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Regional gold-enrichment of conglomerates in Paleoproterozoic supergroups formed during the 2.45 Ga rifting of Kenorland

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A B S T R A C T

We describe the presence of Witwatersrand-type gold mineralization in Paleoproterozoic strata indicating this style of deposit is not confined to the Archean. The discovery of basal and intraformational conglomerate-hosted gold mineralization in the Huronian Supergroup's Mississagi Formation near Sudbury, Ontario, has indicated potential for Witwatersrand-type gold mineralization to occur also in early Paleoproterozoic basin fills on the Hearne, Wyoming and Karelian cratons. The Paleoproterozoic Hurwitz, Snowy Pass and Karelian supergroups, located on these cratons, are similar to the Huronian Supergroup on the Superior Craton, in terms of sequence and litho-stratigraphy, and maximum age of deposition. A review of the stratigraphy and past gold exploration from each supergroup has revealed each basin to contain similar fluvial poly- to oligomictic, pyritic conglomeratic strata with locally anomalous gold and/or uranium concentrations at stratigraphic levels that correlate to those of the Mississagi and Matinenda formations of the Huronian Supergroup.

Examination of gold and gold-enriched pyrite from the Mississagi Formation conglomerates suggests that specific point sources existed for most of the gold therein. Each of the above basins forms part of a larger contiguous continental rift system prior to the breakup of the supercontinent Kenorland at around 2480 Ma. As each basin fill was displaced to different geographic positions following this continental breakup and then subjected to separate orogenic and metamorphic overprints, the gold and uranium mineralization in each of the basins is unlikely to be of a common, post-depositional hydrothermal origin, but in all likelihood of a paleoplacer origin. It is suggested that this period of gold-enrichment is the result of truncation and reworking of underlying stratigraphically older units and/or from former gold deposits/occurrences and gold-enriched greenstone-dominated hinterlands. The omnipresence of detrital and/or syn-depositional pyrite in conglomerates of each basin reinforces the idea that a lack of atmospheric oxygen at the time of Kenorland rifting existed during their deposition and prior to the "great oxidation event". Our comparative analysis of Kenorland rift graben fills reveals that gold potential, which can be determined by the presence of detrital pyrite as observed at the Pardo project, should exist in all stratigraphic equivalents of the Mississagi and Matinenda formations where preferentially reworked fluvial conglomerates rest on an erosional unconformity and where a corresponding Au-enriched Archean hinterland existed.

1. Introduction

Strong interest in the change of Earth's atmosphere from anoxic to oxic conditions, known as the Great Oxidation Event (GOE), has triggered a significant amount of research on Paleoproterozoic basins from around the world. Today, it is widely accepted that the GOE took place between 2450 and 2220 Ma (Van Kranendonk et al., 2012). This major atmospheric transition constrains the occurrence of detrital pyrite and uraninite in Paleoproterozoic basins, an important attribute for Witwatersrand-type deposits that, if having been formed after the GOE, would have oxidized during deposition (Frimmel, 2005). Analysis of the Huronian, Hurwitz, Snowy Pass and Karelian Paleoproterozoic sedimentary basins has illustrated that each have a maximum age of deposition that is close to the very beginning of the transition of rising global atmospheric oxygen (GOE). The lowermost stratigraphic units of

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these Paleoproterozoic basins contain detrital pyrite and uraninite and thus clearly reflect anoxic condition during sedimentation.

1.1. Paleoplacer uranium and gold in the Huronian Supergroup

The discovery in 1956 of uraniferous quartz pebble conglomerates, in the Huronian Supergroup near Elliot Lake, Ontario, signified that Witwatersrand-type paleoplacer deposits had potentially formed in the Paleoproterozoic Huronian Supergroup. Theis (1976) examined the Elliot Lake deposits and demonstrated that the mineralogy and its geochemical expression were controlled by fluvial depositional processes, which suggests they represent paleoplacers. The acceptance of this paleoplacer model conveyed considerable exploration potential for the Huronian as well as other Paleoproterozoic basins. The Witwatersrand Basin in South Africa, similarly sized to the Huronian Basin, is known as the best endowed gold province in the world. In that respect, the numerous conglomerate-hosted gold deposits of the Witwatersrand have been accepted by most to represent (hydrothermally modified) paleoplacers (for a review see Frimmel et al., 2005). Following the Elliot Lake discovery, the Huronian Basin received considerable exploration efforts in the search for additional paleoplacer uranium deposits. Although anomalous gold values were reported in the Elliot Lake area by Roscoe (1969), exploration and geological investigations for gold paleoplacers were unsuccessful. A renewed interest in gold paleoplacers in the Huronian Basin occurred when Mossman and Harron (1983) and Long (1986) reported anomalous gold concentrations throughout the basin and delineated the eastern part of the basin, the Cobalt Embayment, as the most likely for paleoplacer gold deposits. The ultimate discovery of conglomerate-hosted gold in the Huronian Basin was achieved in the Southern Cobalt Embayment at the Pardo project, 65 km northeast of the famous nickel mining camp in Sudbury, Ontario. Duncan McIvor of Endurance Gold Corporation made the discovery in 2007. McIvor demonstrated that previously collected grab samples were, in fact, related to Huronian stratigraphy and he was able to reproduce economic gold concentrations from outcropping basal Huronian strata. Since this initial discovery, exploration by Inventus Mining Corp. (formally Ginguro Exploration Inc.) has further identified and traced the mineralized conglomerates over 45 km^2. Additional gold occurrences, similar to the auriferous conglomerates at Pardo, have been approximately 25 km apart both east and west of the Pardo project area (Inventus Mining, personal communication 2015) (Fig. 1). The Pardo deposit was subsequently studied by Long et al. (2011), who determined the mineralization is contained in laterally extensive, pyrite-bearing, framework-supported, cobble and boulder conglomerates of the Mississagi Formation. Ulrich et al. (2011) found the gold-mineralized pyrite grains to be of detrital origin and concluded that the conglomerate-hosted gold mineralization is of a paleoplacer origin with an Archean gold source about 8 to 10 km to the north.

1.2. Correlation of the Paleoproterozoic basins

Wiik 1876 (in Laajoki and Saikkonen, 1977) first noted similarities between stratigraphy of the Paleoproterozoic Huronian and Karelian basins. These observations were further developed by Ojakangas (1988), who recognized a similar glaciogenic diamictite within the Huronian, Hurwitz, Snowy Pass and Karelian metasedimentary basin fills, which made possible a first imprecise chronostratigraphic correlation. Strong evidence exists that these basins, which are located along the margins and interiors of the Superior, Hearne, Wyoming and Karelian cratons (Aspler and Chiarenzelli, 1998; Ojakangas, 1988; Roscoe and Card, 1993), formed part of an originally coherent and contiguous larger basin on a supercontinent (Fig. 2). This supercontinent has been referred to as Superia (Bleeker, 2004, 2003) and Kenorland (Bleeker and Ernst, 2006; Ernst and Bleeker, 2010; Williams et al., 1991). As the name

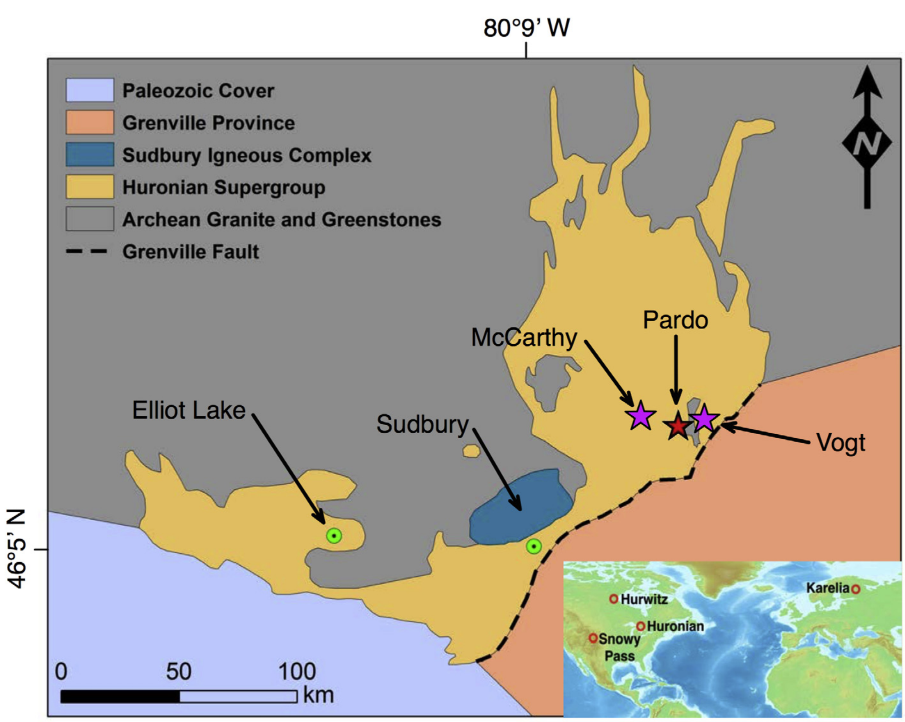

Fig. 1. Location of the Pardo Project (indicated with a red star), and locations of the Vogt and McCarthy occurrences (indicated with purple stars) within the Huronian Basin. Insert map illustrating today's location of the Huronian, Hurwitz, Snowy Pass and Karelian Paleoproterozoic supergroups. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Kenorland was proposed first, we give that name preference. This supercontinent probably accreted along the Great Lakes Tectonic Zone, a major 2.7 Ga suture that was identified by Sims et al. (1980) and is located along the southern boundary of the Superior Craton. The notion that the Huronian, Hurwitz, Snowy Pass and Karelian basins have been originally part of one single larger basin finds further support by the 2475–2445 Ma Matachewan-Hearst mafic dike swarm (Heaman, 1997) and the 2490–2475 Ma East Bull Lake layered mafic intrusive suite (James et al., 2002), which can be related to the rifting of Kenorland. This rifting, followed eventually by continental breakup, resulted in the current displacement of the basin-hosting cratons now located in Ontario, Nunavut, Wyoming as well as Finland and Russia (Fig. 1). Further elaboration on Kenorland rifting was provided by Bleeker and Ernst (2006), who determined that dike swarms within the Superior, Hearne and Karelian cratons can be correlated using a geochronological "bar coding" system. However, the Wyoming Craton was unaccounted for by Bleeker and Ernst (2006), though subsequently Dahl et al. (2006) determined that the 2480 Ma Blue Draw metagabbro in the Wyoming Craton was related to the Kenorland rifting event as well. Recent work by Ciborowski et al. (2015) has revealed that dike swarms, layered intrusions and flood basalt occurrences with ages between 2491 and 2437 Ma preserved on the Hearne, Wyoming and Karelian cratons, all share a similar tholeiitic composition and trace element geochemical signatures that appear closely related to the Matachewan Large Igneous Province (LIP) of the Superior Craton. With mounting geochronological evidence for the Superior, Hearne, Wyoming and Karelian cratons to have once been amalgamated, it becomes more plausible that the lower sequences in the Paleoproterozic Huronian, Hurwitz, Snowy Pass and Karelia strata were deposited during the same supercontinental rifting episode that was initiated by the Matachewan LIP event.

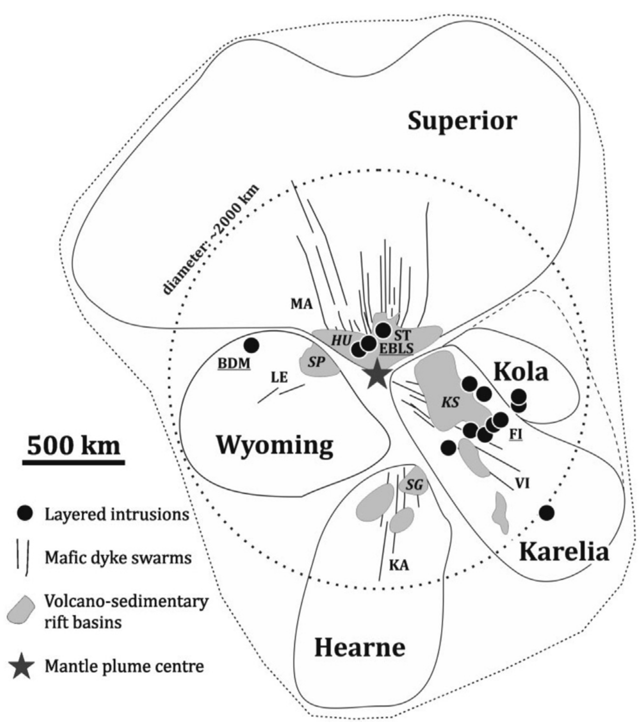

Fig. 2. Early Proterozoic reconstruction of Kenorland; the mafic dike swarms, layered intrusions and volcano-sedimentary rift basins are preserved on the Superior, Wyoming, Hearne, Karelia and Kola cratons. Volcano-sedimentary rift basins: SP, Snowy Pass Supergroup; SG, Spi Group and Hurwitz Supergroup; HU, Huronian Supergroup; KS, Karelian Supergroup. Layered intrusions: EBLS, East Bull Lake Suite; BDM, Blue Draw Metagabbro; FI, Fennoscandian intrusions. Mafic dyke swarms: LE, Leopard; KA, Kaminak; MA, Matachewan; VI, Viianki; ST Streich; after Söderlund et al. (2010) and Ciborowski et al. (2015).

1.3. Criteria for paleoplacer gold enrichment

As discussed by Frimmel et al. (2005) the highest potential for placer gold concentrations is expected in siliciclastic sedimentary rocks derived from a possibly pre-enriched (with respect to Au) Archean to Paleoproterozoic greenstone terrain. Gold potential of sedimentary basins is also discussed by Minter (1991) who outlined three common characteristics of ancient gold-bearing placers. The first characteristic is the lateral extent of mature quartz arenite on unconformities that exceeds >200 km^2 indicating widespread erosion. The second characteristic is the topographic relief, which allows for deeply incised channels of potential previously gold-enriched sediments and a continuous reworking of those sediments. And the last characteristic is the stratigraphic position of placer sediments where stratigraphic stacking of placer events demonstrates degradation/aggradation cycles representing intermittent tectonic rejuvenation of the basin margin.

In this study, we review current knowledge of stratigraphy from the various Paleoproterozoic Kenorland-related basins with the aim to determine if gold mineralization in the pyritic conglomerates at the Pardo deposit is a local phenomenon or reflects an episode of widespread gold concentration in all Kenorland rift-related Paleoproterozoic basins. The host of gold mineralization at the Pardo project, the Mississagi and Matinenda formations, will be compared with regard to their stratigraphic position with the aforementioned Paleoproterozoic Hurwitz, Wyoming and Karelian stratigraphy to determine if similar sedimentary cycles exist and if so, whether they contain any related gold and uranium concentrations. It is hypothesized that gold mineralization, as known from the Pardo project, could have affected all basins that were formed during the Kenorland rifting event. Thus, this paper assesses the exploration potential for additional Witwatersrand-type paleoplacer gold deposits within the Huronian Basin and its equivalents in the Hurwitz, Snowy Pass and Karelian basins.

2. Genesis of the Witwatersrand paleoplacer deposits

The Witwatersrand Basin in South Africa is the world's largest known gold province, having produced >52,000 tonnes of gold accounting for approximately 30% of total global gold production (Frimmel, 2014). Since the discovery of gold in the Witwatersrand in 1886, exploration for similar paleoplacer deposits throughout the world has been moderately successful with the discoveries of several similar deposits/occurrences, e.g., Tarkwa in Ghana, Jacobina in Brazil and the Elliot Lake/Blind River uranium deposits of Canada. Recent additions to success in exploration for such deposits include Novo Resource's Beatons Creek deposit in the Hamersley Basin of Australia and Inventus Mining's Pardo project in Ontario, Canada. These deposits and discoveries, although of importance, have been unsuccessful so far in delineating Witwatersrand-comparable levels of gold endowment (Frimmel, 2014).

The Witwatersrand Supergroup is the oldest discovered paleoplacer-hosting stratigraphic mega-unit in the world, and has been divided into the West and Central Rand groups. The West Rand Group has a maximum depositional age of 2985 ± 14 Ma obtained from U-Pb data of detrital zircon grains (Kositcin and Krapez, 2004). The minimum depositional age for most of the group is 2914 ± 8 Ma, which was obtained from U-Pb zircon data for the Crown Formation basalt (Armstrong et al., 1991). The West Rand Group metasedimentary rocks reflect depositional fluctuations between a fluvio-deltaic and shoreface setting to an offshore setting, which has been attributed to fluctuation in sea level (Stanistreet and McCarthy, 1991). Its tectonic setting has been interpreted as passive margin that evolved from continental rifting (Kositcin and Krapez, 2004; Frimmel et al., 2005).

The Central Rand Group, which unconformably overlies the West Rand Group, is composed of predominantly coarse-grained siliciclastic rocks, laid down mainly by fluvio-deltaic processes with minor tidal reworking (Els, 1998). The maximum depositional age for the group is given by a 2902 ± 3 Ma detrital zircon population at the bottom of the Johannesburg Subgroup (Kositcin and Krapez, 2004). The minimum depositional age for the group is constrained by a 2849 ± 18–2840 ± 3 Ma detrital zircon population in the Krugersdorp Formation obtained near the top of the group (Kositcin and Krapez, 2004).

Since the initial discovery of the Witwatersrand gold province, seven separate goldfields have been delineated, containing at least 30 different reefs. The largely coarse-grained siliciclastic Central Rand Group proved to be the most endowed, comprising 95% of total Witwatersrand gold production, and reflects a foreland basin fill related to collisional tectonic events to the north and west of the basin (Frimmel et al., 2005). The Witwatersrand orebodies occur mainly as auriferous clast-supported oligomictic conglomerates that are associated with cross-bedded quartz arenite and occasionally, for example in the case of the Carbon Leader Reef, as lag surfaces ranging from decimeters to a few metres in thickness (Minter, 1991). The orebodies exhibit lens-like geometry and unimodal paleocurrent directions resembling fluvial bar and channel bed forms (Smith and Minter, 1980). The hanging wall and footwall of the reefs are marked by sharp decreases in gold content, which can range from several ppm to a few ppb (Frimmel et al., 2005).

Although the paleoplacer model has been used to direct gold mining in the Witwatersrand since its initial discovery, the source and mechanisms of gold enrichment have been widely debated. Strong evidence for a placer origin was presented by Minter et al. (1993), who identified gold grains with clear detrital morphological features. However, this hypothesis has not been able to account for the gold source. Loen (1992) suggested that erosion of a hinterland containing 0.4–6.8 ppb, a reasonable assumption for background Au concentrations in Archean greenstones (Stone and Crocket, 2003) which underwent erosion for millions of years, could account for the Witwatersrand's gold endowment. Many attempts have also been made to explain the Witwatersrand deposits by epigenetic hydrothermal models. It is generally accepted that the Witwatersrand basin fill underwent, in most areas, low-grade metamorphism and hydrothermal alteration (Frimmel, 1994). Some workers (Law and Phillips, 2005; Phillips and Law, 1994; Phillips and Myers, 1989; Phillips and Powell, 2011) went so far as to suggest that the gold was introduced from outside the basin by post-depositional hydrothermal/metamorphic fluids. However, this argument has failed to discredit the multitude of micro-textural, mineralogical, geochemical and isotopic data, all of which indicate the hydrothermal gold was derived from local mm- to cm-scale mobilization of originally detrital gold particles. These observations have led to the current widely accepted model of a modified paleoplacer for the Witwatersrand province (Frimmel et al., 2005). The explanation of the exceptional gold endowment of the Witwatersrand province remains a challenge. It has been suggested that reducing environmental and atmospheric conditions during the time of Witwatersrand deposition could have resulted in the pre-concentration of gold from microbially mediated precipitation of gold onto carbonaceous material preserved in places as kerogen (Horscroft et al., 2011; Frimmel, 2014). Erosion and mechanical reworking of microbial mats thus enriched in gold would explain both the detrital shaped micro-nuggets and exceptional gold endowment within the Witwatersrand gold fields.

3. Huronian Supergroup on the Superior craton

The Huronian Supergroup is located on the southern margin of the Superior Province. It spans from Sault Ste. Marie, Ontario to Noranda, Quebec and covers approximately 16,000 km^2. Maximum and minimum ages of 2450 and 2100 Ma are defined by the underlying East Bull Lake intrusive suite (James et al., 2002) and the dikes and sills of the Nippissing diabase (dolerite) that intruded the entire Huronian Supergroup (Van Schmus, 1965), respectively. Uranium-Pb age data of zircon grains from a tuff bed in the Gordon Lake Formation (Rasmussen et al., 2013) has indicated that the Cobalt, Quirke Lake, Hough Lake and Elliot Lake groups were deposited before 2310 Ma. The tectonic setting of the basin is still under debate (Long, 2004), however, all models presented are essentially modifications of Dietz & Holden's (1966), who suggested the Huronian Supergroup represents a rift and passive margin sequence that was later compressed, tectonically buried, and metamorphosed. The passive margin sequence reflects a period of negative relief, resulting in the accumulation of clastic sediments that were sourced from mainly plutonic rock-dominated terranes from the north (Card et al., 1977). In the eastern part of the basin, a gold-enriched Archean source is situated along the northern extension of the Cobalt Embayment, the Abitibi Greenstone Belt, a world class Au, Cu, Pb and Zn camp comprising orogenic Au, magmatic Cu-Ni-PGE and VHMS Au-rich Cu-Zn-Pb deposits (Mercier-Langevin et al., 2014, 2012).

The Huronian Supergroup stratigraphy has been described in detail by Card et al. (1977) and has been divided into four groups. These are, from oldest to youngest, the Elliot Lake, Hough Lake, Quirke Lake and Cobalt groups, which together reach a maximum thickness of 12 km. The Huronian Supergroup experienced lower greenschist-facies and locally up to amphibolite-facies metamorphism during the 1.88–1.83 Ga Penokean Orogeny (Schmus, 1976; Schulz and Cannon, 2007; Young et al., 2001). As the gold-bearing Matinenda and Mississagi formation are parts of the Elliot Lake and Hough Lake groups, the latter two will be discussed in more detail below.

The Elliot Lake Group, the lowermost unit, is generally discontinuous and rests disconformably on Archean granite and greenstone. It is composed of lower mafic and felsic volcanic rocks, sandstone, greywacke, pelite and mature siliciclastic conglomerates and has been subdivided, from oldest to youngest, into the Livingstone Creek, Thessalon, Matinenda and Mckim formations. The Livingstone Creek Formation has been described in detail by Bennett et al. (1991) as an alluvial fan deposit, of a basal polymictic pebble to boulder conglomerate and an upper well-sorted grey sandstone that together reach 100–400 m in thickness. The Thessalon Formation in the western part of the basin consists of both felsic and mafic volcanic rocks and in the central part has been further divided into the Elsie, Stobie and Copper Cliff formations. This series of volcanic units is interpreted to represent one major mafic-felsic volcanic cycle (Card et al., 1977). The Matinenda Formation has been described in detail by Roscoe (1969) as a fluvial deposit composed of sandstone and quartz pebble conglomerates. The formation ranges in thickness from <200 m in the western part of the basin to as much as 600 m in the central and eastern parts from where it rapidly thins further eastwards towards the basin margin. The Matinenda Formation quartz pebble conglomerates in the western part of the basin are host to the Elliot Lake uranium deposits, for which a paleoplacer origin has been established (Theis, 1976). These conglomerates contain abundant detrital pyrite as rounded grains and radioactive minerals, such as uraninite, brannerite and uranothorite. It has been suggested that these deposits were sourced from extensive weathering of an Archean granitic terrain towards the north, with subsequent deposition in shallow braided streams flowing south on a south-dipping paleoslope (Fralick and Miall, 1989). The Mckim Formation is composed of wacke, mudstone, arkosic and minor lithic sandstone, all of which were deposited as a series of submarine turbidite sequences in the course of a marine transgression that gradually drowned the Matinenda fluvial plain (Fralick and Miall, 1989).

The overlying Hough Lake, Quirke Lake and Cobalt groups represent separate sequences each of which begins with a glaciogenic deposit grading into marine deposits that are finally capped by mature fluvial sediments. The transitional sequence has been interpreted by Young et al. (2001) as the product of a partial Wilson Cycle, in which the basin evolved from initial continental rifting.

The Hough Lake Group, has been subdivided, from oldest to youngest, into the Ramsey Lake, Pecors and Mississagi formations. The Ramsey Lake Formation is a thin, <170 m thick, laterally extensive unit and mainly composed of polymictic matrix-supported conglomerates with subrounded to well-rounded pebbles and cobbles interbedded with minor mudstone, wacke and sandstones (Card, 1978). The origin of the unit has been a matter of debate, with interpretations as both a debris flow and glaciogenic deposit. The Pecors Formation, composed of laminated wacke, mudstone, siltstone and sandstone, ranges in thickness from 30 m in the western part of the basin (Robertson, 1968) to as much as 900 m around the Sudbury area (Card, 1978). The Mississagi Formation is mainly composed of sandstone and minor quartz and chert pebble conglomerates that range in thickness from 300 to 700 m in the western part, to 3000 m in the central part of the basin. The recent identification of Mississagi Formation conglomerates by Long et al. (2011) at the base of the formation in the Cobalt Embayment, which are composed of polymicitic clast-supported cobble and boulders with interbedded sandstones, has demonstrated a proximal depositional setting of the formation at that location. The formation has been interpreted by Long (1978) as fluvial braided stream deposits, which display two dominant paleovectors from both the east and west that were depositing towards the center of the basin.

4. The auriferous Mississagi Formation conglomerate

4.1. Stratigraphy

The Mississagi Formation of the Hough Lake group rests disconformably on younger strata of the Pecors, Ramsey Lake, Mckim and Matinenda formations. The younger formations have various subcrop positions and form a wedge of sediment that thickness away from the proximal Mississagi Formation conglomerate outcrops. All of these formations rest on an angular unconformity when in contact with the underlying Archean metasedimentary and volcanic rocks. At the Pardo project, where proximal auriferous boulder conglomerates are present, the Mississagi Formation rests directly on the Archean rocks, with minor amounts of subcropping auriferous Matinenda Formation conglomerates.

4.2. Lithology

The Mississagi Formation is transitional from a proximal to distal setting at Pardo. The distal facies consists of thick sandstone units and thin (up to 30 cm thick), interbedded, well-sorted, fine- to medium-grained quartz and chert pebble conglomerates. The proximal facies is composed of clast-supported, poorly sorted, polymictic boulder to cobble conglomerates that are interbedded with thin sandstone and mudstone beds. The distal conglomerates, which are present as intraformational units, are composed of multiple stacked conglomerate beds and are at a much higher stratigraphic level than the basal proximal conglomerates. Below the proximal Mississagi Formation conglomerates, where preserved and separated in the distal setting by the underlying Pecors, Ramsey Lake and Mckim formations, is an oligomictic quartz pebble to cobble conglomerate with gold values of up to 10 g/t and an increasing content of quartz and pyrite towards the base (Inventus Mining, personal communication 2015). This lower unit is considered by the authors as an equivalent to the Matinenda Formation in terms of both its stratigraphic position and lithology, which is indicative of similar units elsewhere in the Huronian Basin (Theis, 1976). Fluvial erosion of the Matinenda Formation by the stratigraphically younger proximal Mississagi boulder conglomerates may have led to this reworking, a potentially important factor for gold-enrichment that has occurred in the Mississagi Formation conglomerates.

4.3. Mississagi Formation mineralogy

Gold in this formation is hosted by the matrix of conglomerates, which is composed of quartz, chlorite, sericite, and, in places, biotite. Pyrite, with which the gold is typically associated, occurs in three distinct morphological forms: (i) as rounded compact pyrite interpreted to be detrital, (Koglin et al., 2010; Long et al., 2011; Ulrich et al., 2011); (ii) as micro-porous detrital lithic clasts of massive, laminated and concentrically laminated varieties; and (iii) as euhedral and irregular interstitial, undoubtedly epigenetic pyrite (Fig. 3B). Other detrital minerals that are present include rounded uraninite, thorite and zircon. The uraninite is commonly rimmed by a distinct layer of carbon, which confirms the notion of Long and McDonald (2013) that hydrocarbons migrated through the formation during diagenesis. These observations are similar to many of the auriferous and uraniferous conglomerates in the Witwatersrand type region. There evidence is plentiful of post-depositional migration of hydrocarbons in the form of pyrobitumen nodules, in many cases encapsulating uraninite grains (England et al., 2001; Gartz and Frimmel, 1999), and hydrocarbon-rich fluid inclusions (Drennan et al., 1999; Drennan and Robb, 2006).

Four types of gold can be distinguished in the Mississagi Formation: (i) as free visible grains within metamorphic chlorite-biotite-sericite intergrowths, (ii) along boundaries and infilling fractures of epigenetic pyrite, (iii) primary inclusions within un-fractured detrital quartz clasts (Fig. 3A), and (iv) in lithic detrital pyritic clasts containing quartz and chlorite infilling large voids with ±chalcopyrite, pyrrhotite, pentlandite and gold (Fig. 3D). The first two types strongly point at hydrothermal gold mineralization whereas the third type provides unequivocal evidence of sedimentary gold input from an eroded gold-quartz mineralization system similar to orogenic gold deposits. The fourth type, the pyritic clasts that display sulfidation and chloritization within a quartz veins prior to erosion and deposition, provides further evidence of a potential gold source in the hinterland, possibly a lode gold vein-type deposit (Fig. 3C).

In summary, observations from the Mississagi Formation conglomerates indicate that the uraninite, thorite, zircon and rounded pyrite grains that contain inclusions of ±pyrrhotite, chalcopyrite, pentlandite, galena, chlorite and gold, were deposited as *in-situ* detrital grains. The presence of euhedral cobaltite, rutile and secondary epigenetic pyrite, chalcopyrite, pyrrhotite and galena, suggests one or more post-depositional alteration and hydrothermal mobilization event(s). As no hydrothermal veins or structures associated with mineralization were observed when cross-cutting the conglomerates, the secondary sulfides are likely a product of intraformational post-depositional mobilization related to metamorphic fluids. As in the Witwatersrand ores, which both detrital and secondary gold could be distinguished (Minter et al., 1993),

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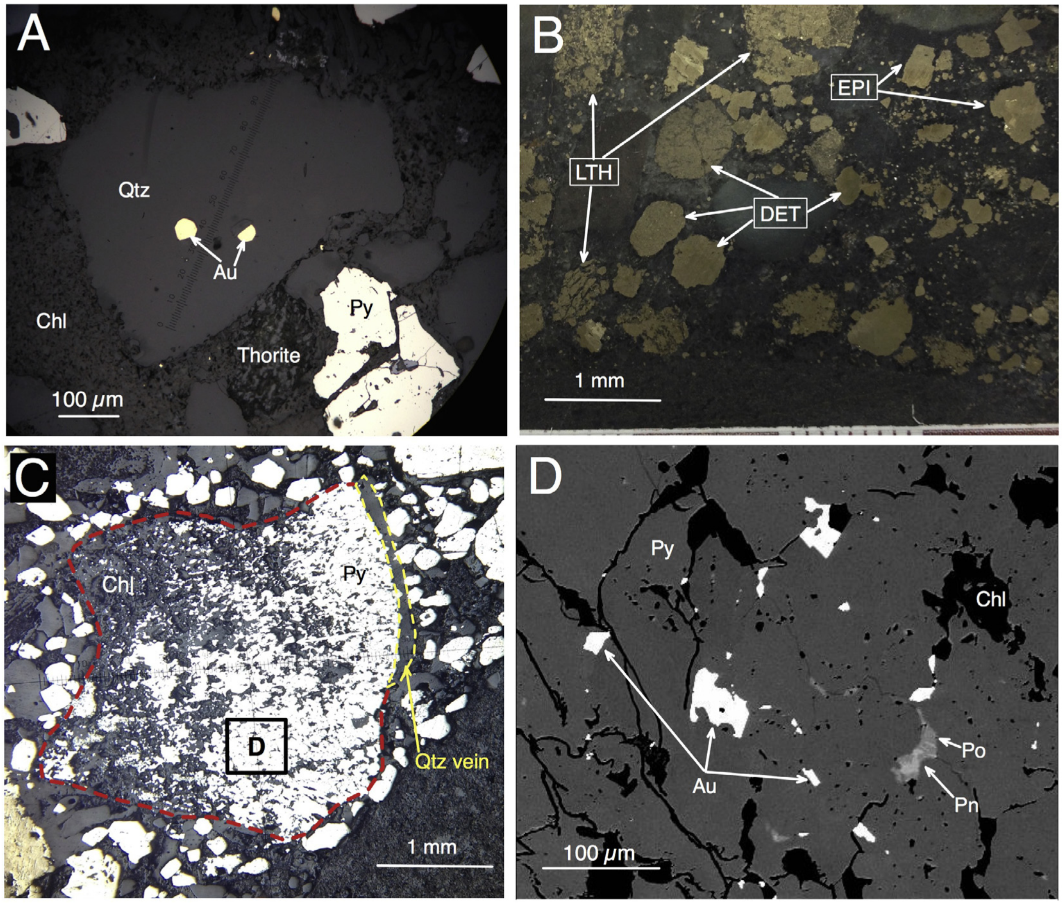

Fig. 3. (A) Reflected light image from the 007 area of two gold grains within an unfractured quartz grain. (B) Pyrite types of the Mississagi Formation conglomerates: (DET) detrital pyrite as rounded and rounded with inclusion; (LTH) detrital pyrite as porous lithic clasts, laminated porous lithic clasts and concentrically laminated porous lithic clasts; (EPI) Epigenetic pyrite as euhedral to sudhedral grains, interstitial grains and recrystallized rims of DET and LTH pyrite types. (C) Reflected light image from the 007 area illustrating a detrital clast (outlined in red) with a quartz vein attached (outlined in yellow) showing both sulphidization and chloritization prior to deposition. Black circle outlines location of the zoomed image D. (D) Backscatter SEM of gold, pentlandite and pyrrhotite infilling fractures and as inclusions within detrital pyrite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the variety of gold types in the Mississagi Formation also attests to syn-sedimentary gold-concentration in the conglomerates followed by post-depositional mobilization of some of that gold. The character of the fluid responsible for mobilizing some of the gold and other minerals is uncertain and cannot be linked to a specific geological event (cf. Ulrich et al., 2011), but both diagenetic dewatering and metamorphic fluid circulation are potential causes.

4.4. Vogt and McCarthy conglomerate-hosted gold occurrences

Since the discovery of the conglomerate-hosted gold anomaly at Pardo, other conglomerate-hosted gold occurrences in Huronian metasedimentary rocks have been discovered near the Pardo project in the Vogt and McCarthy areas (Fig. 1). The Vogt occurrence, located in the most southeastern extent of the Cobalt Embayment, outcrops just south of Lake Temagami and contains anomalous Au and U concentrations in pyritic quartz pebble conglomerates with grades of up to 11 g/t Au and 0.052% U_3O_8/t (Aubay Uranium Mines, 1956). The area has been described by Grant (1964), who observed mature quartz pebble conglomerates of the Matinenda Formation outcropping over a distance of 4 km with an average thickness of 45 m. Follow-up analysis by Inventus Mining (personal communication, 2015) revealed the presence of pyritic, radioactive, poorly sorted, clast-supported pebble to boulder quartz and banded iron formation conglomerates resting on an angular unconformity with a steeply dipping Archean banded iron formation. This conglomerate could represent a more proximal setting of the basal Matinenda Formation.

The McCarthy occurrence was discovered in 2014 by diamond drilling through Huronian strata while targeting a discrete magnetic anomaly in the underlying Archean rocks. The drill hole intersected fluvial sedimentary rocks composed of massive sandstone and intraformational pebble lags of polymictic clast-supported conglomerate. Sampling of the conglomerates returned anomalous gold values of up to 7.5 g/t over 0.5 m (Inventus Mining personal communication, 2015). The conglomerates displayed a gradational contact with an underlying diamictite composed of poorly sorted cobbles to boulders of banded iron formation and granite within a matrix of silty sandstone that unconformably rested on underlying Archean banded iron formation. These units are interpreted to represent the Mississagi and Ramsey Lake formations equivalents to strata at the nearby Pardo project.

Assuming a hydrothermally modified paleoplacer model for the gold mineralization and considering the close proximity of these conglomerate-hosted gold occurrences near the Pardo area, it is likely that a widespread alluvial fan or series of separate river systems, spanning over many kilometres, was responsible for their deposition. Thus, significant potential now exists for elevated gold concentrations in both the Mississagi and Matinenda formations, rocks of which should be present in subcrop under the stratigraphically higher Gowganda and Nippissing Diabase formations that outcrop over many hundreds of square kilometres throughout the Cobalt Embayment.

5. Hurwitz Supergroup on the Hearne craton

The Hurwitz Basin, located on the Hearne Craton, occurs as erosional fragments in the southern part of Nunavut, Canada. The basin fill, divided into four sequences, is composed of siliciclastic and carbonate rocks and has been explained as continental rift graben fill related to the Kenorland rifting (Aspler and Chiarenzelli, 1997; Aspler et al., 2001). The Hurwitz strata were subjected to regional lower to middle greenschist-facies metamorphism during the 2.0–1.8 Ga Hudsonian Orogeny (Davidson, 1970; Stockwell, 1961).

The maximum depositional age of the sediments is defined by the 2450 Ma Kaminak mafic dyke swarm, which transects only the underlying basement rocks (Heaman, 1994). The two lowermost sequences, Sequence 1 and 2, are the only relevant sequences to this study. Sequence 1 is composed of the Noomut, Padlei and Kinga formations and rests nonconformably on Archean gneiss, greenstone and siliciclastic rocks that range in age from 3300 to 2500 Ma (Aspler and Chiarenzelli, 1996). The minimum age of Sequence 2, composed of the Ameto Formation, is defined by a 2111 Ma diabase (dolerite) sill that was emplaced after diagenesis of its country rocks (Patterson and Heaman, 1991).

Sequence 1, which contains the Noomut and Kinga formations, has been described by Aspler and Chiarenzelli (1997) and Aspler et al. (1994). According to these authors, the Noomut Formation represents a fluvial deposit composed of a lower polymictic clast-supported basal conglomerate and an upper sandstone unit, that have filled paleovalleys incised into the Archean basement. Up-sequence the formation matures into a low relief sandy braid plain deposit composed of mature sandstone and quartz pebble conglomerate. The overlying Padlei Formation is composed of greywacke and diamictite suggesting deposition in a glacial environment. The Kinga Formation is composed of both fluvial and Aeolian deposits, reflecting a return to warm fluvial conditions. It has been divided into three separate members, which from oldest to youngest, are the Maguse, Whiterock and Hawk Hill members. The Maguse Member has been further subdivided into a lower, middle and upper unit (Aspler et al., 2000). The lower unit is interpreted as a high energy, un-channeled sheet flood deposit, composed of arkosic to quarzitic sandstones with both polymictic clast-supported pebble to cobble and quartz pebble conglomerates. The middle unit is composed of subarkosic to quartzitic sandstone with black layers of heavy mineral concentrate. The unit also contains a mature quartz pebble conglomerate with clasts of quartz, jasper and chert. The upper two members, the Whiterock and Hawk Hill, are composed of very mature quartzitic sandstone that is capped by bedded discontinuous white, maroon and brecciated cherts (Aspler and Chiarenzelli, 1997).

The second sequence consists of the Ameto Formation, marks a dramatic depositional change, described as a transition to a deep water environment below the wave base. The formation is up to 1500 m thick and is composed of mudstone, siltstone and very fine-grained arkosic sandstone.

6. Snowy Pass Supergroup on the Wyoming craton

The Snowy Pass Supergroup occurs on the Wyoming Craton in two separate areas, i.e., the Medicine Bow and Sierra Madre mountain ranges. Both areas are located at the southeastern boundary of the state of Wyoming and along the southern boundary of the Wyoming craton. The supergroup has been divided into three groups (Karlstrom et al., 1983); the Deep Lake, Libby Creek Lower and Libby Creek Upper. Of these, only the Deep Lake, Libby Creek Lower and lower Archean rocks are of interest in this study.

The Deep Lake Group unconformably overlies the Phantom Lake Metamorphic Suite, which is a series of Archean metasedimentary and granitic rocks. These Archean rocks experienced amphibolite-facies metamorphism, whereas metamorphism in the Deep Lake Group ranges from greenschist- to amphibolite-facies as reflected by the presence of biotite and staurolite (Karlstrom and Houston, 1984). The maximum age for the Deep Lake Group is defined by a U-Pb age of 2451 Ma obtained on detrital zircon from the basal Magnolia Formation, the youngest age of deposition is given by a 2092 Ma gabbro that cross-cuts the entire group (Premo and Van Schmus, 1989). The age of the Phantom Lake Metamorphic Suite, which includes meta-sandstone and radioactive pyritic quartz pebble conglomerates, is not well constrained, however intrusions of the Baggot granite within the suite indicate an age older than 2.5 Ga (Karlstrom et al., 1983) and is in agreement with the aforementioned detrital zircon data from the Magnolia Formation.

The Phantom Lake Metamorphic Suite contains fluvial siliciclastic rocks referred to as the Jack Creek Quartzite in the Sierra Madre area and Lower Bow Quartzite and Upper Conical Peak Quartzite in the Medicine Bow Mountains. The Jack Creek Quartzite and Lower Bow Quartzite have been considered stratigraphically equivalent (Houston and Karlstrom, 1992) and are the only units of the Phantom Lake Metamorphic Suite that are of interest here. The bottom 200 m of the Jack Creek Quartzite have been divided into five units described in detail by Houston and Karlstrom (1987). The bottom three units, which include the Deep Gulch Conglomerate, represent a fluvial succession deposited in a braided river system. Unit 1, the basal unit, is composed of a poorly sorted arkosic conglomerate and quartz pebble conglomerate. The conglomerates are capped by Unit 2, an arkosic sandstone interbedded with quartz and arkosic conglomerates. Unit 3, the uppermost unit, comprises the Deep Gulch Conglomerate, a pyritic radioactive quartz pebble conglomerate with interbedded pebble subarkose and sandstone. The conglomerates range in thickness from 17 to 75 cm and can be traced over 2 km (Houston and Karlstrom, 1987). Above the Deep Gulch conglomerate are units 4 and 5, both composed of quartzitic sandstone beds that are capped by a black phyllite containing lenses of arkosic sandstone. Unit 3, which is of most interest, has been interpreted (Houston and Karlstrom, 1987) to represent longitudinal gravel bars that developed on prograding alluvial fans. The longitudinal bars of the alluvial fan were relatively long-lived suggesting they were reworked and many contain heavy mineral concentrations.

The Deep Lake Group of the Snowy Pass Supergroup has been divided into six different formations, from oldest to youngest: the Magnolia, Lindsey, Singer Peak, Campbell Lake, Cascade and Vagner formations. The basal Magnolia Formation is composed of two members, a basal radioactive conglomerate member and a quartz granule member, each of which have been described in detail by Houston et al. (1977). The conglomerate member reaches a maximum thickness of 330 m and are composed of pyritic quartz pebble conglomerate, matrix-supported conglomerate and interbedded pebbly sandstone. The upper member is 400–600 m thick and is mainly coarse-grained quartzitic sandstone. The conglomerates have an arkosic sandstone matrix and are polymictic with clasts up to tens of centimeters in diameter (Houston and Karlstrom, 1987). The units have been interpreted as transgressional alluvial fan deposits. The Lindsey Formation has been described by Karlstrom et al. (1983) as a 410 m thick massive quarzitic to subarkosic sandstone, containing occasional thin phyllite beds and scattered pebbles on planar foresets. The formation has been interpreted as fluvial lag and overbank sediment deposits that either formed as a discontinuous sheet or as the product of onlapping sediment from the Cascade Formation. The Campbell Lake Formation is up to 65 m thick and composed of a discontinuous, poorly sorted, matrix-supported, polymictic conglomerate with clasts that can reach as much as 75 cm in diameter. The unit has been interpreted by Karlstrom and Houston (1979) as a debris flow with a possible glacial origin, however Bull (1972) suggested it may represent an alluvial-fan debris flow.

The Cascade Quartzite Formation is the thickest and most extensive of the formations with a thickness of up to 850 m throughout the entire basin. The formation is composed of a massive cross-bedded quarzitic to subarkosic sandstone with occasional uniform 5–10 cm thick pebble conglomerate beds. The unit has been interpreted by Karlstrom et al. (1983) as a fluvial deposit and due to its continuity and extension of the sedimentary rocks, it has also been suggested the unit was deposited in an alluvial-plain or deltaic setting. The Vagner Formation, the uppermost formation of the Deep Lake Group, rests unconformably on the Cascade Formation and reaches up to 800 m in thickness. The formation has been described by Karlstrom et al. (1983) as a matrix-supported conglomerate-marble-phyllite-quartzite succession, which marks an important stratigraphic transition from dominantly fluvial to marine conditions.

7. Karelian Supergroup on the Karelia craton

The Karelian Supergroup is located on the Karelia Craton in several fragmented erosional basins along the border of Finland and Russia. The rocks of this supergroup are spatially separated and poorly exposed (Laajoki, 2005) making basin analysis in this study difficult, as many different names have been applied for stratigraphically similar units. Metamorphism of the Karelian supracrustal rocks during the 1.9 Ga Svecofennian orogeny resulted in lower greenschist- to upper amphibolite-facies mineral assemblages (Laajoki, 2005).

The supergroup has been divided into six groups, which from oldest to youngest are the Sumian, Sariolian, Kainuu, Hattusari Jatulian, Ludicovian and Kalevian groups. Only the Sariolian and Jatulian groups are of interest for the purpose of this study. The maximum age of deposition is constrained by a 2440 Ma layered mafic complex that is considered part of the Sumaian Group (Alapieti, 1982). The minimum age of deposition is given by the age of regional metamorphism, i.e. c. 1900 Ma (Lahtinen and Huhma, 1997) and the youngest detrital zircon population within the Kalevian Group, which yielded a U-Pb age of 1920 Ma (Claesson et al., 1993). The youngest age of the Jatulian group is defined by 2200 Ma Karjalites tholeiite sills that cross-cut the group (Vuollo, 1994).

The Sumian Group comprises mainly volcanic rocks, with some minor greywacke, arkosic sandstone and volcanoclastic rocks all of which were deposited in an elongated zone of rifts along the north-eastern margin of the craton (Ojakangas et al., 2001).

Geological descriptions of the Sariolian, Kainuu and Jatulian groups have been provided by Laajoki (2005) and are summarized below. The Sariolian Group, also referred to as the Kyykka, Viesimo and Kurkikyla groups, has been divided into three formations, which from oldest to youngest are the Ilvesvaara, Urkkavaara and Hokkalampi Paleosol formations. The Ilvesvaara Formation is poorly exposed, but is estimated to be not more than 30 m thick. It has an unconformable to disconformable contact with the underlying Archean granitoids and underlying rocks of the Sumian Group. The unit is composed of a weathered granitoid regolith that passes into immature conglomerate containing unweathered pyrite-magnetite clasts and terrigenous pyrite grains. The formation has been interpreted as product of *in-situ* weathering or frost-shattering on a paleosurface, followed by a braided river environment (Ojakangas et al., 2001). The Urkkavaara Formation consists of seven units described by Kohonen and Marmo (1992) and consist of siltstone-argillite, sandstone, diamictite and conglomerates with a maximum thickness of 265 m. The basal unit, which overlies the Ilvesvaara Formation, is a planar laminated siltstone-argillite bed that contains rare pebble to cobble sized dropstones. This unit is followed by a pink arkosic sandstone, metagreywacke and siltstone, which gradually develop into a massive diamictite. The unit is capped by coarse-grained arkosic sandstone, displaying a sharp lower contact. Up-section the arkosic sandstone contains inter-bedded conglomerate beds that become thicker and more frequent stratigraphically higher in the unit. The conglomerate grades into a cross-bedded clast-supported conglomerate that is 10–30 m thick and consists of cobble to boulder conglomerate that is, in turn, capped by a 10–30 m thick cross-bedded arkosic conglomeratic. The Hattusari Formation, only observed in the northern part of the Karelian supracrustal rocks, has an unknown relationship with the Ilvesvaara and Urkkavaara formations. The unit is composed of a 10 m thick lower matrix-supported conglomerate, a 15 m thick middle clast-supported conglomerate and a 70 m thick upper arkosic sandstone. The formation is covered by the Hokkalampi Paleosol composed of quartz and variably sericitized feldspar-bearing schists.

The Jatulian Group, also known as the Herajarvi Group, has been interpreted as both a fluvial braid plain and alluvial plain deposit that evolved into a marine succession (Laajoki, 2005). It is divided into the Vesivaara, Koli, Jero and Puso formations. The Vesivaara Formation is composed of coarse-grained quartzite and quartz pebble conglomerates. The Koli Formation rests unconformably on the Hokkalampi Paleosol where the Vesivaara Formation wedges out and is composed of a basal conglomerate and an upper quartzite with an overall maximum thickness of 280 m. The conglomerate is clast-supported, well-sorted and contains mostly clast sizes of pebble- to cobble- size with occasional boulders of quartz. The Jero Formation is composed of a lower conglomerate member, which grades upwards into an arkosic sandstone. The Puso Formation, the last formation of the Jatulian Group, is composed of lower subarkose and an upper quartzite member.

8. Correlation of the Huronian, Hurwitz, Snowy Pass and Karelian supergroups

8.1. Chronostratigraphic correlation

As discussed for each of the supergroups, the maximum age of deposition is confined by an unconformity on extrusive igneous rocks at the base of each supergroup's siliciclastic units. The ages of these extrusive rocks range are all similar at 2.45–2.44 Ga. Furthermore, all of these volcanic (and subvolcanic) rocks share similar lithological and geochemical characteristics typical of a large igneous province (Ciborowski et al., 2015). The supergroups also have similar minimum ages of deposition, which ares defined by intrusive dykes and sills whose ages range from 2.09 to 2.20 Ga. In all cases they cross-cut the lower parts of each supergroup, indicating the entire lower stratigraphic units of each basin were deposited over a 360 myr period. In the Huronian basin fil, which may yet prove similar in the other basins, is The 2310 Ma tuff bed in the Gordon Lake Formation within the Huronian Supergroup (Rasmussen et al., 2013) suggests that the stratigraphically lower formations were deposited over a 140 myr period. It remains to be seen whether a similar tuff bed is also present in the other supergroups. A further evidence for chronostratigraphic correlation of the supergroups is a regional "mega-event" discussed by Ojakangas (1988), which is interpreted as widespread uncommon glacial event evident in each of the basins at relatively similar stratigraphic levels.

8.2. Lithologic and stratigraphic correlation

Our review of literature on the Huronian, Hurwitz, Snowy Pass and Karelian supergroups demonstrates that similar lithological units are present in similar stratigraphic sequences, at least in regard to the lower parts of the supergroups, deposited before 2.20–2.09 Ga. The basal strata from each of the supergroups, the Matinenda Formation in the Huronian, the Noomut Formation in the Hurwitz, the Magnolia Formation in the Snowy Pass and the Ilvesvaara Formation in the Karelian, consist of basal siliciclastic fluvial sedimentary units. This sequence of sedimentation composed of fluvial deltaic deposits represents the first cycle and initial stage of basin filling. This first cycle was followed by widespread glaciation and marine sedimentation represented by the Mckim/Ramsey Lake/Pecor, Lindsey/Campbell Lake, Padlei and Urkavaara formations. The transition from fluvial deltaic to marine deposits is illustrated in each of the basins as an unconformity followed by the occurrences of argillite, diamictite and minor sandstone units. The marine and glacial deposits signify the beginning of the second sedimentary cycle, which grades into the second occurrence of fluvial deposits. The second cycle consists of the Mississagi, Kinga, Cascade and Vesivaara/Koli/Jero formations from the Huronian, Hurwitz, Snowy Pass and Karelian basins, respectively. This second cycle then ends with an unconformity followed by a thick sequence of overlying diamictite, argillite and marine sandstone that signifies the beginning of the third cycle and is stratigraphically correlated throughout all of the basins.

The differing thicknesses, and in places absent lithological units within the sedimentary cycles of each basin are likely attributed to local and regional cratonic paleotopography, which would have varied widely during basin development. As the minimum age of deposition for each basin is loosely confined and the third sedimentary cycle suggests an oxygenated atmosphere from the appearance of red beds, pyritic conglomerates with gold potential are likely restricted to the siliciclastic sedimentary rocks of only the first and second cycles.

8.3. Correlation of auriferous formations

Comparison of stratigraphy from the Huronian, Snowy Pass, Hurwitz and Karelian supergroups has revealed many lithological similarities that suggest distant stratigraphic equivalents to the conglomerate-hosted gold and uranium deposits of the Mississagi and Matinenda formations (Fig. 4).

The Hurwitz Basin fill, which occurs only as erosional fragments of the original basin fill, is much thinner than that of the other basins of interest, and contains the Noomut and Kinga formations that can be correlated to the Matinenda and Mississagi formations, respectively, of the Huronian Basin. The Noomut Formation contains pyritic quartz pebble conglomerates, polymictic conglomerates and interbedded sandstones that are lithologically equivalent to the Matinenda Formation. Anomalous gold concentrations in pyritic quartz pebble conglomerates of the formation range from 4.2 to 0.1 g/t over 1.5 km (Aspler and Chiarenzelli, 1997). Also, it has been reported that these pyritic quartz pebble conglomerates contain clasts of banded pyritic chert and abundant matrix pyrite that is likely of detrital origin as it is unoxidixed.

The Kinga Formation contains a thick sequence of mature fluvial sandstone and conglomerate analogous to the Mississagi Formation. No gold mineralization has been reported to date from the Kinga Formation. This may be due, however, to the absence of proximal deposits, similar to those at Pardo, where cobble and boulder conglomerates truncate and reworked the stratigraphically lower units.

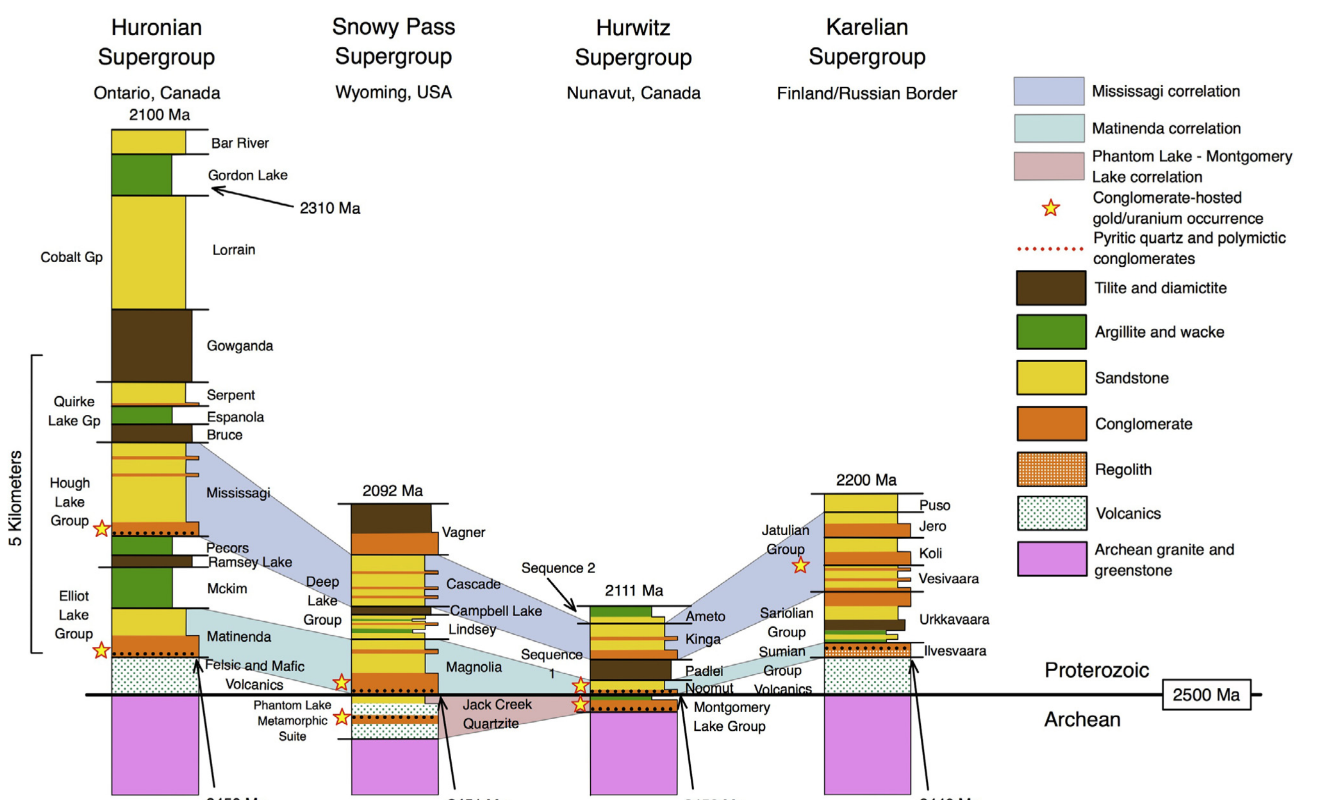

Fig. 4. Suggested correlation of stratigraphic units deposited prior to the 2200–2092 Ma cross cutting mafic intrusives in the Huronian, Snowy Pass, Hurwitz and Karelian basins; following stratigraphic subdivisions of individual supergroups as presented by Aspler and Chiarenzelli (1997), Karlstrom and Houston (1979), Houston and Karlstrom (1987), Laajoki (2005) and Card et al. (1977).

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Anomalous gold values were also reported from various Archean metasedimentary strata of the Hearne Craton. The Woodburn Lake Group, likely an equivalent of the Montgomery Lake Group, is located along the northern boundary of the Hearne Craton and contains elevated gold contents in a host of pyritic quartz pebble conglomerates (Zaleski et al., 2000). Another occurrence along the southern boundary of the Hearne Craton at the northern boundary of the Province of Manitoba was reported by Anderson et al. (2009). At this location, anomalous Au values were obtained from radioactive pyritic quartz pebble conglomerates of the Omand Lake Assemblage. Gold grades of up to 7.5 g/t were reported from quartz pebble conglomerates of this area (Fekete, 2008). It is suggested, therefore, that the Archean strata of the Omand Lake Assemblage may be a stratigraphic equivalent to that of the Montgomery Group strata of the Hurwitz Basin. The presence of subcropping or truncated Montgomery Group strata may also, in part, be responsible for gold-enrichment in the basal Noomut Formation.

The Magnolia and Cascade formations of the Snowy Pass Supergroup correlate well with the Matinenda and Mississagi formations of the Huronian Supergroup, also having lithological similarities. The Magnolia and Matinenda formations both contain mature basal pyritic quartz pebble conglomerates with interbedded sandstones. The Magnolia Formation, which exhibits radioactive quartz pebble conglomerates similar to the Matinenda Formation, was once the object of paleoplacer uranium exploration (Houston et al., 1977). This work was unsuccessful in the discovery of economic concentrations of U at that time, however, Karlstrom et al. (1981) recorded that older sedimentary rocks underlying the Snowy Pass Basin and occurring in the Sierra Madre Mountains returned gold assays of up to 10 g/t Au and 490 g/t U hosted in conglomerates of the Deep Gulch Formation. Although the Deep Gulch conglomerates are Archean in age, and older than the Magnolia Formation, it now becomes likely that the Magnolia Formation may be more enriched in gold where it truncates and reworks the Deep Gulch Formation conglomerates. The Cascade Formation, which correlates well with the Mississagi Formation, has been described as a distal fluvial sediment. It would therefore be of interest to locate a more proximal setting of the Cascade Formation, where it may have truncated and reworked sediments of both the Deep Gulch and Magnolia formations.

The basal Ilvesvaara Formation of the Sariolian Group in the Karelian Supergroup, is composed of basal regolith that matures up-sequence into pyritic conglomerates and arkosic sandstone, and can be correlated with the Matinenda Formation of the Huronian Basin. The presence of unweathered pyrite clasts implies a concentration of compact rounded pyrite similar to pyrites in the Mississagi and Matineda formations at the Pardo project and in Archean paleoplacer basins worldwide. The Vesivaara, Koli and Jero formations of the Jatulian Group can be correlated with the Mississagi Formation. These formations were deposited under similar fluvial conditions and contain mature planar and trough cross-bedded sandstone, quartz pebble conglomerates and polymictic conglomerates. It was noted by Kohonen and Marmo (1992) that the conglomerates of the Nunnanlahti-Koli-Kaltimo area characteristically meet the criteria of gold-bearing placers as outlined by Minter (1991); however, due to the lack of exploration of these sedimentary rocks, no detrital pyrite, gold and uraninite have been discovered thus far. On the Russian side of the Karelian Craton, Lobanov (1964) examined quartz pebble conglomerates of the Jatulian Group and observed a stacking of conglomerate beds that ranged from 1 to 5 m in thickness, traceable for tens of kilometres along strike. The quartz pebble conglomerates in this location contained gold, pyrite (detrital origin not specified), thorite and monazite, indicating that conglomerates of the Jatulian Group potentially contain placers.

Kohonen and Marmo (1992) concluded that the controlling factors for gold potential in the Nunnanlahti-Koli-Kaltimo area was the composition of the contemporaneous atmosphere, which would have been entirely different to that of the Mesoarchaean Witwatersrand deposits, and sediment provenance. An oxidizing atmosphere as such does not preclude formation of placer gold deposits, as illustrated, for example, by the post-GOE Tarkwa paleoplacer in Ghana. Provenance is thus the more likely controlling factor. In the case of the Jatulian Group in the Nunnanlahti-Koli-Kaltimo area, the hinterland was a granitic to gneissic terrane without known gold deposits, lacking older paleoplacers that could have been reworked and being too young to have experienced the continent-wide deep chemical weathering and flux of gold from the land surface as postulated for Mesoarchean times (Frimmel, 2014; Frimmel and Hennigh, 2015). The search for gold potential in the Karelia Supergroup may preclude the Nunnanlahti-Koli-Kaltimo area in future and perhaps be restricted to the Peräpohja and Kuusamo belt areas located in the Central Lapland greenstone belt of northern Finland.

9. Conclusions

The examination of the lithology and stratigraphy from the lower parts of the Snowy Pass, Hurwitz and Karelia supergroups has shown that each can be correlated in terms of chronostratigraphy, sequence stratigraphy, and lithology with those of the Huronian Supergroup. Furthermore, each formation that appears stratigraphically and lithologically equivalent to the Matinenda and Mississagi formations was found to contain pyritic poly- to oligomictic conglomerates that contain elevated Au and U concentrations in sedimentary units, which conform to the criteria for sedimentary placers. These findings confirm that gold mineralization in conglomerates at the Pardo project was not an isolated event, but rather reflects a period of regional gold-enrichment in all sedimentary strata that formed under anoxic conditions and during the rifting of the supercontinent Kenorland. As each of the aforementioned supergroups underwent one or more separate orogenic and metamorphic event(s), of different magnitude and different age, the regional strata-bound and stratiform gold-enrichment indicates that the gold and uranium occurrences in each of the basins were likely the result of a regional episode of paleoplacer genesis. A notable difference to the Witwatersrand basin fill is a younger age of cratonization preceding each of the Paleoproterozoic supergroups discussed in this study compared to the relatively old Kaapvaal Craton hosting the Mesoarchean Witwatersrand deposits. This might explain the order-of-magnitude-difference in gold endowment, which may be related to different pre-enrichment in gold of potential source rocks as elaborated by Frimmel (2014) and Frimmel and Hennigh (2015).

A braided river setting has been suggested for the Mississagi Formation conglomerates at Pardo, where boulder and cobble conglomerates grade downstream into finer-grained gravel bars that were deposited on sandy braid plains. The conglomerate-hosted gold mineralization was likely of a detrital origin, as indicated by detrital gold-rich clasts that must have been derived from specific point sources, most likely, an orogenic lode gold and VHMS deposits in the eroded hinterland, and transported through fluvial processes. Low-grade metamorphism-induced local fluid flow in the Mississagi Formation conglomerates is likely responsible for small-scale remobilization of synsedimentary gold as previously suggested by Ulrich et al. (2011).

The recognition of multiple point sources for detrital gold input into the conglomerates at Pardo presents a substantial difference to the gold-enrichment in the Mesoarchean Witwatersrand deposits. However, the coincidence that each of the Paleoproterozoic basins examined in this study was surrounded by catchment areas that contained similar point sources of detrital gold is unlikely. This reasoning suggests that truncation and reworking of underlying older sedimentary units with placer-type gold-enrichment played an important role to the addition of concrete point sources in a granitoid-greenstone hinterland. Consequently, the potential for conglomerate-hosted gold should exist in all equivalences to the Mississagi and Matinenda formation conglomerates where they rest on an erosional unconformity with anomalous gold contents in the respective footwalls. Furthermore, this insight may also apply to siliciclastic sedimentary units of the Hurwitz, Snowy Pass and to a limited extent, the Karelian basin fills.

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