitoe, 2008; Dubé et al., 2015, and references therein).

Activities comprising this subproject aimed at defining controls of ore formation by examining the following: 1) the characterization of unusual, important, and/or newly discovered mineralization styles, with the goal to contribute new information that will be critical for finding new deposits, or extensions of known orebodies, and that will continuously improve exploration models at various scales; 2) the review of the geological characteristics of gold mineralization at multiple scales in well endowed regions and/or areas that represent exceptional opportunities to study processes relevant to gold deposit genesis, such as in emerging districts and "poorly endowed" terranes; and 3) the synthesis of the available data/knowledge on established and emerging districts to provide basic but critical information on the geological setting and evolution of the most prolific periods/areas for gold mineralization. Many of these research activities emphasized district-to deposit-scale features because they represent key exploration vectors for the mineral industry. Subproject G-1 comprised four activities (Fig. 3) and numerous subactivities, the main results of which are summarized in Boily-Auclair et al. (2020), Boudreau et al. (2020), Castonguay et al. (2020a), Ciufo et al. (2020), Fayard

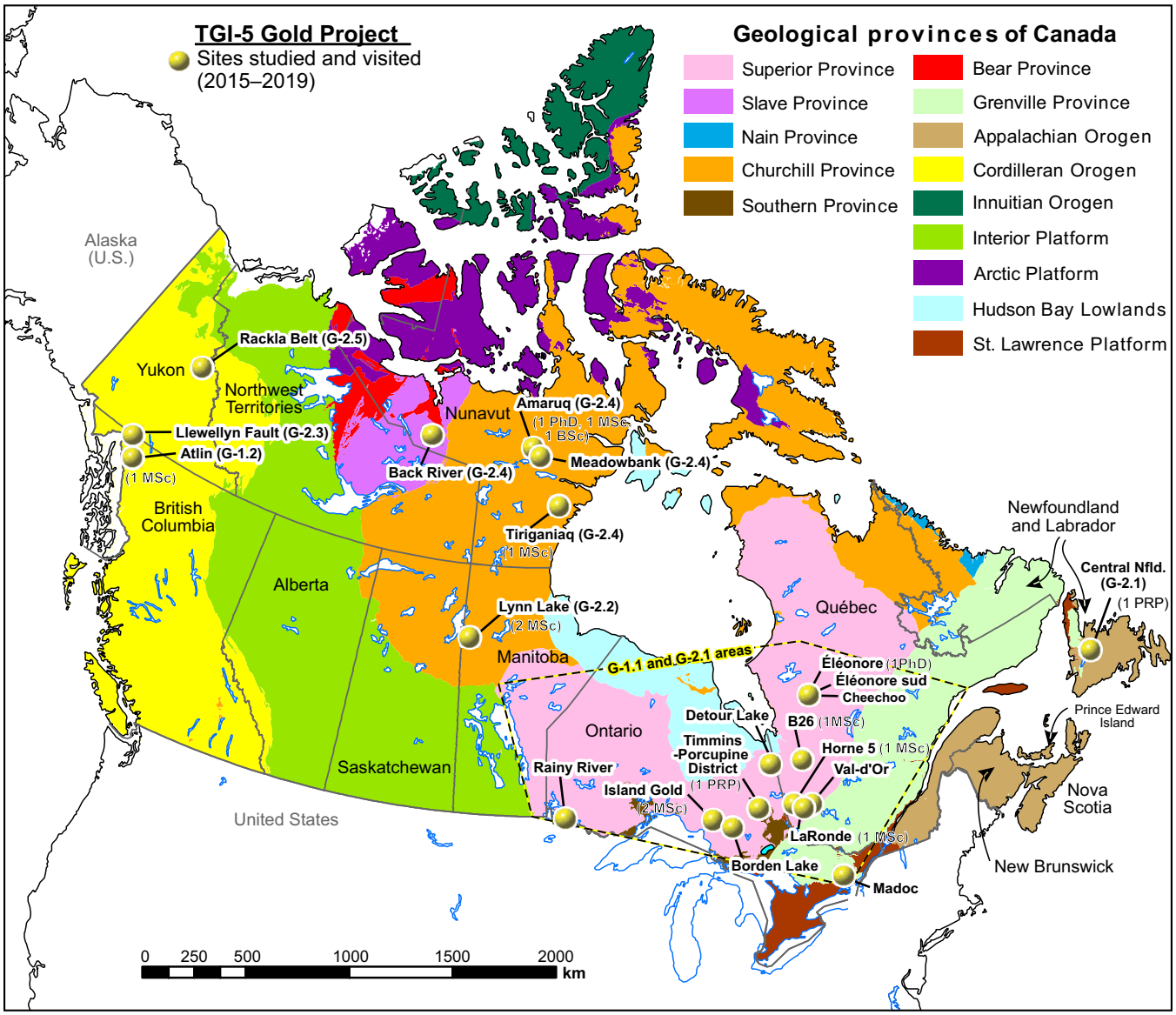

Figure 4. Location map of the principal study sites of the Gold Project (2015–2019). Geology *modified from* Wheeler et al. (1996). *See* Figure 3 for an explanation of the individual gold projects (G-x.x) and the theses. Abbreviation: PRP = postdoctoral research program.

et al. (2020a,b), Krushnisky et al. (2020), Lawley and Kjarsgaard (2020), and Pilote et al. (2020b,c).

Subproject G-2: Tectonic Influences on Gold (Tectonic Drivers and Conduits)

The incomplete understanding of the major fault zones, terrane boundaries, and tectonometamorphic discontinuities in the best endowed regions or metallogenic provinces of Canada hinders efficient regional- to district-scale mineral deposit targeting. Several ore-associated, long-lived structures have been studied in detail, but many still need to be investigated to better establish their extent, kinematic history, and critical role(s) in the formation (and preservation) of gold ore systems. Subproject G-2 focused on the known tectonic controls on gold transport, deposition, and preservation, including an analysis of the nature and evolution of major ore-associated structures in selected gold districts. Many of the research activities of this subproject were based on the results of previous phases of TGI projects. For example, previous research in the Abitibi greenstone belt defined the apparent predictable relationships between deep-reaching (first-order or lithospheric-scale) faults characterized by a synorogenic phase of extensional faulting, preserved panels of clastic sequences, (alkaline) magmatism, and orogenic gold deposits (Bleeker, 2015). New research conducted as part of TGI-5 tested whether these relationships also occur in other gold districts of different ages and variable metal endowment (e.g. Trans-Hudson, Appalachians, Cordillera, etc.). Some key auriferous faults and/or terrane boundaries were specif-

ically targeted by documenting their evolution and significance in the genesis and preservation of gold deposits. Several of these research activities included a significant geochronology component to refine the geological and temporal evolution of each gold district. Subproject G-2 comprised five activities (Fig. 3) and a number of subactivities, which are summarized in Castonguay et al. (2020b), Honsberger et al. (2020a,b), Lauzon et al. (2020), Lawley et al. (2020c), Pinet et al. (2020a,b), St.Pierre et al. (2020), and Valette et al. (2020).

The Gold Project Synthesis Volume

The Open File format

This synthesis volume is published as a GSC Open File report comprising external peer-reviewed and professional copy-edited contributions. The rationale behind using this format was to make the results of the project available to our stakeholders in a timely manner without compromising scientific rigour.

Short- versus long-term outputs and outcomes

Phase 5 of the Targeted Geoscience Initiative ended March 31st, 2020, and the contributions contained in this synthesis volume represent the state of knowledge at the end of 2019. This knowledge had to be summarized in very concise individual reports, which forced authors to limit discussion to key aspects of their research and prevented them from incorporating large data sets and extensive analyses and interpretations. Many of the activities and subactivities described below will be completed after the program has ended and after this synthesis volume is published. Additional reports, scientific papers, data releases, theses, and presentations will stem from the Gold Project.

Throughout the evolution of the project, new results, data, and information from most of the activities have been made available to the public through numerous scientific publications and presentations. Over 170 publications (e.g. peer-reviewed scientific papers, GSC current research and open file reports, theses, etc.) have been published; the reader will find a detailed list of these contributions in the appendices. Participants of the Gold Project have also presented over 200 oral and poster presentations at national and international venues between 2015 and March 2020, a reflection of the commitment of the scientists to disseminate their results in a timely manner.

Selected Research Highlights from the Gold Project Synthesis Volume

System controls on gold through space and time (Subproject G-1)

The study by Krushnisky et al. (2020) of the Horne 5 volcanogenic massive sulphide (VMS) deposit (Rouyn-Noranda, Quebec) shows that the gold is synvolcanic and hosted in some of the oldest volcanic rocks of the Blake River Group, which are predominantly intermediate to felsic in composition and transitional to calc-alkaline in affinity. The Blake River Group is the youngest of the seven volcanic-dominated assemblages of the Abitibi greenstone belt and hosts the largest and best gold-rich VMS deposits of the belt. The Horne system (~15 Moz or 467 t Au), which is found in association with calc-alkaline volcanism, represents a key example of a large synvolcanic gold system formed late in the volcanic construction of the Abitibi greenstone belt.

The Horne deposit host sequence is truncated by the Andesite fault, south of which occur sulphide clast-bearing felsic volcaniclastic units that share similarities with the Horne stratigraphy. However, Boudreau et al. (2020) demonstrate that sulphide clasts in the felsic volcanic units south of the Andesite fault are devoid of metals, which is unlike the Horne West zone and Horne 5 deposit. The presence of barren sulphide clasts south of the fault nevertheless provides further evidence of early (ca. 2701 Ma) hydrothermal activity on the seafloor in different areas during the construction of the Blake River Group.

The association between synvolcanic gold and transitional to calc-alkaline intermediate to felsic rocks has been demonstrated in the Doyon-Bousquet-LaRonde mining camp (e.g. Mercier-Langevin et al., 2007a,b). Boily-Auclair et al. (2020) reinforce this relationship by showing that the LZ5 ore zones (LaRonde Zone 5 deposit, Quebec) are directly associated, in both time and space, with the onset of transitional to calc-alkaline magmatism. The LZ5 ore zones were previously considered to occur lower in the volcanic stratigraphy and were therefore considered to be slightly older than the prospective calc-alkaline felsic rocks.

Pilote et al. (2020c) have studied pyrite nodules hosted in argillite lenses located in the main massive sulphide lens of the LaRonde Penna gold-rich VMS deposit in Quebec. Pyrite textures and geochemistry suggest that the nodules are diagenetic and that their Sn-Cu-Zn-Pb-Bi budget primarily reflects the composition of the host argillite. Trace metals in the argillite are interpreted to come from the exhalative and/or alteration product of the VMS-forming fluids. This implies that interflow argillite with pyrite nodules enriched in the above elements may be good markers of fertile volcanic centres and serve as vectors pointing towards VMS mineralization.

Fayard et al. (2020a,b) describe a ca. 2728 Ma calc-alkaline magmatic centre located in the northwestern Abitibi belt in Quebec, which hosts the B26 precious metal-rich VMS system. They compare the B26 deposit Ag-rich mineralization to the neighbouring

Selbaie mine, which has previously been interpreted as an Archean epithermal system. Geological, geochemical, and mineralogical similarities between both deposits suggest that B26 may have been formed at shallow depths. This setting may have played a role in the geometry, precious metal distribution, and Ag content at B26.

The southern Abitibi greenstone belt is well known as the best endowed part of the Superior Province (e.g. Dubé and Mercier-Langevin, 2019, 2020, in press). However, except for a few major deposits, portions of the northern Abitibi greenstone belt and the Wawa segment of the Abitibi-Wawa Subprovince contain less gold. The factors controlling this variable gold endowment within otherwise similar geological settings remains a knowledge gap in our understanding of the Abitibi belt metallogeny (cf. Robert et al., 2005). Castonguay et al. (2020a) report new results from the Sunday Lake and Lower Detour deformation zones and their associated orogenic gold deposits and showings in the northwestern Abitibi greenstone belt. These regional-scale auriferous deformation zones are spatially associated with bands of polymict conglomerate and intermediate to felsic, typically sub-alkaline to alkaline dykes and small plutons that likely represent polyphase deep-reaching structures. Similarly, Ciufo et al. (2020) describe the Island Gold orogenic deposit in the Michipicoten greenstone belt (Wawa segment, Abitibi-Wawa Subprovince) to be predominantly hosted in intermediate volcanic rocks and associated with the Goudreau Lake deformation zone, which has been interpreted by Leclair et al. (1993) as the extension of the Larder Lake-Cadillac fault west of the Kapuskasing structure. Results show similar controls on the formation and location of the gold-bearing veins and relative timing between host-rock formation, deformation, metamorphism, and ore-forming hydrothermal activity to those of orogenic gold deposits of the southern Abitibi greenstone belt. Comparing and contrasting the geological settings of these lesser known gold deposits with the better studied Destor-Porcupine and Larder Lake-Cadillac deformation zones and gold deposits of the southern Abitibi belt provide new insights into the geological evolution and variable metal endowment across the southern Superior Province.

Determining the ultimate sources of the ore components represents one of the other fundamental knowledge gaps in understanding gold ore systems. The scale of the gold-bearing structures (100s of km), coupled with isotopic tracer studies that point to long transport distances, tend to suggest that some ore components were sourced from the lower crust and/or upper mantle (e.g. McInnes et al., 1999; Sillitoe, 2008; Tassara et al., 2017). Lawley and Kjarsgaard (2020) tested the possibility of gold-enrichment processes in the upper mantle by analyzing upper mantle rocks directly (ophiolites and mantle xenoliths and xenocrysts; British Columbia, Yukon, Ontario, and Nunavut). Their results suggest that previously melt-depleted mantle domains that reacted with upwelling asthenospheric melts are enriched in gold. Re-melting of these pre-enriched domains (i.e. re-fertilized domains of the previously melt-depleted lithospheric mantle) represent one of the possible source regions for melts and/or hydrothermal fluids that transported ore components to orogenic gold deposits in the mid to upper crust.

Sedimentary rocks in the upper crust have also been considered as a potential source of metals through the liberation of gold from diagenetic pyrite (including pyrite nodule-bearing argillite) during high-grade metamorphism (e.g. Kribek, 1991; Large et al., 2009). Pilote et al. (2020b) thoroughly document the textural and geochemical nature of argillite-hosted pyrite and discuss the origin of these distinctive nodules using the Timmins-Porcupine district (Ontario) as a study case. Research results highlight the ability of pyrite nodules to sequester highly anomalous levels of gold, which appears to be controlled by the provenance of the host sedimentary rocks.

Tectonic influences on gold (Subproject G-2)

Notwithstanding the uncertain source(s) of gold, the tectonic drivers and favourable pathways for gold-bearing fluids are well known to exhibit important controls on the genesis of orogenic gold deposits (e.g. Robert et al., 2005; Dubé and Gosselin, 2007; Bleeker, 2015). Documenting the multi-phase history of large-scale, gold-bearing structures is another important contribution of the Gold Project. Honsberger et al. (2020a,b) demonstrate that Paleozoic orogenic gold mineralization in the footwall of the Victoria Lake shear zone (central Newfoundland) is related to approximately 20 to 30 million years of tectonism that spanned Late Silurian and Early Devonian. This phase of tectonism (ca. 430–405 Ma) involved extension-related synorogenic bimodal magmatism followed by crustal-scale thrust imbrication, regional metamorphism, and vein-hosted gold mineralization in the upper crust. The sequence and temporal pacing of events in central Newfoundland appear to be similar to those of the southern Abitibi belt. Lawley et al. (2020c), in their study of the Lynn Lake belt in northern Manitoba, indicate a similar context and timeframe for the formation of orogenic gold deposits within the Paleoproterozoic Trans-Hudson Orogen, with an early gold event associated with the shift from accretionary to collisional tectonics.

Although the broad evolution of some major crustal-scale deformation zones can be similar in different oro-

gens, the metallogenesis can vary in detail and through geological time. The study of the Llewellyn-Tally Ho deformation corridor in the Cordillera (British Columbia and Yukon) by Castonguay et al. (2020b) documents an example of superimposed, polyphase gold mineralization events. There, early gold associated with Late Cretaceous ductile deformation and plutonism is overprinted by early Eocene, dextral, transpressive, brittle faulting and volcanism associated with low-sulphidation epithermal gold. Except for Neoproterozoic high-sulphidation-type mineralization at Hope Brook in central Newfoundland (Dubé et al., 1995), which is older than the orogenic gold deposits studied by Honsberger et al. (2020a,b), late-stage and shallow epithermal-style gold mineralization is notably absent in the other gold districts studied as part of the Gold Project. This may reflect a distinct metallogenic evolution for certain Cordilleran fault zones or some unique preservation control (e.g. shallower erosion?).

St.Pierre et al. (2020) document the structural controls of the 1150 and 1250 "lodes", or ore zones, at the Tiriganiaq gold deposit in the Meliadine district (Nunavut). The 1150 and 1250 lodes are controlled by protracted folding and shearing of the host sedimentary succession in the hanging wall of the Lower Fault, a subsidiary reverse fault of the district-scale Pyke fault. At the Tiriganiaq deposit, moderately north-dipping, late D_2 shears host mineralized quartz and carbonate veins, and are locally associated with bonanza-grade, shallowly south-dipping extension veins that are preferentially developed in tightly folded, metres-thick banded iron formation units. In contrast, the main ore zone (1000 lode), which is also associated with D_2 deformation along the Lower Fault, consists of a large (up to 5 metres thick), continuous laminated shear vein that is predominantly hosted in siltstone. This shows that ore zone geometry and grade distribution can vary significantly within one ore system depending on the local conditions.

The Amaruq deposit, located about 50 kilometres north of the Meadowbank mine in the Kivalliq region of Nunavut, consists of replacement- and vein-style gold hosted in Archean chert, argillite, silicate-facies iron formation and to a lesser extent in mafic-ultramafic volcanic rocks and greywacke (Valette et al., 2020). The deposit was deformed and metamorphosed during the Trans-Hudson orogenesis at approximately 1.85 Ga. New field observations, textural evidence, and preliminary Re-Os and $^{40}Ar/^{39}Ar$ ages suggest that an early stage of veining may pre-date Trans-Hudsonian peak metamorphism and is potentially much older than 1.85 Ga (Lauzon et al., 2020). These new results agree with the complex and multi-phase metallogenic history proposed by recent work elsewhere in the region (Lawley et al., 2015).

Pinet et al. (2020a,b) review the regional to nanoscale characteristics of the Rackla belt Carlin-type gold zones in the Selwyn Basin (Yukon) and show that the mineralized zones exhibit the main characteristics of sediment-hosted micron-gold Carlin-type deposits of Nevada. Several early deformation events led to the development of favourable traps (structural ground preparation). These structures control the location of mineralized zones at the regional scale (juxtaposition of two crustal blocks), prospect scale (generation of complexly shaped fold-fault traps), and mineralized-zone to sample scale (formation of several fracture and vein sets). Sedimentary processes also influenced the development of favourable traps. The primary sediment properties (e.g. silty layers and impermeable barriers, reactive carbonates) and post-depositional processes (e.g. slope facies and sedimentary breccia) helped create and preserve porosity and permeability. New results further suggest that the gold mineralizing event in the eastern Rackla belt is associated with minor (in terms of bulk strain) reactivation of early structures and is significantly younger than the main intrusion-related gold mineralizing events in the Selwyn Basin.

Updated Compilation of Gold Deposits of the Superior Province

Based on the premise that gold is a major economic target for many exploration and mining companies in Canada, the GSC developed, with the help of sponsors from industry, the World Minerals Geoscience Database Project (WMGDP: 1998–2004). The aim of this joint initiative was to produce geoscience data sets to be used in conjunction with GIS (Geographic Information Systems) and database software to help understand the broad relationships between global tectonics and the regional geological settings of mineral deposits. This endeavour led to the Canadian Gold Database (Gosselin and Dubé, 2005b, 2015), which collated lode gold deposit information from all of Canada's geological provinces.

The Canadian Gold Database was updated to include the location, metal content (reported data from industry at the end of 2018), and relevant geological information for new and previously reported gold deposits (≥100,000 oz or 3.2 metric t Au, including production, reserves, and measured and indicated resources) in the Superior Province. The revised database (Bécu et al., in progress, 2020) will be released separately, following the publication of this synthesis volume.

The revised database comprises 181 entries. Deposits with 1 Moz (31.1 t) gold or less represent 61% of those deposits (110/181; Fig. 5a). Seventy-one deposits contain more than 1 Moz gold, with more than half of these containing less than 3 Moz (93.3 t gold).

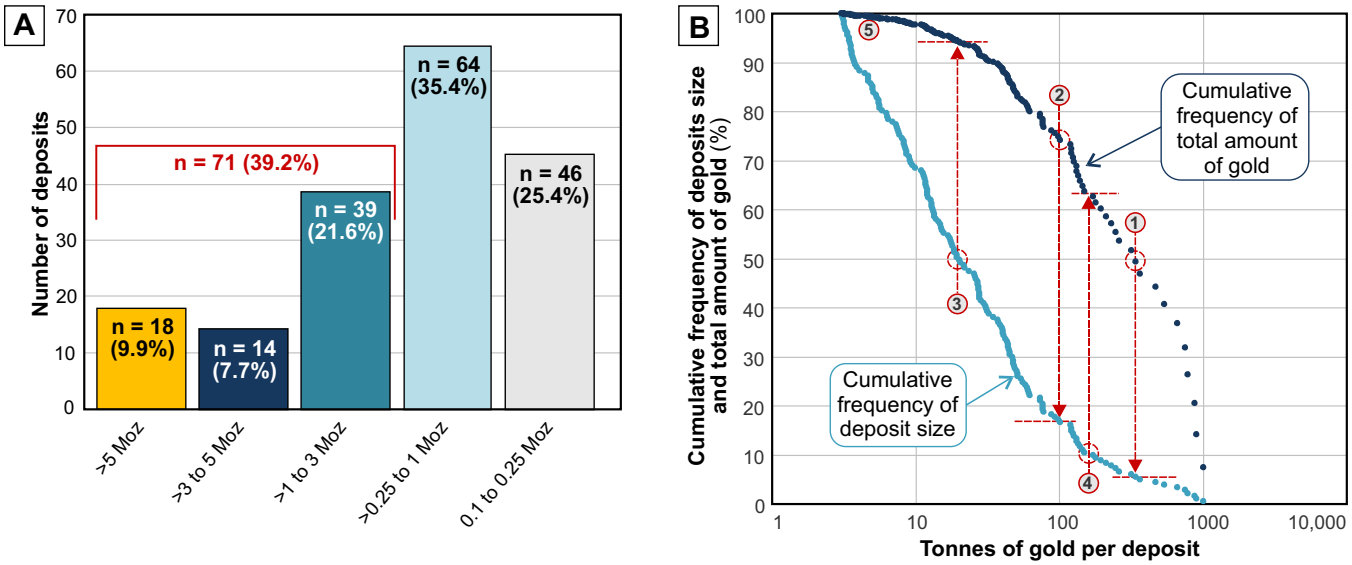

Figure 5. Gold deposits (≥100,000 ounces, or 3.1 metric t Au) of the Superior Province. The data includes production, reserves, and resources (measured and indicated). Inferred resources are excluded. **a)** The number of deposits versus the deposit size (n = 181). Only 10% of the deposits (18/181) contain 5 million ounces (Moz), or 155.5 t, of gold or more. Seventy-one deposits contain 1 Moz (31.1 t) gold or more, which amounts to about two-fifths of the total number of gold deposits in the Superior Province with over 0.1 Moz gold. **b)** Plot of the cumulative frequency of deposit size (light blue) and the total contained gold (dark blue) among gold deposits of the Superior Province. 1 = the 10 largest deposits, which account for 5.5% of the total number of deposits, which contain almost 50% of the total gold; 2 = deposits with 100 t (3.2 Moz) gold or more and account for approximately 75% of the total gold; 3 = 50% of the deposits included in the database that have less than 20 t (0.64 Moz) gold and account for only about 6% of the total gold; 4 = the top 10% of the deposits in terms of size, which each have 171 t (5.5 Moz) gold or more and account for approximately 63% of the total gold, indicating that a large proportion of the gold in the Superior Province is contained in only a few deposits; 5 = flattening of the cumulative gold tonnage curve despite a large number of deposits with less than 10 t gold (0.32 Moz), indicating that the use of a ≥0.10 Moz (3.1 t) gold cut-off in our compilation allows for a representative image of gold distribution across the Superior Province.

Thirty-two world-class deposits (i.e. with >3 Moz Au) are present in the Superior Province (32/181; Fig. 5a). These world-class deposits, however, account for over 75% of the total gold of the Superior Province (Fig. 5b). Figure 5b shows that the 10 largest deposits of the Superior Province, accounting for 5.5% of the total number of deposits, contain almost 50% of the total gold. The top 10% of the deposits in terms of size, which each have 171 t (5.5 Moz) of gold or more, account for approximately 63% of the total gold. Interestingly, although the largest deposits are dominantly orogenic, five of the 18 deposits with more than 5 Moz (155.5 t) of gold can be classified as intrusion-associated (n = 2), and synvolcanic (n = 3: Table 1), indicating some diversity in the types of very large deposits. At district scale, orogenic gold also dominates, but two of the 10 largest gold districts of the Superior Province consist predominantly of synvolcanic gold (Table 2). Approximately half of the deposits included in the database have less than 20 t (0.64 Moz) of gold and account for only about 6% of the total gold. These data indicate that a large proportion of the gold in the Superior Province is contained in just a few deposits. Similar figures have been previously reported (e.g. Hodgson and MacGeehan, 1982) and our data further highlight the importance of world-class deposits to global gold production, emphasizing that ore system research should focus on identifying the geological settings that are most prospective for giant to world-class deposits. Almost 80% of the gold of the Superior Province is in the Abitibi-Wawa terrane, with a significant proportion of these deposits in the Abitibi belt (Fig. 6). Smaller deposits are also more abundant in the Abitibi greenstone belt than in the rest of the Superior Province (Fig. 6). Since 2005, 49 new entries were added to the Superior Province gold database (Fig. 7). These additional entries consist of five past producers, nine past producers with significant new reserves and/or resources (e.g. Akasaba, Buffalo), and 35 new discoveries or recently discovered deposits that were put into production since 2005, or for which significant gold ounces were added since 2005 (Fig. 7, 8). Despite increased exploration in greenfield areas, more than 60% of the new (2005–2018) entries, and almost 70% of the associated gold, are from the Abitibi greenstone belt (Fig. 8, 9), specifically along the Destor-Porcupine and Cadillac-Larder Lake fault zones in well established districts (e.g. Timmins West in Timmins, and Westwood in the Doyon-Bousquet-LaRonde camp). Emerging areas that were previously considered less prospective (e.g. Kapuskasing structural zone: Borden mine, and the Swayze greenstone

Table 1. Gold deposits of the Superior Province containing more than 5 Moz (155.5 t) of gold.

Deposit[2]	Terrane	Location	Main deposit type	Total gold (production, reserves, and measured and indicated resources)[1] Tonnage (Mt)[3]	Au grade (g/t)	Au (metric t)	Au (Moz)	Rank
Hollinger-McIntyre-Coniaurum	Abitibi	Ontario	Orogenic	120.3	8.43	1,013.6	32.6	1
Kirkland Lake (Main camp)	Abitibi	Ontario	Orogenic	63.5	14.25	904.7	29.1	2
Red Lake[4]	Uchi	Ontario	Orogenic	53.0	16.60	879.8	28.3	3
Hemlo	Wawa	Ontario	Orogenic	176.9	4.49	794.1	25.5	4
Detour Lake	Abitibi	Ontario	Orogenic	738.2	1.03	759.6	24.4	5
Dome	Abitibi	Ontario	Orogenic	276.4	2.40	664.5	21.4	6
Canadian Malartic[5]	Abitibi	Quebec	Orogenic	361.7	1.45	523.1	16.8	7
Horne	Abitibi	Quebec	Synvolcanic	144.9	3.22	466.6	15.0	8
Kerr Addison	Abitibi	Ontario	Orogenic	40.3	8.42	339.1	10.9	9
Sigma-Lamaque-Triangle	Abitibi	Quebec	Orogenic	61.0	5.54	337.6	10.8	10
Côté Gold	Abitibi	Ontario	Intrusion-associated	326.2	0.95	310.1	10.0	11
LaRonde Penna	Abitibi	Quebec	Synvolcanic	64.6	3.85	248.6	8.0	12
Musselwhite	North Caribou	Ontario	Orogenic (BIF-hosted)	40.9	5.87	239.6	7.7	13
Pamour	Abitibi	Ontario	Orogenic	120.5	1.90	229.2	7.4	14
Rainy River	Wabigoon	Ontario	Synvolcanic	200.7	1.02	205.0	6.6	15
Young-Davidson	Abitibi	Ontario	Orogenic	73.5	2.65	194.5	6.3	16
Casa Berardi	Abitibi	Quebec	Orogenic	46.8	3.69	172.6	5.6	17
Doyon	Abitibi	Quebec	Intrusion-associated	32.6	5.26	171.7	5.5	18

Notes: [1]inferred resources are not included; [2]In many cases, deposits consist of more than one mine; [3]Million tonnes (metric); [4]Includes Red Lake, Campbell, New Dickinson, and Young mines. [5] Includes Canadian Malartic, Barnat, Sladen, and East Malartic mines. Abbreviation: BIF = banded iron formation.

Table 2. Gold deposits of the Superior Province containing more than 25 Moz (755.5 t) of gold.

Camp	Subprovince	Location	Main deposit type	Total gold (production, reserves, and measured and indicated resources) Tonnage (Mt)	Au grade (g/t)	Au (metric t)	Au (Moz)	Rank
Timmins	Abitibi	Ontario	Orogenic	649.8	4.03	2619.5	84.2	1
Val d'Or-Malartic	Abitibi	Quebec	Orogenic	620.3	2.40	1487.8	47.8	2
Kirkland Lake-Larder Lake	Abitibi	Ontario	Orogenic	132.6	10.49	1391.9	44.8	3
Red Lake	Uchi	Ontario	Orogenic	145.6	8.18	1190.0	38.3	4
Hemlo	Wawa	Ontario	Orogenic	189.3	4.26	806.3	25.9	5
Bousquet (DBL)-Cadillac	Abitibi	Quebec	Synvolcanic and orogenic	158.3	4.99	790.1	25.4	6
Noranda	Abitibi	Quebec	Synvolcanic and orogenic	237.7	3.31	787.7	25.3	7
Detour	Abitibi	Ontario	Orogenic	741.1	1.05	776.2	25.0	8

Abbreviation: DBL = Doyon-Bousquet-LaRonde camp.

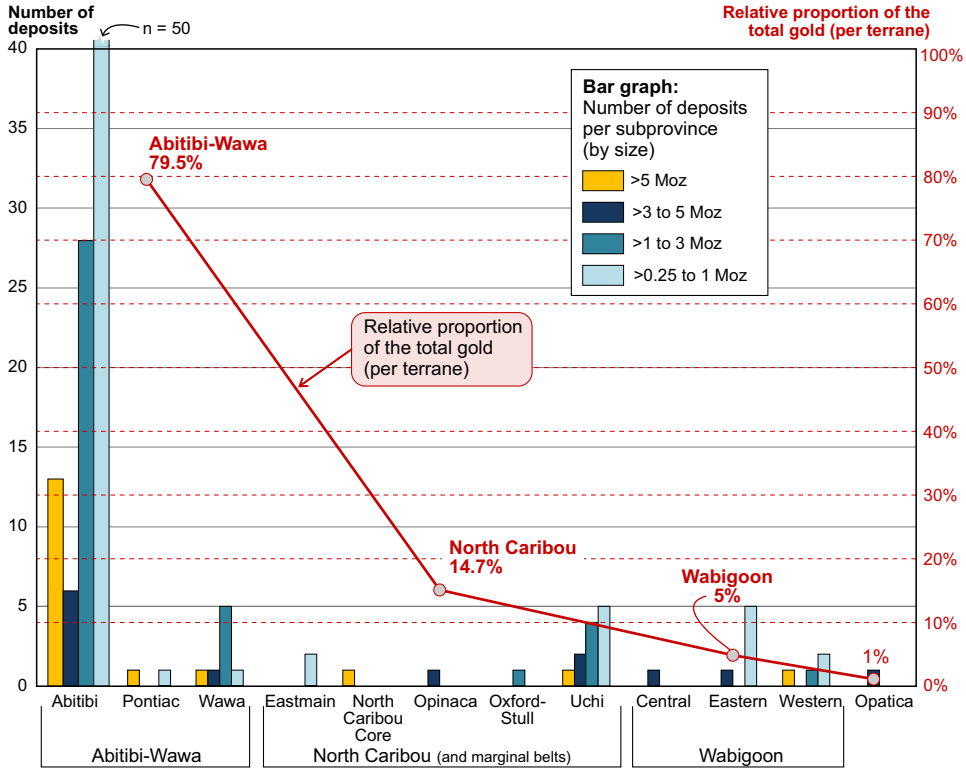

Figure 6. Distribution of gold deposits within individual terranes of the Superior Province based upon their total gold content. From a total of 181 deposits, 135 contain more than 0.25 million ounces (Moz), or 7.8 metric t of gold (total production, reserves, and measured and indicated resources). Almost four out of five deposits in the Superior Province with more than 0.25 Moz (7.8 t) of gold are in the Abitibi-Wawa Subprovince (79.3%: 107/135). The Abitibi greenstone belt is especially well endowed, with a total of 98 deposits (72.6%: 98/135), the Uchi terrane ranks second, with a total of 12 deposits with more than 0.25 Moz (7.8 t) gold. The Canadian Malartic deposit is included in the Pontiac in this diagram, but a significant part of the ore is hosted in the Piché Group of the Abitibi belt.

belt: Coté Gold deposit) clearly indicate significant potential outside of the well established districts. In recent years, there has also been a renewed interest in the western Superior Province. This follows the commercial production at the Island Gold (Wawa) and Rainy River (western Wabigoon) mines and the delineation of considerable resources at the Hammond Reef and Goliath deposits, for example (Fig. 8, 9b,c). The database also includes updated reserve and/or resource estimations for more than half of all producing and indexed deposits (n = 132).

Although the revision and updating of the compilation of gold deposits in the Superior Province is ongoing and contains the usual limitations and shortfalls associated with large compilations and classifications of complex deposits (*see* Singer, 1995, Franklin et al., 2005, and Mercier-Langevin et al., 2011), some general observations can be made. Volcanic rocks represent the dominant host lithology for almost half of the deposits (49.7%: n = 90/181; Fig. 10a), whereas intrusive and sedimentary rocks represent the dominant host for about one-third (34.3%: n = 62/181), and less than one-sixth of the cases (16.0%: n = 29/181), respectively. The favourable prospectivity of volcanic rocks is further highlighted by their total gold content. Volcanic rocks are the main (but not necessarily the only) host lithology for deposits totalling 240.6 million ounces (7485 t), which represents approximately 55% of the total contained gold in the Superior Province (Fig. 10b). Such a figure is expected considering that orogenic gold is preferentially found in greenstone belts

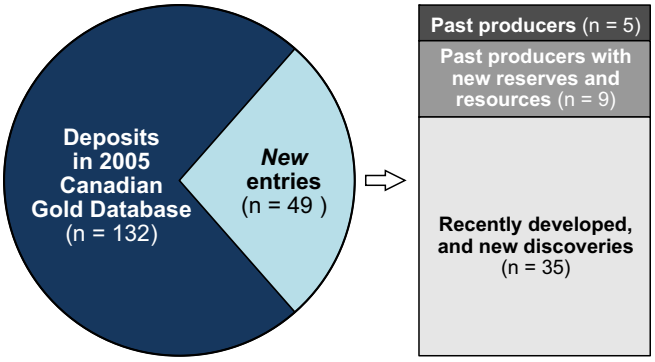

Figure 7. Compilation of 181 gold deposits of the Superior Province with ≥0.1 Moz (3.1 metric t) gold (total production, reserves, and measured and indicated resources), including the 49 new entries since the GSC's previous compilation in 2005 (Canadian Gold Database: *see* Gosselin and Dubé, 2005a,b). These 49 new entries consist of 5 past producers that were not included in the 2005 gold database (mainly from the Chibougamau area; e.g. Cedar Bay, Portage-Henderson); 9 past producers with significant new reserves and/or resources (e.g. Akasaba, Buffalo); and 35 deposits that were recently discovered and put into production since 2005, deposits for which significant gold ounces were added since 2005, and new discoveries that were made after 2005 (e.g. Lapa, Borden, Rainy River, and Windfall Lake).

(Fig. 8). A similar observation can be made in other Archean cratons (e.g. western Churchill Province: Lawley et al., 2015; Mercier-Langevin et al., 2018). Of note, our compilation includes gold-rich VMS deposits that are hosted in volcanic rocks. Volcanic rocks with mafic to intermediate bulk compositions (74 deposits and 191.5 Moz, or 5960 t Au; Fig. 10b) are the most

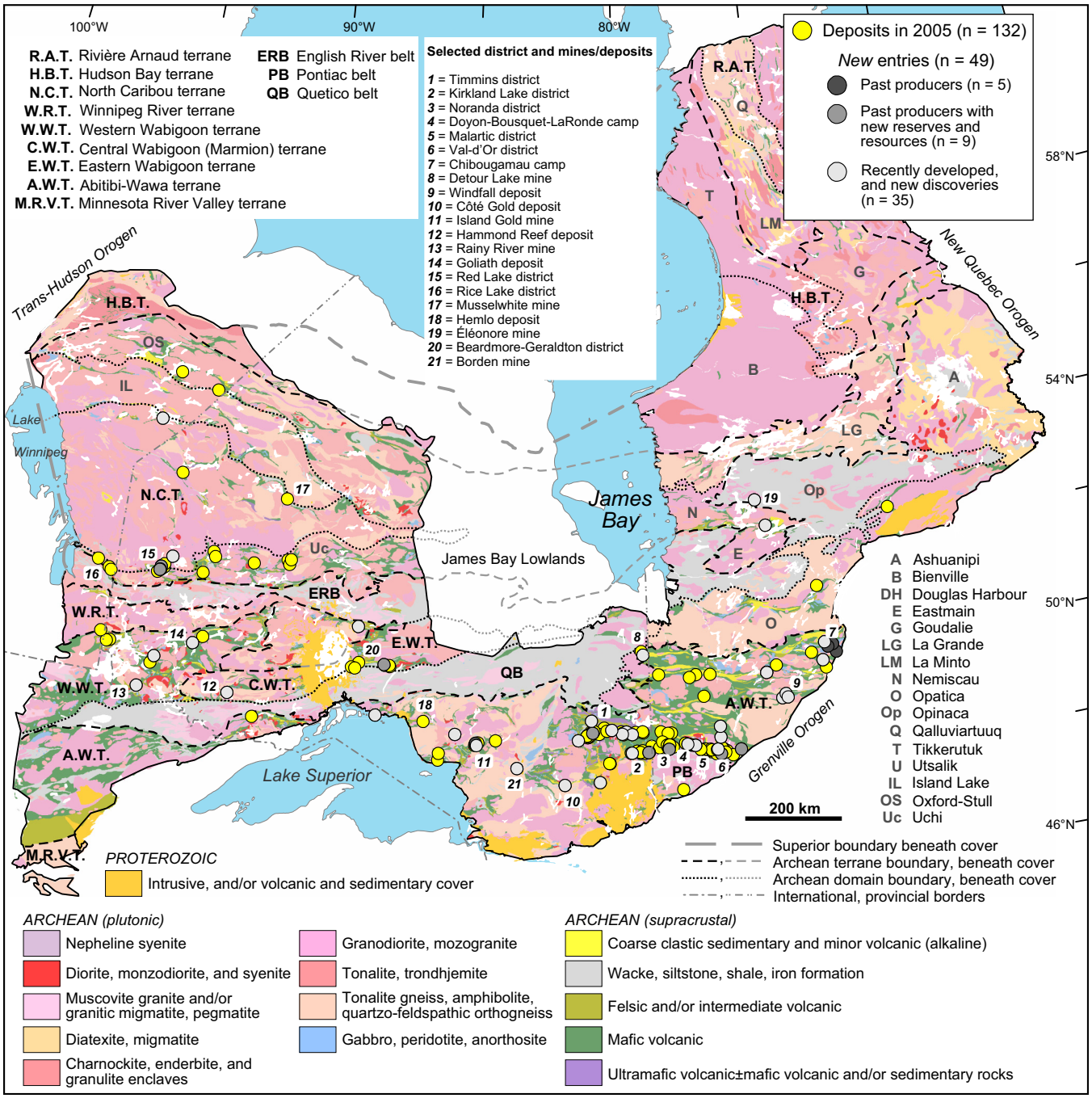

Figure 8. Bedrock geology compilation of the Superior Province (*from* Percival et al., 2012) showing the location of the gold deposits with ≥100,000 ounces. Yellow dots are the deposits that were included in Gosselin and Dubé (2005b, 2015) compilation. Grey dots are the 49 new entries (dark grey = past producers that were not included in the 2005 gold database; medium grey = past producers with significant new reserves and/or resources; pale grey = recently discovered deposits that were put into production since 2005, or for which significant gold ounces were added since 2005, and new discoveries made after 2005) (*see* Fig. 7 for details about the new entries).

prospective, in agreement with previously reported data (e.g. Hodgson and MacGeehan, 1982; Robert et al., 2005; Dubé and Gosselin, 2007). Intrusive and sedimentary rocks are associated with 113.6 million ounces (3533 t: 26% of the total gold) and 84.8 million ounces (2638 t: 19% of the total gold), respectively (Fig. 10b). The importance of volcanic rock-dominated, and to some extent sedimentary rock-dominated successions as the main hosts to gold becomes even greater when data are "normalized" relative to rock-type abundance, using the surficial area as a proxy. The best gold-bearing terranes all have a greater ratio of volcanic and sedimentary rocks to intrusive (and gneiss) rocks than the entire Superior Province (Fig. 10c). The Abitibi-Wawa terrane is the best endowed in terms of total gold and total number of deposits (Fig.

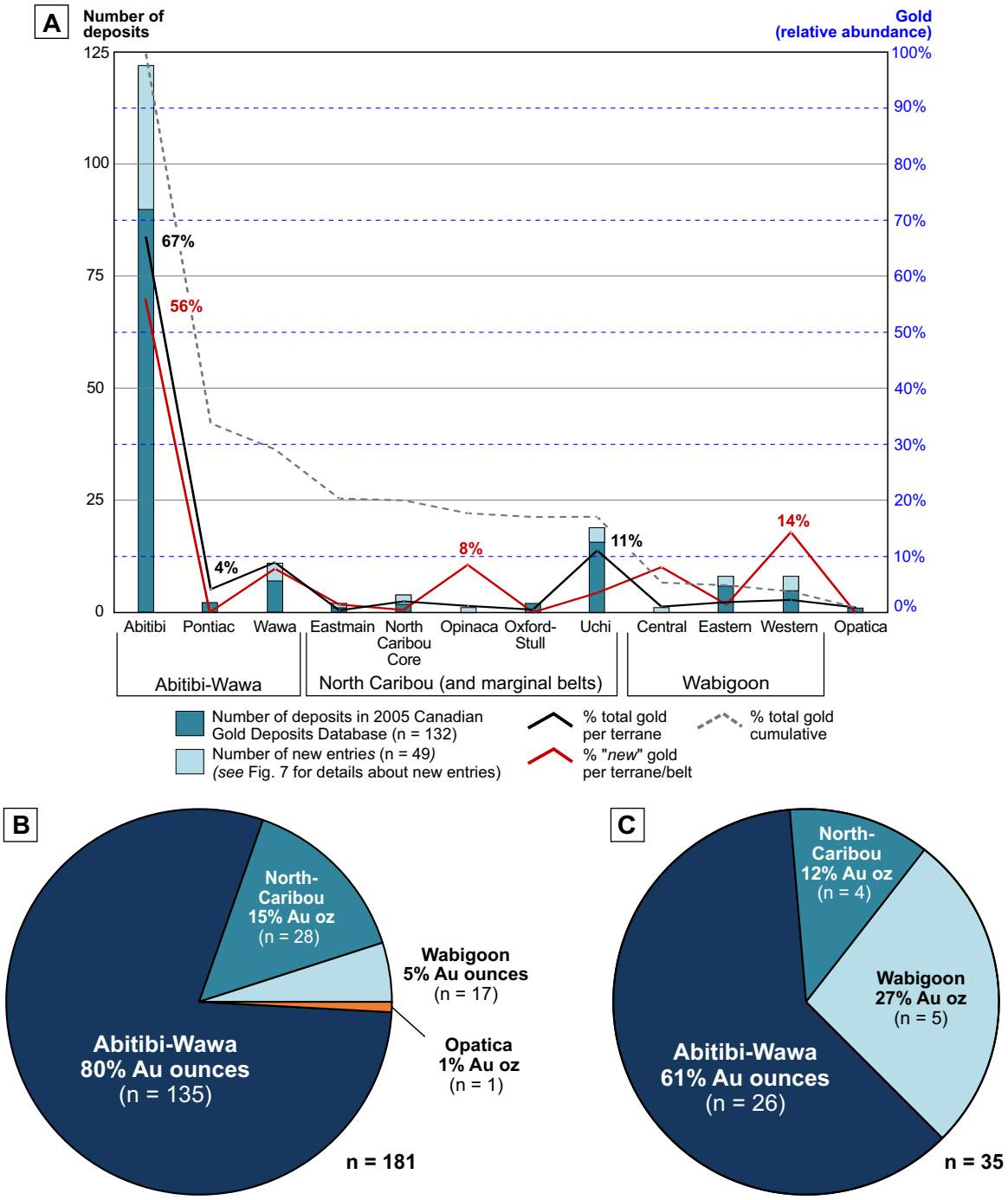

Figure 9. Location and gold content of the deposits of the Superior Province. **a)** Total number and total gold proportion per terrane for deposits with ≥0.1 million ounces (3.1 metric t) gold (n = 132; production, reserves, and measured and indicated resources) that were included in the Canadian Gold Database in 2005 (*see* Gosselin and Dubé, 2005b), which have since been revised and updated, and for new entries made in this compilation (n = 49 new entries, *see* Fig. 7). **b)** Total gold content and deposits per subprovince (n = 181). **c)** Total gold content and deposits per subprovince for the new entries (post-2005: n = 49).

8), but it is also recognized as the best preserved and largest Archean greenstone belt in the world. It contains approximately 50 kilograms of gold per square kilometre, which is six times more than the western part of the Wabigoon Subprovince and 10 times more than the North Caribou terrane that is largely dominated by intrusive and gneissic rocks (Fig. 8, 10c). Again, it must be noted that this analysis is preliminary and does not take into consideration that most gold deposits are not hosted in more than one lithology. Further work is under way to properly scale gold endowment against rock type and gold endowment versus regional tectonostratigraphic units. For example, many of the orogenic gold deposits in the Abitibi greenstone belt are spatially associated with panels of synorogenic conglomerate, which represent only a

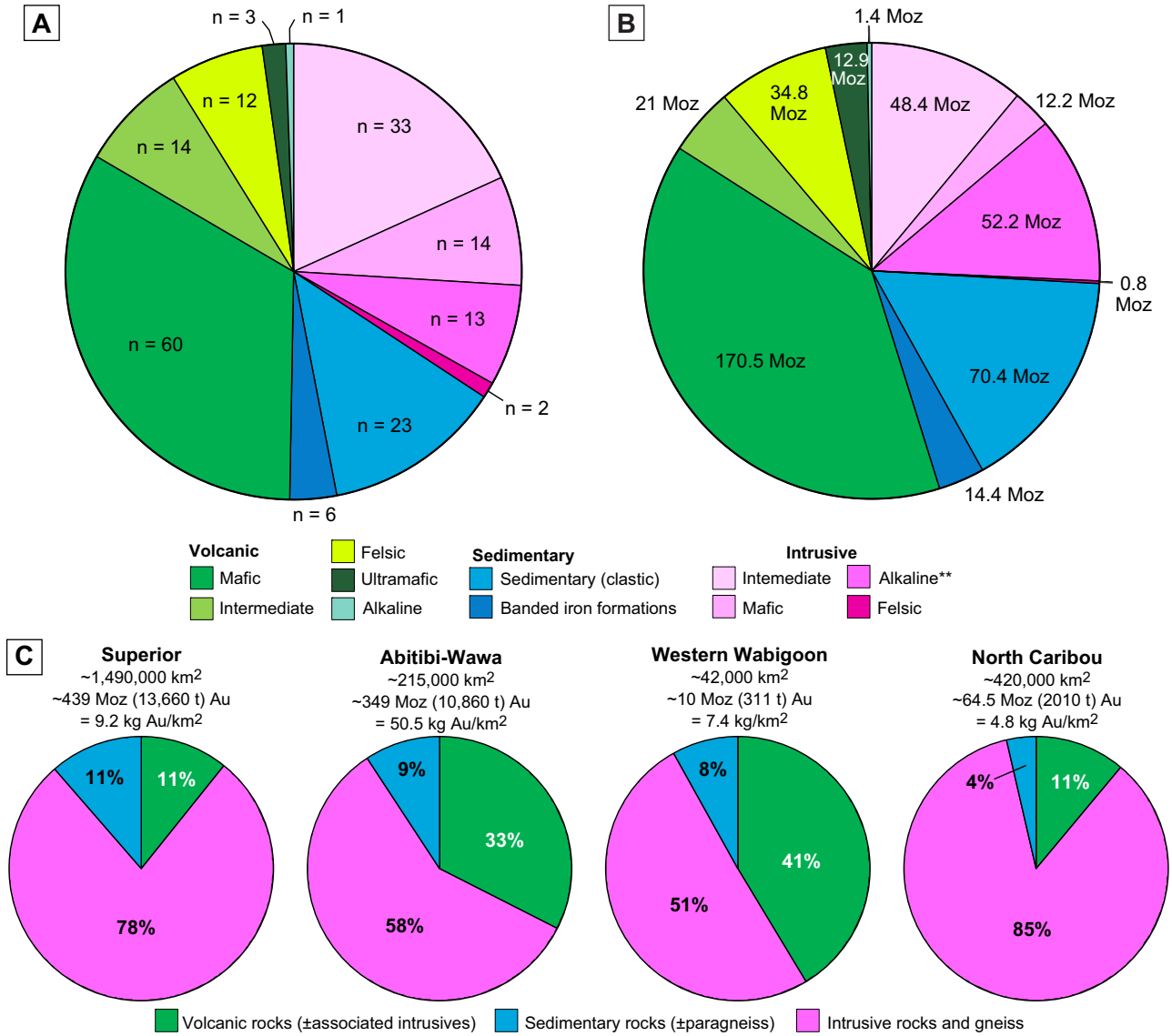

Figure 10. a) Total number of gold deposits in the Superior Province with ≥0.1 million ounces (3.1 metric t) gold (n = 181) versus the dominant host lithology. **b)** Total gold content is in million ounces (Moz) versus the deposit's dominant host lithology. The data in (a) and(b) include production, reserves, and resources (measured and indicated). Inferred resources are not included. **this also includes intrusive rocks that are subalkaline but which are often associated with the alkaline intrusive rocks (*see* Dubé and Mercier-Langevin, in press, for details about these intrusive rocks). **c)** Relative proportion of volcanic, sedimentary, and intrusive rock types in the Superior Province, Abitibi-Wawa terrane, Western Wabigoon Subprovince, and North Caribou terrane. Total surface estimated from the map of Wheeler et al. (1996). Values given here represent estimates and include only the Canadian part of the Superior Province. Gold "endowment" can be roughly estimated from these data, showing that the Abitibi-Wawa terrane favourably compares to other mineralized parts of the Superior Province. Except for the Western Wabigoon, volcanic and sedimentary rocks are not as abundant (based on surface exposure) as intrusive rocks but tend to be more commonly the main host lithologies for gold deposits.

minor proportion of all rock types in the belt. Similarly, Algoma-type banded iron formation generally represent a minor component of Archean sedimentary successions but appear to be associated with a significant number of large gold deposits.

The revised database of known deposits and the newly discovered deposits exemplify the broad range of auriferous ore styles and highlight the previously underestimated potential of certain areas of the Superior Province (Dubé et al., 2015). The updates to the gold database will provide key information about the distribution and gold content of known deposits and will be complemented, in specific cases, by recent geological knowledge. The classification of ore styles through common geological and genetic characteristics of individual deposits is on-going. The overall end-product will provide a useful framework for thematic studies investigating potential source(s), conduits, and processes at the depositional sites for gold mineralization in the Superior Province.

ADVANCING CANADIAN GOLD MINERAL SYSTEM MODELS

Context

Gold deposits are the final product of multiple processes that pre- to post-date the main stage(s) of ore formation and operate across a range of spatial scales (Fig. 1). Many aspects of the complete pathways from source to ore of these systems remain unanswered despite decades of research (*see* Boyle, 1988). For the Gold Project, the framing question was, what are the essential controls on the formation of gold mineralization? Or more specifically, by what cause and how did the most favourable conditions develop at specific times and locations? A large proportion of TGI-5 research activities focused on orogenic gold mineralization. However, several studies identified multiple overprinting styles of gold mineralization, even within a single deposit. The multi-phase character of gold deposits and districts that were identified as part of TGI-5 present a challenge for the ore system approach because the processes and critical time window for ore formation may vary during each evolutionary stage of an ore system (Fig. 1). As a result, a single deposit may represent the final product of multiple passes through the critical ore-forming window at different times (Fig. 1). Progress on these key questions and other gold ore system knowledge gaps that were addressed as part of TGI-5 are described below.

Sources and Transport Mechanisms

Two important questions remain largely unanswered for most gold ores systems: 1) what is/are the source(s); and 2) what are the different extraction and transport mechanisms. Some initial forms of gold enrichment, either at or below the seafloor have been clarified in the last few decades through the study of fossil and modern seafloor VMS deposits (e.g. Hannington et al., 1999; Huston et al., 2000; Dubé et al., 2007a). Modern examples have been particularly important because they demonstrated that gold-enrichment processes are clearly synvolcanic and therefore unequivocally not related to overprinting metamorphism and deformation during ocean basin closure. Results from past phases of TGI suggested that similar processes were also responsible for the precious metal endowment of some ancient gold-rich VMS deposits (e.g. LaRonde Penna: Dubé et al., 2007b; Mercier-Langevin et al., 2007a,b; Bousquet 2-Dumagami: Dubé et al., 2014; Lemoine: Mercier-Langevin et al., 2014b; Westwood: Yergeau et al., 2015; Lalor: Caté et al., 2015).

Multiple interpretations to explain synvolcanic gold enrichment at these early or syngenetic deposits have been proposed (e.g. inherently enriched source and fluids, direct magmatic input, efficient transport and capture, boiling, zone refining, etc.: Hannington et al., 1999; Huston, 2000; Dubé et al., 2007a; Mercier-Langevin et al., 2015; Gartman et al., 2018). As part of TGI-4 and -5, an empirical association has been established between Archean synvolcanic gold deposits (including many of the world's best examples of gold-rich VMS deposits) and transitional to calc-alkaline felsic magmatic centres (e.g. Mercier-Langevin et al., 2011, 2015). The temporal and spatial relationships between ore-forming fluids and shifting volcanic rock compositions (i.e. from tholeiitic, mid-ocean ridge basalt (MORB) to enriched mid-ocean ridge basalt (E-MORB) style to crustal-contaminated, mid-crustal calc-alkaline magmatism) suggest that the gold content of a VMS deposit might be related to, at least in part, underlying igneous petrogenetic processes. Krushnisky et al. (2020) added to the list of major gold-rich VMS deposits associated with transitional to calc-alkaline volcanic rocks by showing that the giant Horne and Horne 5 deposits are hosted in rocks of similar composition. Boily-Auclair et al. (2020) provide further evidence for a possible link between the magmatic evolution of Archean volcanic centres and the formation of synvolcanic gold deposits by showing that the onset of the gold-rich hydrothermal activity in the central part of the Doyon-Bousquet-LaRonde mining camp coincided with a transition from tholeiitic to transitional to calc-alkaline magmatism. This association between igneous petrogenesis and metal endowment may also be true for other precious metals such as silver, as indicated by the work of Fayard et al. (2020a,b) at the B26 project in the Brouillan calc-alkaline volcanic centre in the northern Abitibi belt. Ongoing work on the Archean synvolcanic gold deposits of the southern Superior Province (e.g. zircon geochronology and geochemistry) will help to improve our understanding of the potential genetic relationships between igneous petrogenesis and synvolcanic gold, at least in Archean settings.

Sedimentary rocks and their associated diagenetic sulphides represent another form of early gold enrichment in the upper crust. Pyrite nodules in carbonaceous to non-carbonaceous argillite units intercalated with volcanic flows of the Abitibi greenstone belt (e.g. Kidd-Munro, Tisdale, and Blake River assemblages) and deep basin-related settings (e.g. Porcupine) yield gold concentrations that range from a few ppb to 10s of ppm (Pilote et al., 2019a,c, 2020b,c). New TGI-5 research demonstrates that these gold-rich pyrite domains are genetically related to early pyrite crystallization rather than gold-upgrading during later hydrothermal and/or metamorphic overprinting. The factors controlling syn-sedimentary and/or diagenetic gold enrichment remains equivocal, but preliminary results suggest that sediment provenance (source)

could be one of the primary factors (Pilote et al., 2019a,b). The metal signature and budget of pyrite nodules, at least for those formed in interflow argillite, also appear to be controlled by syn-sedimentary enrichment from "distal" VMS vents. Pyrite nodules at the LaRonde VMS deposit (Blake River assemblage) provide such evidence, with a primary VMS-style trace metal enrichment (e.g. Au, Zn, Sn), which was likely inherited from the host sediments that were initially enriched in trace metals due to nearby synvolcanic hydrothermal activity (Pilote et al., 2020c).

The preliminary results and on-going TGI-5 research cited above demonstrate that parts of the greenstone belts that host orogenic gold deposits were pre-enriched in ore components. The large time gap between initial gold enrichment and the main phase of orogenic gold is one of the complicating factors that obscures the ultimate source of ore components for most orogenic gold districts and deposits. Orogenic gold deposits postdate their host rocks by 10s to 100s of millions of years, which indicates that the drivers of initial synvolcanic and/or syn-sedimentary gold-enrichment processes are unrelated (i.e. different geological setting) to late-stage orogenic gold systems.

The conventional view on the formation of orogenic gold deposits is that they are genetically related to metamorphic fluids that liberate gold from local volcanic and/or sedimentary rocks during the transition from greenschist- to amphibolite-facies metamorphism (e.g. Card et al., 1989; Colvine, 1989; Craw and Koons, 1989; Hagemann and Cassidy, 2000; Ridley and Diamond, 2000; Goldfarb et al., 2005; Goldfarb and Groves, 2015; Pitcairn et al., 2017, 2019). A growing number of studies further suggest that sedimentary sulphides and pyritic argillite act as one of the possible pre-enriched source rocks for gold and sulphur during metamorphism (e.g. Chang et al., 2008; Large et al., 2011; Tomkins, 2013; Steadman et al., 2015; Gregory et al., 2016; Selvaraja et al., 2017). If correct, the sedimentary source model would predict that the metal endowment of orogenic gold deposits is dependent, at least in part, on the distribution of these favourable sedimentary source rocks. Pilote et al. (2020a) address this question using field mapping, trace element chemistry, and multiple isotope tracers of sedimentary (e.g. nodules), ore vein-associated, and non ore-related metamorphic pyrite from the Timmins-Porcupine district. Complete isotope results are pending; however, preliminary results from triple sulphur isotopes indicate that ore vein-associated pyrite at the Bell Creek, Bradshaw, and Pamour orogenic gold deposits have non-zero mass independent fractionation values (negative and positive). These preliminary results suggest that atmospheric-derived sulphur (sequestered in sediments as S_8 or SO_2) was incorporated into the mineralizing fluids in addition to any possible magmatic input. Moreover, the restricted range of isotope compositions (in both $\delta^{34}S$ and $\Delta^{33}S$) from the ore vein-associated pyrite plots in the centre of the much broader isotopic signature field defined by pyrite nodules (negative $\delta^{34}S$ and $\Delta^{33}S$ array). In contrast, non ore-related metamorphic pyrite defines a broad positive $\delta^{34}S$ and $\Delta^{33}S$ array that is unlike the sedimentary or ore vein-associated pyrite types, and more akin to the "Archean reference array" (e.g. Thomassot et al., 2015). The restricted range of measured values in ore vein-associated pyrite and their overlap with the field defined by the pyrite nodules could be explained by mixing between the ore-forming fluid and the sedimentary rock S-isotope values at depth (cf. LaFlamme et al., 2018). If correct, this would imply that diagenetic (sedimentary) pyrite is likely to have contributed ligands (sulphur) to the ore-forming fluid through metamorphic recrystallization of sulphides at depth in the crust. This work and complementary isotopic analyses (e.g. Pb and Fe isotopes) will shed further light on the potential role of (or absence thereof) sedimentary pyrite in the genesis of orogenic gold deposits.

The southern Abitibi greenstone belt contains numerous orogenic and synvolcanic gold deposits, suggesting some sort of genetic relationship between these ore systems. If correct, this would provide a possible explanation for the exceptional prospectivity of this specific area (e.g. Hutchinson, 1993). For example, the corridor defined by the Larder Lake-Cadillac and Destor-Porcupine fault zones, often referred to as the southern Abitibi gold belt, hosts approximately 85% of the orogenic gold of the whole belt and also about 90% of the synvolcanic gold (e.g. Mercier-Langevin et al., 2014a; Dubé and Mercier-Langevin, in press). The spatial relationship between both ore systems has previously been used as evidence to suggest that gold in orogenic deposits was locally sourced (i.e. from pre-existing synvolcanic deposits) (e.g. Hutchinson, 1993). However, this is incompatible with the fact that synvolcanic gold deposits are gold-rich and that most mass balance estimates for sulphur and gold within pre-enriched volcanic rocks, where available (e.g. Detour deposit: Dubosq et al., 2018), typically conclude that an external source is required for some of the gold. Giant gold deposits also occur in the absence of significant synvolcanic/syngenetic gold deposits (e.g. Red Lake district, Ontario: MacGeehan and Hodgson, 1982; Pirie, 1982; and Homestake, Black Hills, South Dakota: Paterson et al., 1990), which casts additional doubt over the role of older synvolcanic deposits on the total metal endowment of orogenic gold districts. Even if the early synvolcanic mineralization or the pre-enriched volcanic rocks were the ultimate source of gold in later metamorphic fluids, it still would not

explain the exceptional endowment and provinciality of synvolcanic gold in the southern Abitibi belt and its preservation during later orogenesis.

Debate over gold transport mechanisms also contributes to uncertainty over the ultimate source of ore components in these systems. The conventional view is that metamorphic fluids that are released during the transition from greenschist- to amphibolite-facies metamorphism are the primary transport mechanism for gold (e.g. Hodgson and Hamilton, 1989; Hodgson, 1993; Goldfarb et al., 2005; Dubé and Gosselin, 2007; Phillips and Powell, 2009). This inference is fully consistent with the pressure and temperature conditions of most auriferous veins and the trace element and isotopic compositions of their fluid inclusions (Bodnar et al., 2014; Prokofiev et al., 2019). Bulk-rock gold concentrations that decrease systematically with increasing metamorphic grade provide additional support for gold mobility during metamorphism (Pitcairn et al., 2017). However, some gold deposits that are metamorphosed to mid-amphibolite facies, including examples from the Paleoproterozoic Lynn Lake greenstone belt (Lawley et al., 2020c), preserve auriferous veins that predate peak metamorphism. These early-stage veins suggest that syn-peak amphibolite-facies metamorphic fluids are, at least in some cases, ineffective at transporting gold from their original depositional site. The apparent limited mobility of gold during metamorphism is further evidenced by minor, small-scale (millimetre to metre scale) remobilization of gold in several Abitibi deposits metamorphosed up to upper greenschist facies (e.g. Horne 5: Krushnisky et al., 2020; B26: Fayard et al., 2020b; LZ5: Boily-Auclair et al., 2020; LaRonde Penna and Timmins auriferous pyrite nodules: Pilote et al., 2020b,c). Similarly, research on gold deposits in Nunavut further suggests that although metamorphic fluids and/or synmetamorphic polymetallic melts (Bi-Te-Au-Ag) may remobilize and/or upgrade gold from pre-peak metamorphic veins into high-grade and late-stage ore shoots (e.g. Lawley et al., 2017), precious metals do not appear to be transported over long distances during the greenschist- to amphibolite-facies transition (e.g. Janvier et al., 2015; Lawley et al., 2015; Mercier-Langevin et al., 2018; Lauzon et al., 2020; Valette et al., 2020). The rare examples of larger scale metamorphic remobilization (e.g. 10s of metres at the Lalor VMS deposit, Snow Lake: Caté et al., 2015; Caté, 2016; Lam, 2019) indicate that gold transport is limited to short distances during metamorphism, even at amphibolite grade in highly favourable conditions (e.g. H_2O and CO_2-rich rocks and gold- and trace metal-rich sulphides at the Lalor mine). Similar features were documented at the former Montauban mine in the Grenville Province (Jourdain et al., 1987; Tomkins, 2007). The Roberto deposit (Éléonore mine) has also been overprinted by upper greenschist-facies metamorphism and except for evidence of recrystallization, changes in the mineralogy, and local remobilization, gold does not appear to have been mobilized on a large scale (Fontaine et al., 2017; Fontaine, 2019). The Borden deposit is hosted in upper amphibolite- to granulite-facies rocks exposed along the Kapuskasing structural zone in Ontario. The deposit, located west of Timmins, is associated with a panel of Timiskaming-age metaconglomerate dated at ≤2667 ± 2 Ma (Krogh, 1993). Gold at the Borden mine is interpreted to have been introduced late during granulite- to amphibolite-facies retrogression and associated deformation based on its spatial association with late overprinting structures that are developed at the contact between preserved lenses of competent granulite-facies rocks and softer amphibolite-facies rocks after 2629 Ma (Lafontaine, 2016; Bouvier et al., 2017). Interestingly, Hf isotopes from Borden indicate that the protolith of the ore-associated biotite-garnet gneiss, host to recrystallized and deformed laminated auriferous veins, is probably a hydrothermally altered mafic rocks (Bouvier et al., 2017). This, combined with the presence of Timiskaming-age conglomerate and pelite in the host sequence, along the interpreted eastern extension of the Larder Lake-Cadillac fault zone (Leclair et al., 1993), may suggest that gold was present, at least in part, prior to peak metamorphism and has been locally remobilized during granulite-facies metamorphism and retrogression to amphibolite facies (Dubé and Mercier-Langevin, in press). This scenario, although in disagreement with the currently interpreted timing of gold introduction at Borden (*see* Bouvier et al., 2017), suggests that even at granulite facies, gold may not be remobilized over major distances. These examples of strongly metamorphosed gold deposits indicate that specific conditions, specific timing of events, or a combination of both are necessary to mobilize gold on a large-scale during metamorphism.

Magmatic fluids represent an alternate gold transport mechanism that is known to play an important role in some gold ore systems, including synvolcanic gold deposits in the southern Abitibi greenstone belt described above. The role of magmatic fluids in the genesis of orogenic gold deposits is less certain. New TGI-5 research highlights important differences between the timing of magmatic activity and the formation of most orogenic gold deposits (Castonguay et al., 2020a,b; Honsberger et al., 2020b; Lawley et al., 2020c; Pinet et al., 2020b; Dubé and Mercier-Langevin, in press). In fact, the timing of peak gold deposition in most accretionary settings is concomitant with a distinct lull in magmatic activity after the cessation of subduction (Bierlein and Crowe, 2000; Kerrich et al., 2000). Intrusive bodies that are interpreted to be

coeval with gold deposition tend to be smaller plutons, plugs, and/or dykes (e.g. Burrows and Spooner, 1989; Perring et al., 1989) that represent relatively minor parts of the gold deposits' host succession. They are unlikely to represent a major contributor to the total endowment of entire gold districts, but rather are a manifestation of larger magmatic systems at depth and part of important thermal/metamorphic perturbations (e.g. Fyon et al., 1989; Cameron, 1993; Bleeker, 2015). The evolution in the geochemical composition of pre-, syn-, and post-orogenic magmatism is thus likely an important proxy for the drivers and overall tectonic setting of orogenic gold deposits (Fyon et al., 1989; Kerrich et al., 2000). The tectonic evolution of the host successions is otherwise difficult to determine from the older host greenstone belts alone, and a subject of debate in itself (e.g. subduction versus subcretion tectonics in the Archean: Percival et al., 2012; Polat et al., 2015; Bédard, 2018). The isotopic signature and trace element composition of the alkalic rocks found in proximity to gold deposits suggest that the alkalic magma interacted with previously modified lithospheric mantle during ascent, which likely occurred during a phase of crustal extension. A similar setting is proposed for younger gold districts such as the Deseado Massif, an epithermal gold district in southern Argentina, where enriched domains of the upper mantle and/or lower crust are interpreted to have been a reservoir of gold that was tapped at different times throughout the tectonic evolution of the region (Tassara et al., 2017, 2018). New TGI-5 results demonstrate that some of these modified lithospheric mantle domains are up to 10x enriched in gold and other ore components relative to the primitive mantle (i.e. the expected composition of the mantle prior to crust extraction) and the continental crust (Lawley and Kjarsgaard, 2020 and references therein). The contribution of these pre-enriched lithospheric mantle domains to ascending alkalic melts is not fully understood, although oxidation of the ascending alkalic melts through interaction and surrounding mantle appears to enhance melt fertility by helping scavenge gold from previously modified areas of the sub-continental lithospheric mantle (Lawley et al., 2020a; Tassara et al., 2020). The degree of enrichment (10x continental crust) of those mantle domains is however modest relative to the exceptional gold grades observed at almost all orogenic gold deposits (1000x continental crust), suggesting that multiple gold concentrating mechanisms are likely involved during transport and/or deposition.

Drivers, Conduits, and Traps

The common occurrence of alkalic rocks, sanukitoids, and lamprophyres along major deformation zones that host orogenic gold deposits points to a specific orogenic stage that is critical in the development of auriferous systems (Dubé and Mercier-Langevin, in press, and references therein). Upwelling asthenosphere and interaction with lithospheric mantle is the most likely driver of alkalic magmatism, and the switch from crustal shortening to extension is likely responsible for transferring deep-seated melts and fluids into the mid- to upper-crust (e.g. Hodgson and Hamilton, 1989; Cameron, 1993; Robert et al., 2005; Bleeker, 2015). This extensional phase postdates the initial assembly and deformation of the host greenstone belts but predates the peak of crustal thickening, which, in some cases, ultimately led to late-stage crustal-derived melts (e.g. pegmatite and peralkaline granite). Upwelling asthenosphere is also likely important for transferring heat to the overlying crust, driving auriferous fluids along crustal-scale faults (e.g. Fyon et al., 1989; Perring et al., 1989), and may also provide a possible mechanism for the high-temperature and low-pressure metamorphism that is typically related to gold ore systems (e.g. Bleeker, 2015).

TGI-5 research has provided new multidisciplinary, field-based observations and data sets, including high-precision geochronology to better define the geological and metallogenic settings and sequencing of events in other prospective belts such as the central Newfoundland Appalachians, the northern Abitibi greenstone belt, and parts of the Canadian Cordillera. Gold in these study areas is related, at least spatially, to long-lived faults or deformation zones with a polyphase kinematic evolution.

In Newfoundland, Paleozoic gold mineralization and fluid-pressure cycling with associated devolatilization were coincident with crustal-scale re-imbrication and thickening between ca. 415 and 405 Ma, which occurred subsequent to a phase of extension-related synorogenic bimodal magmatism between ca. 430 and 418 Ma (Honsberger et al., 2020b). The authors compare this evolution with that of the Archean Abitibi greenstone belt and consider both districts to have undergone a very similar history in terms of sequential key events and pacing, reinforcing the notion that crustal/lithospheric thinning, synorogenic magmatism, and structural re-imbrication are critical for generating and preserving orogenic gold systems in the footwall of crustal-scale fault zones. The timespan between the onset of extension, uplift, thrust imbrication, and the main phase of mineralization is approximately between 20 and 30 million years in the Abitibi belt and in Newfoundland, as well as in Proterozoic rocks of the Lynn Lake belt in Manitoba, and is followed by late granitic magmatism and possible late-stage mineralization that extends for a few 10s of million years (Honsberger et al, 2020a; Lawley et al., 2020c).

The development of the poorly exposed, but prospective northwestern part of the Abitibi greenstone belt is similar to the inferred evolution of its exceptionally well endowed southern part. There, major, long-lived deformation zones (Sunday Lake and Lower Detour) are spatially related to structurally controlled gold deposits, such as the giant Detour Lake gold mine (Castonguay et al., 2020a, and references therein). These deposits occur as disseminated gold, or gold-bearing veins, within highly strained mafic volcanic and intermediate to felsic, commonly alkaline, plutonic rocks. The deformation zones, which are locally delineated by bands of polimict conglomerate, juxtapose volcanic rock packages against younger sedimentary rocks, indicating a polyphase structural evolution (i.e. basin-bounding extensional faults inverted as reverse faults). Although these fault zones are steep to sub-vertical, gold mineralization mainly occurs in the apparent structural hanging walls (as opposed to footwalls in the southern Abitibi belt). The syn-thrusting geometry of these deposits was likely modified by steepening, overturning, and late-stage strike-slip faulting, which further complicated the structural setting of the mineralization.

Major fault zones represent one of the characteristic features of most gold districts, but not all auriferous faults have the same metallogenic history. The Canadian Cordillera represents another area to study the role of fault zones as conduits and traps of gold, especially in the lower metamorphic-grade (epizonal to mesozonal) parts of the orogen. The work of Castonguay et al. (2020b) and Pinet et al. (2020a,b) tackle different aspects of some of the various types of Cordilleran gold mineralization.

The Llewellyn-Tally Ho deformation corridor in northwestern British Columbia and southern Yukon is a long-lived deformation zone that is spatially associated with numerous gold deposits and prospects of various styles and ages (Castonguay et al., 2020b). As in the Abitibi belt, the Llewellyn-Tally Ho deformation zone has undergone a polyphase structural evolution, including early (Late Cretaceous and older) ductile reverse faulting that is associated with coeval plutonism and intrusion-related and shear-hosted gold mineralization. Eocene transpressional deformation subsequently reactivated parts of the deformation zone as brittle dextral strike-slip faults, which are associated with volcanic complexes and epithermal gold mineralization (Ootes et al., 2018, 2019). This setting differs from the Abitibi greenstone belt in that both the pre-metamorphic extensional faulting and the late brittle-ductile structural event are devoid of preserved epithermal-style gold mineralization, even for fault zones that demarcate conglomerate-filled synorogenic basin remnants with minor subsequent exhumation and erosion. Such first-order comparisons not only highlight similarities, but also differences (e.g. preservation control) in the structural and metallogenic evolution of these major structural corridors.

The shifting tectonic regime that is common to several ancient gold ore systems is also suggested by new TGI-5 research on younger gold mineralization of the Rackla belt (Yukon; Pinet et al., 2020a,b). These gold zones represent some of the best examples of Carlin-type, sediment-hosted micron gold mineralization outside of Nevada. Like Carlin-type deposits, gold mineralization in the Rackla belt is much younger than the Neoproterozoic to mid-Paleozoic host rocks. However, Carlin-type deposits in both Nevada and central Yukon represent the end-product of long-lived, tectonically mature systems in which the host-succession permeability and fluid focussing were locally enhanced through repeated sedimentary and tectonic processes (*see* Muntean, 2018, and references therein) that led to a favourable upper crustal architecture. In Nevada, mineralization is contemporaneous with a relatively short-lived geodynamic event that modified the thermal state and tectonic regime of the lithosphere (the "perfect storm of events" of Cline, 2018). In Yukon, only a few dykes have been documented in proximity to the gold zones, and the spatial and temporal link between mineralization and magmatism remains elusive at the district scale. Pending U-Pb age constraints on calcite from mineralized veins will address the potential association between mineralization processes and regional geological events such as magmatism and, consequently, further document the similarities and differences with the Carlin-type deposits of Nevada.

Gold Project's Contributions to Methodology Development

While understanding the complete source-to-ore pathways of auriferous fluids is the goal of the mineral system approach and is critically important for grassroots exploration, most of the mineral exploration activity occurs within established gold mining districts. The importance of near-mine exploration makes recognizing deposit-scale depositional controls from the rock record particularly important. As demonstrated by Grondin LeBlanc et al. (2017) and St.Pierre et al. (2020), these depositional controls also have the greatest influence on mine design and gold recovery. Wood (2018) wrote, "*once in operation, about 70% of mines perform below the prediction of their feasibility studies, with underperformance usually caused by deficiencies in the collection of primarily geology related data prior to designing the mine and planning its operation*", indicating that research at district- to deposit-scale is still required, especially at the early stages of exploration and mining. Such research, if timely, can

have a major impact. To address this, the TGI-5 Program not only generated the new geoscience as discussed above, but also is developing and testing new tools for the detection and delineation of ore system markers and vectors towards mineralized areas. These techniques (*see below*) have had a major impact on the research conducted as part of TGI-5 and have the potential to be further applied for mineral exploration targeting.

The Gold Project has stimulated and facilitated the development of new and improved methods for quantitative trace element mapping in the GSC's laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) laboratory. Improvements in the efficiency and optimization of the mapping protocol have resulted in the acquisition of element maps at higher spatial resolution or in less time than previously produced in the laboratory. Notable examples of this improved capability include the acquisition of nearly 1,000,000 multi-element data points for pyrite nodule-bearing samples from the Timmins-Matheson gold corridor (Pilote et al., 2020b,c), resolving gold-enriched pyrite rims (<4 µm in thickness) associated with Carlin-type mineralization in the Rackla belt in Yukon (Sack et al., 2019), and mapping the distribution of suspected native gold nanoparticles within samples of metasomatized mantle lithosphere (Lawley et al., 2020a).

Furthermore, data analytics tools and open-source workflows have been developed to process LA-ICP-MS results (Lawley et al., 2020a) and expand the capability of interrogating element maps (e.g. Lawley et al., 2020c; Pilote et al., 2020b,c). Applications of these advanced data analytics tools include extracting element data from mineralogically distinct features of interest (Sack et al., 2019), quantifying elemental relationships across multiple mapping experiments (Lawley et al., 2020a; Pilote et al., 2020b,c), and semi-automating the process of feature extraction for trace metal deportment at the micron-scale (e.g. Lawley et al., 2020a).

New processing code was also written to produce the first large-area map results by hand-held laser-induced breakdown spectroscopy (LIBS). The code was used to rapidly map the spectral signature of hydrothermal alteration minerals, including gold, related to gold-bearing quartz veins. Maps were acquired directly on the sawed surface of drill core. This technology represents an emerging tool for mineral exploration vectoring when combined with conventional geochemical analyses. Because the LIBS device is handheld, the same mapping approach can also be used in the field. Machine learning tools were also applied to convert qualitative LIBS concentrations to feature-of-interest maps that can be used to quantify the distribution of mineral vectors at the microscale (Harmon et al., 2019). In a separate study, the same advanced data analytics tools were used to distinguish ore-related and metamorphic biotite based on qualitative LIBS concentrations. Rapid acquisition of mineral chemistry on smooth, but otherwise untreated rock surfaces will certainly become a key geochemical vectoring tool.

A new, nano-powder analytical method was also developed for whole-rock analyses. This innovative method is based on wet-milling whole-rock powders to a median grain size of 0.7 to 2 µm followed by direct analysis of pressed powder pellets by LA-ICP-MS. Powdered reference materials that were reprocessed following this wet-milling approach indicate that major, trace, and ultra-trace whole-rock concentrations were in excellent agreement with their accepted values for most elements. Replicate analyses of these reprocessed reference materials show that measurement repeatability is only 2x less precise than glass reference materials for some elements, which represents a significant improvement over LA-ICP-MS analysis of the original, coarser rock powders. The nano-powder method was used to investigate enrichment of ore-forming elements in the upper mantle, which is normally challenging because of their low concentrations and heterogeneous distribution within rare accessory phases (Lawley et al., 2020b). Because the wet-milling method was miniaturized, the approach is also suitable for analyzing small-volume mantle xenolith samples (Kroner, 2019). Improved trace element determination of ore-forming elements has the potential to be further applied for studying cryptic geochemical footprints in other poorly mineralized rocks.

The next scientific and technical advances in the understanding of gold systems will most probably involve obtaining better resolution on the timing of tectonic, magmatic, metamorphic, and hydrothermal events (at all scales) that lead to the formation of gold deposits. In the Rackla belt, resolving the timing of mineralization was hampered by a lack of traditionally suitable minerals to date (e.g. arsenopyrite, hydrothermal titanite, xenotime, or monazite). Instead, Pinet et al. (2020a,b) have chosen to use in situ U-Pb dating of calcite at Rackla, where mineralization is associated with abundant calcite veining. In situ LA-ICP-MS U-Pb dating of calcite is a relatively new method that holds much promise for determining the age of mineralization and associated geological events. Carefully selected samples were analyzed at different spot sizes (160 and 210 µm diameter) through several analytical sessions, with reproducible results. Notably, the results of this work have been used to establish a preliminary age for the timing of gold mineralization at Rackla. Some of the samples revealed a complex record, as

indicated by a large spread in isotope ratios. This variability has been explained by multiple generations of calcite growth, isotopic mixing, and/or partial resetting of U-Pb ratios (i.e. open system behaviour). Extracting meaningful ages from this complex data has been made possible through detailed petrographic characterization, before and after U-Pb analyses, and by carefully establishing each sample's geological setting. The following list of ideal conditions for successfully dating calcite have been identified through this work: 1) samples with distinguishable generations of calcite; 2) a closed isotopic system; and 3) calcite that inherited variable proportions of common Pb during formation (i.e. significant spread data along an isochron). Improved sample targeting, using imaging techniques such as cathodoluminescence microscopy and LA-ICP-MS element mapping, allow for the identification and targeting of a uniform growth zone in complex samples (i.e. areas with no evidence of vein re-opening, diagenetic/metamorphic overprint, or cement dissolution-reprecipitation). Current development at the GSC includes targeting calcite with smaller spot size (e.g. Petts et al., 2019), which may further reduce variations and limitations due to micro-scale heterogeneity of the targeted samples. U-Pb dating of calcite will become a valuable tool in studying ore deposits.

Calcite clumped-isotope thermometry was also applied to the Rackla belt mineralized samples (N. Pinet et al., unpub. isotopic data, 2020). This technique does not require the initial isotopic composition of the parent water to estimate the temperature of crystallization, which is a major advantage relative to classic stable isotopic studies. The technique had previously been applied to low-temperature systems and complex calibrations and protocols had to be established to obtain reliable experimental data up to 725ºC. Though clumped isotope results can be partially or fully reset at temperatures above 100ºC (i.e. via solid-state reordering), such as during diagenesis, the application of thermal history reordering models can provide insights on the extent (i.e. temperature and duration) of the re-equilibration that may have occurred after primary crystallization. This technique has excellent potential to further constrain the conditions of ore formation.

The Contribution of the Gold Project to the Training of Highly Qualified Personnel (HQP)

Training and mentoring of students and post-doctoral researchers (HQP) represents one of the core objectives of the TGI-5 program. As such, the Gold Project has directly supported three undergraduate thesis projects at Université Laval (Dubé, 2016; Boily-Auclair, 2017; Lauzon, 2017), ten M.Sc. research projects (three completed: Krushnisky, 2018 at Institut de la Recherche scientifique – Centre Eau Terre Environnement; Ciufo, 2019 and Jellicoe, 2019 at University of Western Ontario, and seven ongoing: Boily-Auclair, Grondin LeBlanc, and St.Pierre at Institut de la Recherche scientifique – Centre Eau Terre Environnement; Fayard at Université du Québec à Chicoutimi; O'Connor at University of Ottawa; Veglio at University of Alberta; and Watts at University of Windsor), and two Ph.D. research projects (Fontaine, 2019 at Institut de la Recherche scientifique – Centre Eau Terre Environnement; Valette, ongoing at Université du Québec à Montréal). Three post-doctoral fellows at the GSC in Ottawa and Québec (PRPs: J.-L. Pilote, I. Honsberger, and J. Jautzy) have been involved and were key in delivering three of the Gold Project's activities (Fig. 3). The Gold Project also supported TGI-4 Lode Gold students in completing the final stages of their M.Sc. and (Pelletier, 2016) and Ph.D. theses (Caté, 2016; Janvier, 2016; Oswald, 2018) at Institut de la Recherche scientifique – Centre Eau Terre Environnement. Numerous students and professionals were hired and trained as part-time support for many of the activities, among them are A. Abraham, E. Boily-Auclair, D. Diekrup, V. Janvier, A. Krushnsky, A. Laberge, and C. Gray.

CONCLUDING REMARKS

The stable supply of mineral commodities depends on the continued development of known resources (e.g. through optimized mining and recovery methods) and, critically, on the discovery of new mineral deposits. In the future, new mineral deposit discoveries will have to occur in established districts as well as in emerging camps and new areas, i.e., most likely in more remote, deeper, and/or buried geological settings. To address this demand, governments have invested in making pre-competitive geoscience data and improved ore-system models freely available to the public through programs like TGI-5. A subset of highlights from the TGI-5 Gold Project and its implications for advancing gold ore system models are described in this synthesis volume.

Our understanding of gold systems has evolved with time and with the exploration, discovery, and study of new or redeveloped gold deposits and districts. Our ability to establish the relative and absolute timing of events has also improved significantly. Very precise constraints are necessary to define the sequence of events that led to the formation of gold deposits. Therefore, properly establishing the key mechanisms and their interactions that ultimately resulted in forming and preserving a gold deposit depends on an in-depth understanding of the geological events and their evolution in both space and time. For example, fundamental questions such as the role of magmatism in some Archean gold deposits will only be answered

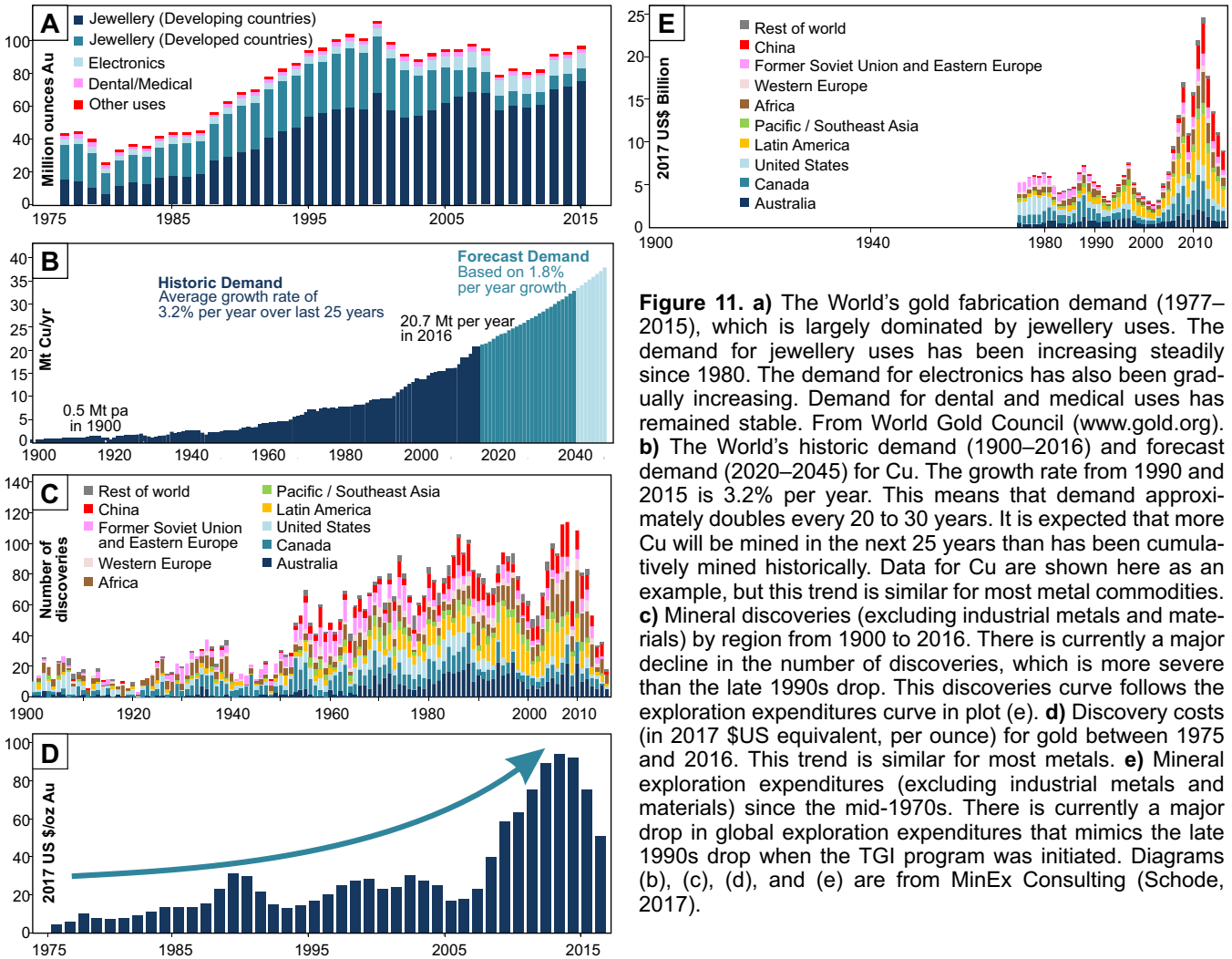

Figure 11. a) The World's gold fabrication demand (1977–2015), which is largely dominated by jewellery uses. The demand for jewellery uses has been increasing steadily since 1980. The demand for electronics has also been gradually increasing. Demand for dental and medical uses has remained stable. From World Gold Council (www.gold.org). **b)** The World's historic demand (1900–2016) and forecast demand (2020–2045) for Cu. The growth rate from 1990 and 2015 is 3.2% per year. This means that demand approximately doubles every 20 to 30 years. It is expected that more Cu will be mined in the next 25 years than has been cumulatively mined historically. Data for Cu are shown here as an example, but this trend is similar for most metal commodities. **c)** Mineral discoveries (excluding industrial metals and materials) by region from 1900 to 2016. There is currently a major decline in the number of discoveries, which is more severe than the late 1990s drop. This discoveries curve follows the exploration expenditures curve in plot (e). **d)** Discovery costs (in 2017 $US equivalent, per ounce) for gold between 1975 and 2016. This trend is similar for most metals. **e)** Mineral exploration expenditures (excluding industrial metals and materials) since the mid-1970s. There is currently a major drop in global exploration expenditures that mimics the late 1990s drop when the TGI program was initiated. Diagrams (b), (c), (d), and (e) are from MinEx Consulting (Schode, 2017).

once we have the necessary resolution in the timing of events, which is based on robust field observations and high-precision geochronological data. These field and laboratory data will translate into a series of parameters and diagnostic features that can be included in regional- to deposit-scale geological, genetic, and exploration models.

The TGI-5 Gold Project was successful in seeding and/or making significant improvement to a relatively large number of analytical methods. Advanced conceptual ore-system models, coupled with new or improved mineral-exploration methodologies, are essential for improving mineral-exploration targeting, particularly for deep deposits in remote areas with sparse geological data. This knowledge, and the improved skillsets associated with these scientific advancements, must however be transferred. Many of the students or early career researchers that participated in TGI-5 will go on to take leadership roles in the mining and mineral exploration industry. Field-based research activities play a critical role in the training of the next generation of highly qualified personnel (Gemmell, 2018). The long-term impact of the research continues, together with field-based training and mentoring opportunities since the beginning of the TGI Program in 2000, and represents the seminal impact of this government-led research.

At the time of writing, it is unclear whether the TGI program will be renewed or replaced. Nonetheless, geological surveys fulfil an essential role in providing objective and freely available pre-competitive geoscience information to inform land-use decisions, environmental management, and investments in mineral resources development (Duke, 2010). Government-funded research programs also complement new, collaborative, multidisciplinary, and industry-led mineral system research programs that tend to be shorter and, in some cases, comprise proprietary data sets. The global demand for metals keeps increasing (Fig. 11a,b), which will place additional pressure on governments to provide the mineral exploration and mining industry with these critical pre-competitive geoscience data sets. As discussed above, global demand is increasing at a time when new gold deposits are more difficult to find, as

demonstrated by the steep decline in the number of discoveries since 2010 (Fig. 11c; Kirwin, 2019) and higher discovery costs (Fig. 11d). The recent decline in exploration expenditures (Fig. 11e) is similar to that of the late 1990s when the TGI program was initially designed and launched, and suggests that governments must continue to invest in pre-competitive data sets. Innovative ways for meeting future resource demands are required, and geologists will need to become better explorers to find new deposits, requiring advanced knowledge, practical training, and tools (Kirwin, 2019). Similarly, sustainability in geoscientific research necessitates long-term investment to tackle major knowledge gaps and develop improved exploration models and tools. The Canadian Minerals and Metals Plan, a pan-Canadian collaborative (Federal, Provincial, and Territorial governments and industry) public geoscience strategy for mineral exploration should set the tone for future mineral resources-related research at the GSC.

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