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Applications of the combined portable XRF-benchtop SEM methodology to PGE exploration

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ABSTRACT

Portable XRF (pXRF) and benchtop scanning electron microscopes equipped with energy dispersive systems (bSEM-EDS) are two real-time analytical techniques that can be combined to collect on-site lithogeochemical and mineral chemical results at dramatically reduced cost and time compared to traditional analytical methods. The Coldwell Complex, northwestern Ontario, is used as a case study on how the combination of these techniques can be applied to mineral exploration. Our results show that whole-rock Ba, V/Ti, Cu/S determined by pXRF, and plagioclase, olivine, and clinopyroxene compositions measured by bSEM-EDS can be applied to exploration for PGE deposits. Cu/S ratios for disseminated sulfides are a proxy for metal tenor, which can be applied as a vector towards higher grade mineralization. Potential magma recharge zones are identified by inspecting down-hole variations in plagioclase, olivine, and clinopyroxene compositions. Fluctuating down-hole variations in these parameters are interpreted to reflect episodic magma recharge. Whether rocks contain PGE mineralization can initially be assessed by documenting the variability of mineral chemistry, i.e., the greater variability of mineral chemistry could be used to vector higher grade PGE mineralization, particularly if the mineralization is conduit-related. Lastly, geochemical mapping of the igneous stratigraphy enables identification of favorable hosts for mineralization. Down-hole whole-rock variations in Ba and V/Ti from pXRF, and mineral chemical profiles from bSEM-EDS are used to discriminate the mineralized Marathon Series from the barren Layered Series throughout the Coldwell Complex. Whole-rock Ba and V/Ti from pXRF and mineral chemical results from bSEM-EDS could prove useful in other settings of the Midcontinent Rift (e.g., the Duluth Complex, Eagle and Eagle East intrusions, Tamarack Intrusive Complex, and the Sonju Lake intrusion) and elsewhere (e.g., the Stillwater Complex) to identify mineralized host rock types. An additional important application is a rapid interpretation of petrogenesis. Down-hole variations in olivine-clinopyroxene Mg-Fe exchange coefficients determined by bSEM-EDS analyses show that olivine-clinopyroxene pairs in the Marathon Series units, particularly for those within PGE mineralized zones, have compositions that are closer to chemical equilibrium (constant) compared to units of the barren Layered Series (highly variable), and thus could be a tool for interpreting petrogenetic processes active in the magma chamber or during the mineralization forming event.

1. Introduction

Recent advances in technologies have resulted in several field portable analytical techniques being developed to collect data in the field at low cost, which facilitates rapid decision making. This includes assays of drill core for ore elements and major and trace element analyses of the hosts rocks to establish a lithogeochemical stratigraphy, which are essential components of mineral exploration. At the Coldwell Complex in northwestern Ontario the laboratory-based results of Good et al. (2015) show that platinum-group element (PGE) in mineralized and barren intrusive rocks are geochemically distinctive, and can be discriminated using Ce vs. Y and Nb vs. Zr diagrams. However, the low concentrations of Ce, Y and Nb in the host gabbros means that these discrimination diagrams are not suited to their application in the field using portable X-Ray fluorescence (pXRF) analyses. Thus, there is a need to develop new discriminant diagrams using elements that can be analyzed by pXRF at the concentrations present in gabbros.

Mineral chemistry is another means of discriminating lithological units and the molar Fe/Mg exchange coefficients between olivine and clinopyroxene ($Kd^{Ol/Cpx}_{Fe/Mg} = (Fe/Mg)_{Ol}/(Fe/Mg)_{Cpx}$) is a fundamental

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characteristic of an intrusive unit (Good, 1992; Loucks, 1996). Variations in this coefficient could be useful in correlating units or contacts between drill holes, but analyses of this kind have not been undertaken using field portable instrumentation. However, it is now possible to measure molar Fe/Mg exchange coefficients using a benchtop scanning electron microscopy equipped with energy dispersive spectroscopy (bSEM-EDS). This instrument can easily sit on a table in a field setting and can analyze cut rock and drill core samples without polishing and carbon-coating.

Cao et al. (2016) presented a proof of concept paper that combined pXRF and bSEM-EDS data from a single drill hole and concluded that: 1) pXRF and bSEM-EDS both produce results that are comparable to their lab-based counterparts; 2) the combination of these methods gave a more robust means of distinguishing between different gabbro series than by pXRF only; 3) whole rock Cu/S ratios can be used as a proxy for Pd grades; and 4) platinum group minerals can be identified in drill core samples by bSEM-EDS with minimal sample preparation.

The current work builds on the proof of concept study and tests the application of the combined pXRF-bSEM-EDS approach to PGE exploration by examining drill holes from three areas of the Eastern Gabbro of the Coldwell Complex. New data was collected to 1) develop new discriminants that can be analyzed by pXRF and evaluate whether these discriminants are applicable to other deposits in the Midcontinent Rift and elsewhere; 2) test whether the combined pXRF-bSEM-EDS can be applied to igneous stratigraphic mapping at the scale of an intrusion; 3) apply $Kd^{Ol/Cpx}_{Fe/Mg}$ values from bSEM-EDS to evaluate processes such as undercooling, and 4) evaluate whether the integration of pXRF-bSEM-EDS can be used to identify possible magma conduits.

2. Geological setting

The Coldwell Complex is the largest alkaline complex in North America and is related to the Midcontinent Rift (Fig. 1). It is a subcircular composite pluton that has a diameter of approximately 25 km and a surface area of 580 km^2 (Walker et al., 1993). It intruded the Archean Schreiber-White River greenstone belt during the early stages of Midcontinent Rift development (Walker et al., 1993; Heaman et al., 2007). The Eastern Gabbro suite constitutes the oldest part of the Coldwell Complex. It occurs along the eastern and northern margin of the complex (Fig. 2) and comprises numerous cross-cutting gabbroic and ultramafic intrusions that were emplaced into a thin meta-volcanic package (Good et al., 2015).

Shaw (1994, 1997) interpreted that the Eastern Gabbro formed by multiple intrusions of basaltic magma into a partial ring-dike structure that cut the Archean country rock. The Eastern Gabbro Suite consists of a diverse assemblage of discrete gabbroic intrusions that cut a less than 1 km-thick package of the Metabasalt (equivalent to Fine-Grained Gabbro in Good et al., 2015), and the Metabasalt represents the earliest magmatism in the Coldwell Complex (Good et al., 2017). The gabbroic intrusions were grouped into two distinctive magmatic series: an older Layered Series and a younger Marathon Series. The relative ages of these units were established from crosscutting relationships, particularly within the numerous units of igneous breccia (Good et al., 2015). The Layered Series constitutes the bulk of the Eastern Gabbro and is composed of massive to mineralogically layered olivine gabbro, with a lesser amount of weakly layered oxide augite melatroctolite. The Marathon Series comprises numerous small intrusions composed predominantly of subophitic gabbro, apatitic olivine clinopyroxenite, and oxide melatroctolite, as well as small volumes of augite troctolite (Good et al., 2015).

Three Cu-Pd occurrences hosted by the Marathon Series were examined in this study. Area 41 is a Cu-Pd prospect located approximately 16 km northwest of the Marathon Cu-Pd deposit. The Area 41 intrusion is approximately 100 m thick and extends for at least 1200 m along strike (Good et al., 2017). It cuts a sequence of the Metabasalt and consists of several cross-cutting units that resemble the Two Duck Lake intrusion, the main host unit for the Marathon deposit (Good et al., 2015). Disseminated sulfide mineralization (dominantly chalcopyrite, pyrrhotite, and pyrite) occurs as three bifurcating and sub-parallel zones, predominantly within a subophitic gabbro horizon, with lesser amounts hosted by apatitic olivine clinopyroxenite. Mineralization hosted by subophitic gabbro generally has a higher Pd grade (> 1.0 ppm) than that hosted by apatitic olivine clinopyroxenite (0.1–0.8 ppm). The second area is Four Dams, approximately 2.5 km north of the Marathon deposit. It consists mainly of two mineralized occurrences: Four Dams North and Four Dams South (Fig. 3). Four Dams North consists of Cu-PGE mineralization within a 100 m-thick lens of apatitic olivine clinopyroxenite that strikes northwest for 350 m and dips 60° to the southwest (McBride, 2013). Sulfides consist of disseminated to blebby chalcopyrite with lesser amounts of pyrrhotite and trace bornite. Four Dams South consists of disseminated chalcopyrite and pyrrhotite with negligible PGE. The sulfides are hosted in mineralogically layered olivine gabbro that is continuous for 700 m along strike, dips 40°to the southwest, and varies 4 to 50 m in thicknesses (McBride, 2013). The third area is the WD zone, which is located 4 km south of the Marathon deposit. The Cu-Pd mineralization here consists of disseminated chalcopyrite and pyrrhotite and is hosted by subophitic gabbro that texturally resembles the Two Duck Lake gabbro.

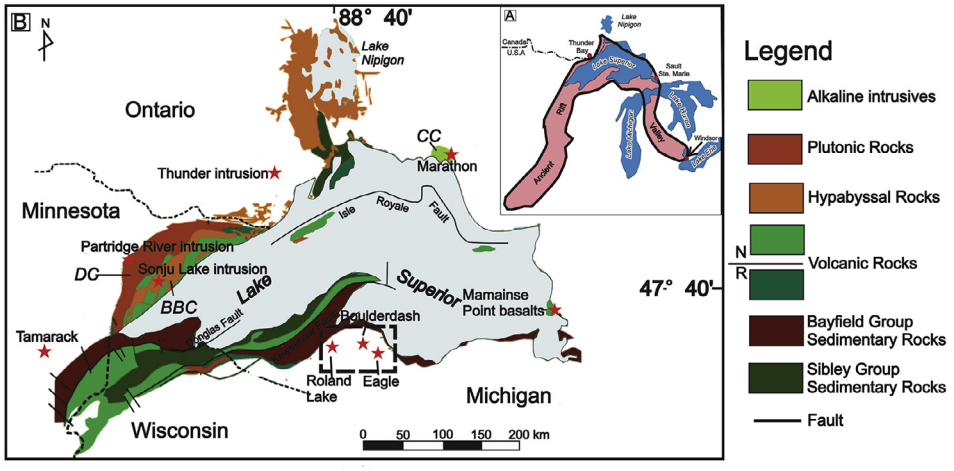

Fig. 1. (A) Extent of the Midcontinent Rift System from Van Schmus et al. (1987). (B) Locations of the Marathon deposit, the Partridge River Intrusion, the Thunder Intrusion, the Tamarack Intrusive Complex, the Sonju Lake intrusion, the Roland Lake Intrusion, the Boulderdash Intrusion, the Eagle Intrusion, and the Mamainse Point basalts (indicated as red stars) within the Midcontinent Rift (after Miller and Nicholson, 2013). The Baraga Basin Area is outlined using a dashed square. The outside area to the north of Lake Superior is Archean basement, and to the south is Phanerozoic undivided units. N/R indicates normal and reverse magnetic polarity (Miller and Nicholson, 2013). Abbreviations: DC = Duluth Complex, CC = Coldwell Complex, BBC = Beaver Bay Complex. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)