Rathbun Lake revisited: a magmatic-hydrothermal Pd-Pt-Cu occurrence possibly related to the Sudbury impact

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Abstract. Quartz diorite dykes resulting from impact melts, locally referred to as Offset Dykes, occur concentrically and radially around the 1.85 Ga Sudbury Igneous Complex (SIC), and are a principal host to world class Ni-Cu-PGE-sulfide deposits. Here we report on a new discovery of such an Offset Dyke at Rathbun Lake, 15 km east of the SIC, at a location known for its high grade Pd-Pt-Cu mineralization at the intrusive contact between gabbro of the 2.2 Ga Nipissing Suite and wacke. Amphibole-quartz diorite occurs in direct vicinity to the mineralization and contains abundant mafic inclusions of locally derived country rock, the latter being a diagnostic feature of mineralized Offset Dykes. Preliminary bulk geochemical analyses support its correlation to the SIC. PGM-, sulfide- and silicate assemblages, ore textures and Pd/Ir of >50,000 are consistent with a hydrothermal modification and re-mobilization of magmatic sulfide. This massive and high-grade (>30 ppm PGE) sulfide concentration is unique within the large area over which Nipissing Suite diabase is exposed and, therefore, genetically presumably not related to this suite. The local presence of inclusion-bearing quartz diorite rather points to an impact origin of the Rathbun Lake Pd-Pt-Cu occurrence, analogous to known Offset Dyke-hosted deposits in the SIC.

1 Introduction

The 1.85 Ga Sudbury Igneous Complex (SIC) around Greater Sudbury, Ontario (Fig. 1), the deformed and eroded core of the second largest preserved impact structure on Earth, is one of the richest known ore provinces as it hosts numerous world-class Ni-Cu-PGE-sulfide deposits. Consensus exists on a genetic link between mineralization and impact-induced crustal melts through separation of sulfidic melt droplets and gravitational accumulation thereof at the base of sloping sides of the impact crater (see review by Lightfoot 2016). As much as 50% of the total metal resources of the Sudbury mining district are, however, not hosted by the central igneous complex, but by surrounding impact-melt dykes. The so called “Offset Dykes”, 17 of which are known to date, are narrow (10s to 100s metres wide) igneous bodies of quartz (monzo-)dioritic composition that disect the footwall rocks either radially to, or concentrically around, the SIC and can be traced for several kilometers along strike (Grant and Bite 1984; Lightfoot 2016). Formed at an early stage of the impact cratering process (e.g. Ostermann et al. 1996), maybe during crater collapse, they are thought to preserve the undifferentiated composition of the impact melt, although their exact mode of emplacement is not yet fully understood.

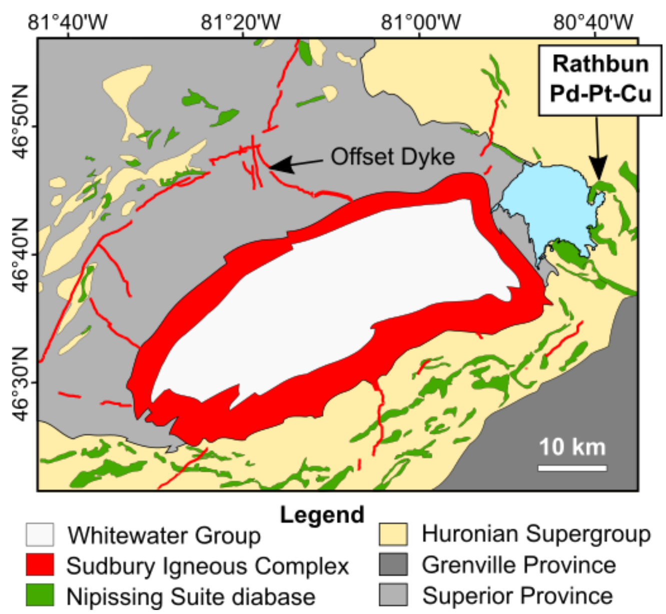

Figure 1. Geological sketch map of the Sudbury Igneous Complex and surrounding dykes related to impact melts.

The recognition of similar, yet unmineralized, Offset Dykes as much as 50 km east of the SIC (Kawohl et al. 2019) has prompted exploration activities which also include re-mapping and re-visiting of known intrusive rocks and ore occurrences in the area. One such prospect is the frequently cited Rathbun Lake showing (Fig. 1), where anomalously high Pd (up to 53 ppm) and Pt concentrations (up to 33 ppm) have been reported for massive Cu-Fe-sulfide within a hydrothermally altered diabase of the regional 2.2 Ga Nipissing Suite (Rowell and Edgar 1986; Lightfoot et al. 1993). Here, we report on a hitherto unrecognized lithology in the direct vicinity of the mineralization and provide first evidence of this quartz diorite being related to the Sudbury impact event, likely another impact melt-related dyke, with some implications for future exploration regarding the Nipissing Suite, distal Offset Dykes and the eastern periphery of the SIC.

2 Geological background

2.1 Nipissing Diabase

The 2.2 Ga Nipissing Diabase is a voluminous suite of mafic intrusive rocks in the Southern Province, Ontario, extending over an area of 250 km, covering ~25% of the Huronian Basin and having an estimated volume of 10^5 km^3 (Lightfoot et al. 1993). The gabbroic melts intruded the 2.45-2.31 Ga siliciclastic Huronian Supergroup as undulating sills with thicknesses ranging from a few hundred to >1000 m. Predominant rock type is a tholeiitic orthopyroxene gabbro, but calc-alkaline granophyric, granodioritic and aplitic varieties are typically found in the upper parts of the intrusive bodies. All of the geochemical and lithological variations are explicable by in-situ differentiation and assimilation of Huronian country rock (Lightfoot and Naldrett 1996). Least differentiated rocks, i.e. the chilled margins, have a remarkably uniform composition. The parental magma had elevated SiO_2 contents (50-51.5 wt%) and was low in Ni (80-160 ppm) and MgO (8-9 wt%). All chills show geochemical features indicating an enriched, maybe subduction-modified or subcontinental lithospheric mantle source (Lightfoot et al. 1993; Lightfoot and Naldrett 1996). The Nipissing Diabase is considered as the root of an eroded flood-basalt province and might have been part of a larger radiating dyke swarm linked to an ancient mantle plume (Ernst 2014).

Using the Rathbun Lake showing as an argument, some workers have tried to emphasize the economic potential of the Nipissing Suite for Cu-Ni-PGE, but over the past decades only one deposit was discovered throughout the Nipissing magmatic province (Sproule et al. 2007; Lightfoot 2016). If at all, disseminated sulfide (<5 vol%) is typically found in the center of a Nipissing intrusive body, several hundred meters above the basal contact. Assimilation did not seem to have played an important role in the sulfide saturation of the magma, nor did the addition of external sulfur as the most intensely contaminated Nipissing bodies are generally unmineralized (Lightfoot and Naldrett 1996), and no S-rich evaporates or shales are known in the Huronian Supergroup. Only one case is documented where Nipissing magma might have assimilated uraninite-pyrite-bearing conglomerates (Sproule et al. 2007; Dasti 2014). Instead, Lightfoot and Naldrett (1996) proposed sulfide saturation was commonly achieved upon crystallization.

2.2 Rathbun Lake showing

The Rathbun Lake showing is located at the intrusive contact of an ordinary Nipissing Diabase body, referred to as the Wanapitei intrusion, and laminated wacke of the Gowganda Formation, both of which experienced greenschist-facies metamorphic overprint (see Dressler 1982). Except for a higher modal proportion of hypersthene, the Wanapitei intrusion does not differ significantly from other unmineralized Nipissing complexes in terms of size, shape, level of emplacement, footwall rocks, geochemistry, degree of assimilation and alteration, parental magma composition or PGE- and base metal enrichment/depletion (Lightfoot et al. 1993; Lightfoot and Naldrett 1996). It is, however, the only known example of massive sulfide at the base of a Nipissing intrusive body. Much of the original ore had been excavated during sinking of an exploration shaft in the 1920s, and previous studies indicate that the massive sulfide (55% chalcopyrite and 40% pyrite ± millerite, violarite, arsenopyrite, magnetite, pyrrhotite, covellite, molybdenite) was a vein-like body, 12 m long and up to 0.6 m wide, which did not follow the diabase-sediment contact but stroke perpendicular to it (Dressler 1982; Edgar 1986). The transition from massive to disseminated sulfide has been described as gradational over several meters, with all sulfide confined to the "diabase" (Dressler 1982). According to Dressler (1982) and Rowell and Edgar (1986) the mineralization is associated with footwall irregularities, shear zones and, most remarkably, an alteration zone, where the original mafic host was altered to biotite, chlorite, sericite, epidote and quartz. Several authors have reported anomalously high values of Pd (up to 53 ppm, on average 21 ppm) and Pt (up to 33 ppm, average 10 ppm) as well as ~3 ppm Au for the massive sulfide (up to 20 wt% Cu and 0.5 wt% Ni), whereas all other PGE concentrations are far below 20 ppb (Rowell and Edgar 1986; Lightfoot et al. 1993). PGM are sperrylite ($PtAs_2$), bismuthian merenskyite ($PdTe_2$), subordinate kotulskite (PdTe) and temagamite (Pd_3HgTe_3), all of which are associated with hydrous silicates, chalcopyrite, or entirely enclosed in pyrite (Rowell and Edgar 1986). Most of the Wanapitei intrusion is unaltered and contains only disseminated (<1 vol%) magmatic sulfide.

3 A Sudbury Offset Dyke at Rathbun Lake?

Poor outcrop conditions and previous excavation limit in-situ investigations to the cliffs at the southern shoreline of Rathbun Lake. The Offset Dyke, obscured by a gossan, is exposed at the entrance of the old exploration shaft, located at the contact between wacke and diabase (46°45'51''N / 80°39'21''E) and it is easily overlooked in outcrop. Additional material was found on a nearby stockpile. Even on freshly broken and wet surfaces, the rock can be easily confused with diabase, but polished slabs (Fig. 2) reveal the presence of abundant dark-grey aphantic inclusions embedded in a light-grey phaneritic matrix. The inclusions are spherical, between a few mm and 10 cm in diameter, and exhibit sharp but undulating contacts with the matrix. This groundmass consists of ~45 vol% altered plagioclase, ~35 vol% quartz, ~20 vol% amphibole. Plagioclase is up to 0.8 mm large, compositionally zoned, and arranged in an interlocking manner. Alteration to epidote/sericite is omnipresent, leaving only rims of albite behind. Quartz occurs as up to 3 mm-large, undeformed, anhedral poikilitic grains enclosing plagioclase. Amphibole, up to 1.5 mm in length, is green in thin section and has a needle-like habit. Accessory minerals are ilmenite/magnetite, chlorite after biotite, and sericite maybe after K-feldspar. There are two types of inclusions, minor arkosic wacke and predominantly mafic inclusions. The latter have a spherulitic to doleritic texture of, in places radiating, plagioclase/epidote, clinopyroxene and minor (~10 vol%) tremolite replacing hypersthene, and contain less than 1 vol% quartz. One sample of the mafic inclusion-bearing quartz diorite contains disseminated chalcopyrite (5 vol%).

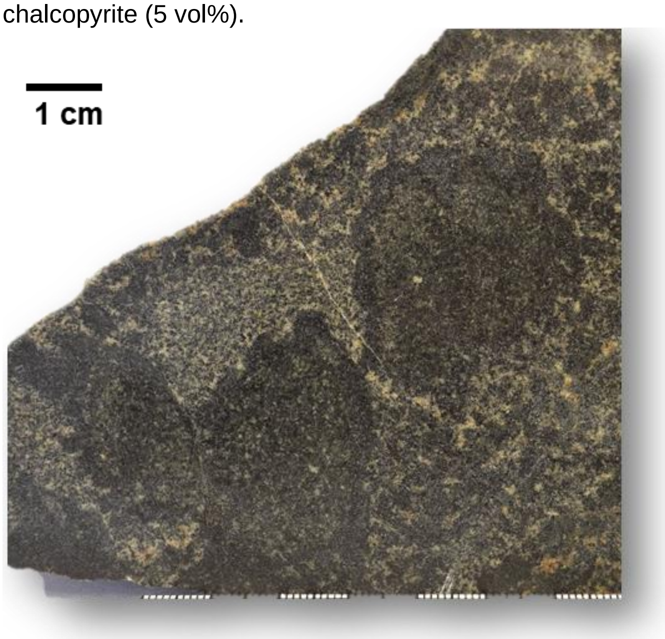

Figure 2. Polished slab of the mafic inclusion-bearing quartz diorite at Rathbun Lake.

The petrography of the quartz diorite at Rathbun Lake is different to the adjacent Nipissing Diabase, Gowganda wacke and to any other Proterozoic rock in the area, but remarkably similar to the 1.85 Ga quartz dioritic Offset Dykes. Its major element concentrations are with 55 wt% SiO_2, 3.5-4.5 wt% Na_2O+K_2O, 5 wt% MgO, 8-10 wt% $Fe_2O_3^t$, 0.1 wt% P_2O_5, and 0.6 wt% TiO_2, typical of a calc-alkaline diorite and similar to those in known Offset Dykes (e.g. Grant and Bite 1984; Lightfoot 2016). Minor discrepancies are likely due to incomplete separation of mafic inclusions or their assimilation. The mafic inclusions are classified as tholeiitic gabbro and have geochemical features (e.g. 51.5 wt% SiO_2, 8 wt% MgO) that match the chilled Nipissing Diabase nearby, in agreement with their quench textures. Their shape and dark reaction rims suggest they were incorporated into the diorite, and have likely undergone partial melting. Only a superheated melt, as it is discussed for the impact melt dykes (>1700°C, Ostermann et al. 1996), would be capable of this.

Although we are not aware of any other diorite of similar age, petrography and geochemistry around the SIC, unequivocal evidence for the diorite having formed during the 1.85 Ga Sudbury impact event would require radiometric age dating. However, this will be a challenge, partly because of regional metamorphism and hydrothermal alteration. Suitable mineral grains for U-Pb dating will be rare, small, and in the case of zircon, most of them are likely to be inherited grains older than 1.85 Ga (e.g. Ostermann et al. 1996). Alternatively, trace element patterns combined with whole-rock Nd-Sr-Pb isotopes proved to be a useful tool for discriminating SIC impact melt rocks from other “normal” magmatic rocks in the wider area (Kawohl et al. 2019), and this will be done in next step of the project. Field work will show whether the quartz diorite at Rathbun Lake is a single isolated occurrence or part of a larger dyke.

4 Metallogenetic considerations

PGE-, sulfide- and silicate mineralogy and textural relationships (Fig. 3) as well as extreme Pd/Ir ratios of >50,000 (Pd being the most fluid-mobile PGE, Ir the least mobile one) are consistent with a hydrothermal origin, modification or re-mobilization of magmatic sulfide (e.g. Wood 2002; Holwell et al. 2017). This could have taken place during Proterozoic orogenies and faulting, the 1850 Ma Sudbury impact itself, or the ~1700 Ma metasomatic event documented by Schandl et al. (1994), but as unclear as the timing of the sulfide formation remains the ultimate source of the metals.

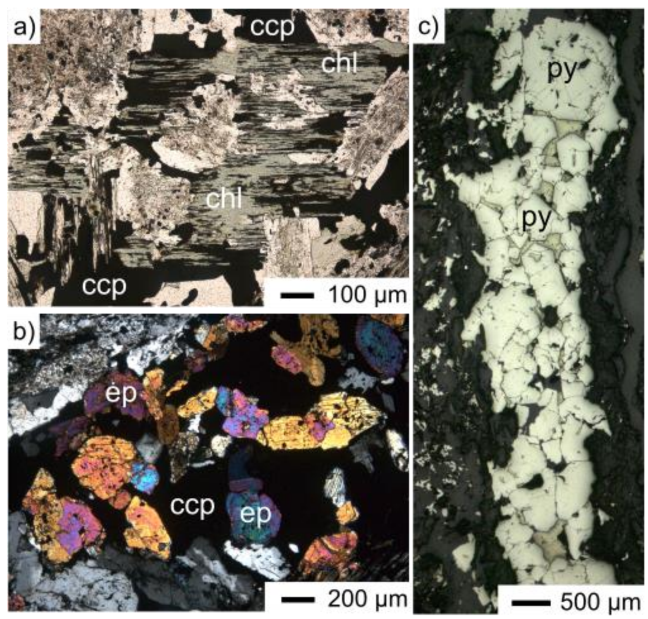

Figure 3. Microphotographs of ore textures at Rathbun Lake. a) Chalcopyrite (ccp) replacing chlorite (chl) along cleavage planes; b) chalcopyrite and epidote (ep) replacing diabase; c) decimeter-long vein of pyrite (py; white) and interstitial chalcopyrite (yellow) cutting through altered wacke (reflected light).

Lightfoot and Naldrett (1996) found disseminated (<1 vol%) globules of sulfide within the Wanapitei and other intrusions, which show an internal segmentation into lower pyrrhotite+pentlandite and upper chalcopyrite (see Lightfoot 2016 p. 91), as it is expected for closed-system fractional crystallization of a sulfide liquid. Consequently they related the massive sulfide at Rathbun Lake to gravitational settling of dense sulfide melt droplets and their accumulation at the base of the intrusion. This hypothesis fails, however, to explain (i) why settling occurred only there and in no other Nipissing intrusion or at any other position of the Wanapitei intrusion; (ii) a lack of evidence of base metal depletion in the silicate rocks overlying the massive sulfide; (iii) a lack of enrichment of the parental magma in PGE (Edgar 1986; Lightfoot and Naldrett 1996); (iv) the close spatial relation between ore and hydrothermal alteration; and (v) – assuming that hydrothermal alteration/re-mobilization of proto-ores from the Nipissing Diabase did occur – the remaining of the Ni-rich counterparts of the original (magmatic) pyrrhotite-chalcopyrite-pentlandite assemblage.

We propose an alternative explanation for the Pd-Pt-Cu mineralization that does not invoke the Nipissing Diabase as the source of the metals. The mere presence of a Sudbury impact-related lithology right next to the mineralized zone already suggests a genetic relationship. The ores at Rathbun Lake could have formed by similar processes as the SIC footwall deposits, that is, either residual highly fractionated Cu-rich sulfide liquid percolated into the brecciated footwall rocks underlying the impact melt, and/or metal redistribution by high-T hypersaline fluids (exsolved from the crystallizing impact/sulfide melt, released by the partially molten footwall, or just heated groundwater) (see Péntek et al. 2008 for a discussion). Cu-PGE-Au vein-type deposits can occur as far as 1500 m away from the Ni-dominated PGE-poor “contact” ore, i.e. the former MSS (monosulfide solid solution) cumulates on the crater floor. Rathbun Lake, for which we notice striking similarities to the Broken Hammer deposit (cf. Péntek et al. 2008), could represent the distal part of such a footwall system, with the overlying Ni-rich contact ore having been eroded.

Besides, Rathbun Lake strongly resembles the Vermilion Deposit in terms of metal ratios, ore and gangue mineralogy and textures, and geological setting (Szentpéteri et al. 2003): There, located between amphibolite and Huronian sedimentary rocks, isolated pods of xenolith-rich quartz diorite of the Vermillion Offset Dyke (south of the SIC) host small veins and lenses of sulfide with average grades of 21 ppm Pt and 54 ppm Pd. Highest grades are associated with gabbroic inclusions in the diorite. Like at Rathbun Lake, PGM are bismuthotellurides and sperrylite, intergrown with hydrous silicates; sulfide assemblages are essentially the same, but with more Ni arsenides, and with a further advanced alteration stage (Holwell et al. 2017) marked by bornite replacing some chalcopyrite. Szentpéteri et al. (2003) referred to this as a hydrothermally modified Offset Dyke deposit and proposed a complex multistage magmatic-metamorphic-hydrothermal origin of the ores, with involvement of saline ($NaCl$-$CaCl_2$-H_2O±CO_2) fluids at temperatures between 480°C and 150°C. Previous descriptions together with our own new findings imply an analogous origin for the Rathbun Lake Pd-Pt-Cu occurrence.

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