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Geology and high grade hydrothermal PGE mineralization of the Vermilion quartz diorite offset dike, Sudbury, Canada

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ABSTRACT: Geology mapping supplemented by detailed mineralogy, revealed zones of low sulphide extremely PGE-rich mineralization that is not typical among Sudbury ores. PGE values are over 70-100 g/t (Pd+Pt+Au). Two major rock types, a felsic granophyric biotite quartz diorite, and foliated Sudbury Breccia were found to host high grade ore. Such finely disseminated zones are irregularly distributed. They form halos around or are associated with massive chalcopyrite shoots that were formerly mined from the deposit. The close spatial association of PGM with hydrous alteration silicates, their finely disseminated nature, the appearance of sulphide in veins and PGM along foliation planes, multistage replacement textures, and some fluid inclusion evidences all suggest a complex multistage magmatic to hydrothermal and metamorphic-hydrothermal origin of sulphide-PGM assemblages.

1 GEOLOGICAL CONTEXT

The Vermilion quartz diorite offset dike (Grant and Bite, 1984) is located at the southwest corner of the 1.85 Ga. old Sudbury Structure (Krogh et al., 1984; Corfu and Lighfoot, 1997). It is one of the quartz diorite intrusions that host Cu-Ni-PGE deposits around the perimeter of the Sudbury Structure. It occurs in a northwest-striking zone. The dike narrows to depth, plunges to the southwest, is 200m long, and consists of amphibole-biotite quartz diorite pods in a Sudbury Breccia zone (Fig. 1). Apparently it is not connected with the basal contact of the main mass of the Sudbury Igneous Complex that is located 2 km to the North. The Vermilion quartz diorite dike is related to a zone of Sudbury Breccia (pseudotachylite) forming a concentric belt around the Main Mass of the Sudbury Structure (Grant and Bite, 1984).

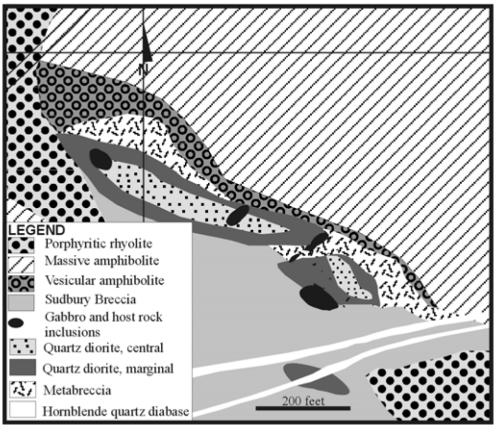

Figure 1. Geology map of the Vermilion quartz diorite at the old Vermilion mine.

2 PETROLOGY AND MINERALOGY OF HOST ROCKS

At surface, quartz diorite appears in two large NW trending pods, and in a small irregular pod. They intruded brecciated Lower Proterozoic (Huronian) metavolcanic and metasedimentary rocks. Quartz diorite pods are fine- to medium-grained from the margin to the centre, respectively. Pods of quartz diorite and the surrounding Sudbury Breccia contain (0.5-8m) xenoliths of enclosing units, and grey gabbro fragments that are usually round, strongly altered hornfels. The pods contain 3-5 % amphibolite and 5-10% feldspar-rich inclusions in size ranges 0.4-1.5 cm and 1-5 cm, respectively. The proportion of these inclusions increases toward the central axis of the pods along the main NW-SE strike direction. The eastern contact of the quartz diorite reveals a distinct zone of metabreccia composed of hornfels with coarse-grained amphibole porphyroblasts. Sudbury Breccia at the western contact of the dike consists of brecciated fine-grained, vesicular to massive amphibolite and variably textured biotite rich matrix.

The Vermilion quartz diorite is composed of 50-55% zoned plagioclase (labradorite-oligoclase), quartz, apatite, 35-45 % amphibole (actinolite to ferro-tschermakitic hornblende), 3-10% biotite plus accessory ilmenite, titanite, epidote, chlorite and disseminated to blebby sulphide. Marginal quartz diorite contains granophyric intergrowths of oligoclase-quartz that is interstitial to the labradorite framework (Fig. 2) of the rock with subordinate biotite; however the amount of biotite increases in proportion toward the centre.

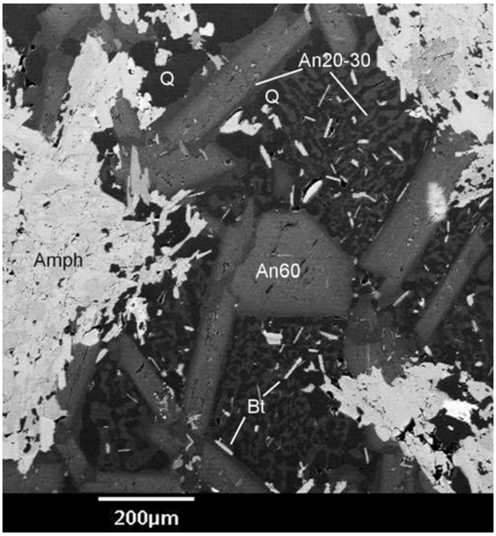

Figure 2. BSE image of granophyric amphibole(Amph) biotite(Bt) quartz(Q) diorite. Note zoned plagioclase(An60-An20-30) and granophyric intergrowth of oligoclase(An20-30) and quartz(Q) that is interstitial to the labradorite(An60) framework.

At the NW contact with quartz diorite, Sudbury Breccia consists of amphibolite fragments in the fine grained matrix. To the southwest and to the south, the Sudbury Breccia widens where it is matrix-supported with irregularly-textured lepidoblastic fine to medium-grained texture. The matrix comprises biotite, quartz, ilmenite, and feldspar. In some zones garnet, chlorite, and sulphides with accompanying alteration minerals also occur. Farther west, about 80-100 metres from the contact, 1-5 m long, round, metasedimentary inclusions are abundant as the western footwall of the breccia is composed of arkose and intercalated wacke. Foliation is very well seen in the medium grained breccia by the aligment of biotite flakes whereas in fine grained samples fragments are flattened to an ellipsoidal shape and they are oriented along the foliation plane. At the surface and in drill core there are foliated biotite- and/or chlorite-rich zones containing 3-10 % of 0,3-2 cm large garnet porphyroblasts. There is a well developed foliation-lineation throughout the Sudbury Breccia, characterized by 170/85 dip, around 70 E pitch. This strike (80°-260°) is parallel to the elongation of hornblende-quartz-diabase dikes 30 metres southwest of the main quartz diorite pod (Fig. 1).

3 THE VERMILION DEPOSIT

4000 tons of ore grading 6.64% Ni and 6.69% Cu and 21 g/t Pt, 54 g/tm Pd were exploited from the Vermilion deposit between 1887 and 1918 (Farrow and Lightfoot 2002). H.L. Wells (1889) discovered sperrylite from this deposit. The ore occurred in small veins and irregular lenses from a few inches to 15 ft. in diameter (the largest being 15 x 38 ft.) along, and striking parallel to quartz diorite within the Sudbury Breccia.

4 MINERALOGICAL STUDIES

Mineralized samples were investigated from historical collections, available muck pile, grab and drill core samples in order to draw a systematic picture of the mineral assemblages.

4.1 *In situ surface and drill core samples*

Modern re-evaluation of the Vermilion deposit by reconnaissance drilling revealed existing ore zones spatially associated with large gabbroic inclusions in quartz diorite and Sudbury Breccia. These are located at the eastern side of quartz diorite. Our detailed (1:200) surface mapping found a relatively small area with extremely high PGM enrichment spatially related to a biotite quartz diorite variety of the dike behind a large gabbroic inclusion at the south-western corner of the pod (Fig. 1). The host rock of precious metal minerals is a partly deformed biotite quartz diorite in which sulphides occur as disseminated grains and aggregates of, mainly, less than 1 millimetre but a maximum of 3-4 millimetre size and tends to appear along foliation planes. Larger grains display very complex mineralogy. Alteration minerals, such as chlorite, quartz, epidote, albite, and carbonate are intergrown with them. This rock type yielded extremely high PGE values greater than 100 g/t (Pd+Pt+Au).

Among sulphides of the deformed quartz diorite abundant maucherite and sparse nickeline appear as euhedral to anhedral fractured grains included in silicates and in chalcopyrite and bornite of 1-3 mm size. Small (100-500 micrometre) grains are perfectly euhedral with prismatic habit in silicates Grain boundaries between maucherite and nickeline are sharp and straight compatible with equilibrium crystallization. Both maucherite and nickeline are replaced by bornite, millerite and gersdorffite. Usually maucherite contains only rare inclusions of sudburyite. Some grains of maucherite, however, contain numerous sudburyite inclusions.. Sudburyite inclusions are aligned along sector boundaries and widely distributed within sectors (Fig. 3). Sudburyite inclusions are inhomogeneous showing varying Ni→Pd, Bi→Sb substitutions. Chalcopyrite, the major sulfide, is extensively replaced by bornite, millerite, and gersdorffite along its edges. Millerite appears as groups of acicular crystals or larger euhedral wedge-shaped grains growing from margin to the centre of the chalcopyrite grains. It is usually mantled by bornite. Bornite replaces chalcopyrite in larger areas as well. Bornite contains numerous blebs of chalcopyrite, wittichenite, hessite, froodite. Wittichenite characteristically forms an oval radial grain aggregate rimming froodite-hessite. Wittichenite contains very fine Au inclusions. Bornite also contains exsolution networks of chlacopyrite in various forms. Bornite alters to digenite along edges and it is totally altered to this mineral at some places. Sperrylite occurs as coarse, subhedral, slightly round solitary grains included partly in chalcopyrite or entirely in silicates.

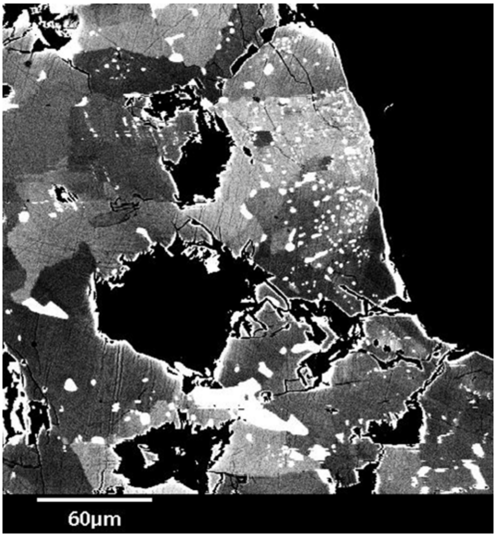

Figure 3. BSE image of sudburyite (PdSb) inclusions in sectored maucherite ($Ni_{11}As_8$).

An interesting feature of this ore type is that small (40-200 µm) aggregates of numerous phases are scattered in the silicate matrix. Such complex aggregates contain an assemblage of hessite, froodite, sudburyite, michenerite, gold, parkerite, and annivite, associated with chalcopyrite, bornite and digenite which implies disequilibria (Fig. 4). Fine euhedral grains of gersdorffite are disseminated in the silicate matrix and attached to the rims of larger grains. Sometimes gersdorffite occurs as myrmekitic intergrowths with former sulphides. Molybdenite is a rare mineral as euhedral plates. Galena is moderately abundant and occurs included in silicates.

From drill core samples, another type of PGM assemblage consisting of 10-60 µm sized aggregates of michenerite, froodite, bismuthinite and gold was recognized. Precious metal minerals are mostly included in silicates or associated with the larger chalcopyrite and millerite grains attaining 1-3 mm in size. These composite grains are most commonly emplaced along the cleavage planes of biotite and chlorite. The host rock is the foliated Sudbury Breccia composed of biotite, chlorite, garnet and quartz. Sulphide grains are aligned along the foliation plane.

The northern tip of the dike contains deformed primary magmatic blebby sulphide. Suphide blebs consist of pyrrhotite, pentlandite and coarse-grained cobaltite-gersdorffite solid solution.

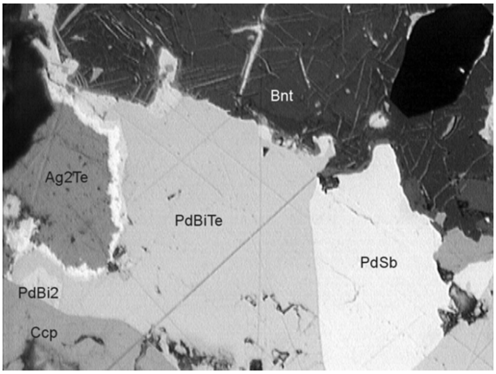

Figure 4. Reflected light photomicrographs of complex intergrowths of PGM. From left to right the phases are as follows; hessite (Ag_2Te, note its double reaction rim), michenerite (PdBiTe) with lighter inclusions of froodite ($PdBi_2$) along its rims, sudburyite (PdSb) associated with bornite (Bnt)-digenite-chalcopyrite lamelle (up) and chaclopyrite (Ccp, down). With of view is 60 microns, 100x obj., oil.

4.2 *Historical, muck pile samples*

Massive chalcopyrite contains numerous large (20-400 µm) round, subhedral inclusions of michenerite, complexly rimmed intergrowths of maucherite-nickeline-gersdorffite-galena, gold, and euhedral grains of cobaltite-gersdorffite with Ir+Rh enrichment in their core. Millerite and violarite are accessories. Other specimens consist of violarite-millerite with coarse (1-4 mm) sperrylite. Sperrylite was rarely found to be associated with massive chalcopyrite. Some specimens contain massive maucherite-nickeline with abundant sudburyite inclusions in maucherite that was later replaced by chalcopyrite, millerite, and gersdorffite. Close spatially associated violarite and millerite appear as pseudmorphs after former pentlandite manifested by the straight outline, parting, and shrinkage fractures. Alteration minerals accompanied by massive chalcopyrite are garnet, biotite, quartz, or albite, epidote and quartz. Alteration mineral assemblage associated with the millerite-violarite ore-type consists of quartz, epidote, albite, biotite, zircon, rutile and monazite.

5 FLUID INCLUSION STUDIES

There are abundant quartz, feldspar-quartz, quartz-carbonate veins in Sudbury Breccia, quartz diorite and amphibolite. Some veins contain chalcopyrite, violarite-millerite, pyrite, and bornite, and a significant PGM enrichment was found in a chalcopyrite-quartz vein. In that vein, michenerite and galena are extremely abundant too. Primary polyphase (L-V-H) fluid inclusions of quartz homogenized close to and above 350 °C. Fluid composition can be modeled in the H_2O-NaCl-$CaCl_2$ system. Many quartz veins are re-crystallized, but some are not and these latter veins contain numerous two-phase (L-V) or polyphase (L-V-H) secondary fluid inclusions. Their typical homogenization temperatures are between 150-170 °C and their chemical composition is in the H_2O-NaCl-$CaCl_2$ system. Preliminary Raman spectral analysis also indicate the presence of CO_2 in these inclusions.

6 CONCLUSIONS

The disseminated appearance of ore minerals in different rock types, their close association with quartz, hydrous minerals, and quartz veins, the lack of pyrrhotite, abundant precious metal minerals and the high presence of arsenides are distinctly different from the characteristics of typical magmatic ore of the Sudbury Structure. All these observed attributes suggest a magmatic-hydrothermal genetic model for the Vermilion deposit. Upon detailed microprobe work, textural analyses, and fluid inclusion thermobarometry, we propose a multistage model for the formation of mineral assemblages observed in different samples. Primary immiscible blebby sulphides reacted with hydrothermal fluids from which a nickeline-maucherite +/- sudburyite, gold paragenesis precipitated, then at temperatures higher than 350 °C, saline (NaCl-$CaCl_2$-H_2O) fluids precipitated a chalcopyrite-pentlandite-michenerite association. A second hydrothermal stage caused complete alteration of pentlandite to millerite and violarite, and marginal to complete replacement of nickeline by gersdorffite, replacement of chalcopyrite by bornite and introduction of the described complex PGM-rich assemblage at a temperature range of 480-150 °C. Temperature constraints can be considered from the stable assemblage of michenerite and froodite that defines the upper temperature limit at 480 °C. Garnet-biotite thermometry from Sudbury Breccia also shows a maximum temperature of 450-500 °C. However, PGM enrichment in Sudbury Breccia is related to a second hydrothermal event resulting in abundant chlorite alteration. Its lower temperature range is suggested by the secondary fluid inclusions at around 150-170 °C. The inversion twins observed in hessite also indicate a temperature higher than 155 °C. The extensive replacement of chalcopyrite by bornite must have taken place above 300 °C because of the presence of many exsolution forms in bornite. This later-PGM rich phase of mineralization might be related to the NW directed thrusting of the Sudbury Structure at around 1460 Ma.

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