# SIDEROPHILE MINERALS IN THE MELT SHEET OF THE MOROKWENG IMPACT CRATER, SOUTH AFRICA: SIMILARITIES AND DIFFERENCES WITH THE SUDBURY DEPOSITS.

M. A. G. Andreoli[1, 2], W. D. Maier[3], I. McDonald[4], S. – J. Barnes[s], F. Roelofse[6], M. C. Cloete[6], C. Okujeni7, and R. J. Hart[8], [1]Necsa, P. O. Box 582, Pretoria 0001, South Africa, marco@necsa.co.za, [2]University of the Witwatersrand, P. O. Box 3, Wits 2050, South Africa, [3]University of Western Australia, Crawley, WA6009, Australia 3, [4]Cardiff University, Cardiff CF10 3YE, U.K., [5]Universite' du Quebec, Chicoutimi G7H 2B1, Canada, [6]Council for Geoscience, P.O. Box 112, Pretoria 0001, South Africa, [7]University of the Western Cape, P. Bag X17, Bellville, 7535, South Africa, [8]iThemba Labs, South Africa, P. Bag 3, Wits 2050, South Africa.

**Introduction:** The ~144 Ma Morokweng impact crater, buried beneath Cenozoic Kalahari sediments [1, 2], coincides with multiple concentric rings (radii up to 130 Km) in the airborne magnetic and Bouguer gravity images of the Kaapvaal craton [3, 4]. Its voluminous melt sheet (diameter: ~30 km, maximum thickness > 900 m) is exceptionally enriched in PGE and displays a patent, vertical differentiation from more siliceous near the top to more mafic (quartz) norite 500 m below [1, 2, 5, 6]. Crystallization of the impact melt was protracted and complex, as shown in borehole WF 05 by a dyke of a more mafic impact melt intruding a more siliceous pyroxene granophyre [1]. The melt in borehole M3 is instead unique because it hosts scattered, cm to dm-scale inclusions of pristine to partly recrystallized LL chondrite [7]. The melt also hosts numerous inclusions of nickel-PGM rich sulphides and oxides, particularly between 300 to 350 m in borehole M3 [2, 5, 6, 8]. Given these features, and the observation that a significant percentage of impact structures is host to economic mineral deposits [9], we assess here the possibility that Morokweng may host Sudbury type deposits.

**Methods:** Due to the regional Kalahari sand cover, our knowledge of the Morokweng melt sheet is derived from gravity and airborne magnetic data [3, 10, 11], soil (sand) geochemistry [12, 13], diamond and percussion drilling [1, 2, 6, 14]. The borehole cores were carefully logged, sampled at regular intervals [2, 5] and characterized by mineralogical and geochemical techniques.

**Results:** Most boreholes drilled in the melt sheet were found to intersected a gamut of minerals rich in siderophile elements (here referred to as "siderophile minerals") within these four main stratigraphic settings:

*Disseminated siderophile minerals in quartz norite*. These are the more common type, and in M3 ( between 350-365 m), the minerals are spatially associated to swarms of small inclusions of (pre-impact) deeply altered, serpentinized ultramafics [6] and of (impact melt) melanorite/hyperstenite. Millerite (NiS) and trevorite (a Ni-magnetite) are almost ubiquitously present as a pair, in complex aggregates ~0.1-3.0 cm across and in variable proportions [6] . Associated to this pair we also found minor to trace amounts of bornite, chalcopyrite, chalcocite, selenides, and possibly talnachyte [$Cu_9(Fe, Ni)_8O_{16}$; [2, 8] see below). Other siderophile minerals observed in in borehole WF 05 bunsenite (almost pure NiO), liebenbergite (the Ni olivine end member), willemseite (a Ni-rich serpentine), and ilmenite with_NiO ~11.0 wt%. Platinum-group elements (PGE) associated to the siderophile minerals include both native minerals (platinum), and complex, poorly characterized siderophile – chalcophile element (Fe, Ni, Cu, Se, S, Br, Mo, Pb, etc.) aggregates where Pt varies between ~0.4 wt.% and ~14 wt.% [2, 8].

*Siderophile minerals in vein.* In WF 05, at a depth of 270 m, a flute-shaped, subvertical vein (>6 cm x ~3 cm wide) was found in quartz norite that consisted almost entrely of pegmatoidal millerite+trevorite in subequal proportions, in addition to small amounts of chalcopyrite and graphite [2]. An INAA analysis of this vein yielded Fe 18.4.wt%, Ni: 27 wt%, Co: 0.45 wt%, Cu: ~1% wt%, Ir: 7.5 ppm, Pt: 2.7 ppm, Pd: 23 ppm [2]. Absolute PGEs values in the vein are 10x chondrite, and the Pt/Pd ratios ratios depart from chondritic inter-element ratios [2].

*Siderophile minerals in meteorite inclusion.* Main opaque phases in the ~30 cm LL-chondrite boulder intersected by M3 at a depth of ca. 750 m are pyrrhotite, pentlandite and minor chalcopyrite [7] displaying embayed outlines suggestive of late crystallizate textures. Metallic phases are absent, and the only PGM noted are minute (1-2 □m long) grains/platelets of Pt- and Rh arsenides (PtAs, RhAs) [15].

*Sulphides in footwall dyke.* In M3, a subvertical, vein of impact melt (depth: 1000 m; length: ~1 m) that intrudes mafic pyroxene gneiss displays euhedral ortho- and clinopyroxe and pools of interstitial pyrite ($FeS_{1.9-2.0}$) in a glass matrix of (Na>>K) syenitic to tonalitic composition. Minor consituents of the vein include pyrrhotite, pentlandite, and chalcopyrite.

**Discussion:** The data presented provide clear evidence that siderophile-chalcophile minerals, inluding sulphides, are widely distributed in the Morokweng melt sheet. This inference is supported by a) a broad sulphur anomaly (500 to ~1200 ppm $SO_4$) in groundwater from the area underlain by the melt sheet (Necsa , unpblished data). Similarly, soils from the same area yield localized siderophile elements (Ni, Pd) anomalies [12, 13]. On the basis of the available data, the sulphide occurrences in the Morokweng boreholes may be divided into: High-, Intermediate- and Low-Temperature Assemblages.

The High-T Assemblage is represented by the sulphides in the meteorite and in the footwall dyke, as these are the only minerals in our investigation that are truly magmatic sulphides. Textural observations suggest that these phases are not primary, but are probably secondary after a transient monosulphide solid solution (MSS) that existed when the clast was thermally re-equilibrated with the host impact melt. The stability field in the footwall dyke is constrained by the 710 °C, upper stability limit of pyrite [16] and by the quenched character of melt sheets in general. The Medium-T Assemblage is represented by the pair millerite+trevorite. This assemblage has never been describede before in magmatic Ni deposits including Sudbury. The presence of millerite, a Ni sulphide common in metamorphic, hydrothermal environments, suggests that the pair might represents a low temperature condensate rich in Ni,-Fe,-Cu, C- and PGE. The Low-T Assemblage is represented by the pyrite-chlorite-coated subvertical joints that were predominantly intersected below a depth of 600 m. This hydrothermal assemblage (not listed above) has yet to be investigated.

The siderophile-rich minerals described above provide direct evidence for heterogeneous sulphur distribution in the melt sheet, whereby the very rare crystals of liebenbergite (in WF 05) may perhaps record (transient?) *sulphur-depleted* domains, The millerite-trevorite-C(?) assemblage could testify instead to the *sulphur-undersaturated* nature of the known melt sheet, but only if we knew the thermodynamic conditions for the simultaneous crystrallization of the said pair. However it formed, the condensate was apparently capable of migrating, even if only on a limited scale (cm / dm?) and to collect in small veins. In M3, the broad association of the PGMs-rich trevorite-millerite pairs and mafic-ultramafic nodules seems to favour the latter as the primary source of the metals-rich condensates. What the nodules represent is debatable, as some resemble meteorite fragments [7], while others best compare to orthopyroxene cumulates (coarse melanorite – hypersthenite). Finally, the sulphides (pyrite-pyrrhotite-pentlandite-chalcopyrite) in the impact melt dyke (M3; depth: 1000 m) implie derivation from a *sulphur-oversaturated* melt compartment quite separated from the previously described S-understurated compartments.

**The mineral potential of Morokweng:** The data presented place Morokweng as a potential candidate to impact-related Ni, PGE (Cu, Co) mineral deposits like those of Sudbury [17]. Indeed, the preserved thickness/volume of the melt sheet [6], its complex crystallization history [2], the clear evidence for vertical differentiation [5, 6], and the widespread occurrence of economically significant minerals even in footwall dykes, all reinforce the Sudbury analogue. However, unlike Sudbury, the crustal contribution to the PGEs budget of the Morokweng melt sheet appears minimal [5, 6, 17]. Likewise, the quartz-norite of the Morokweng boreholes differs from its Sudbury equivalent because it lacks the diagnostic magmatic sulphides (pyrrhotite, pentlandite, chalcopyrite) of the latter [16].

In conclusion, the potential for economically mineable deposits at Morokweng [18] appears linked to the probability to find large volumes of millerite-trevorite condensates. Alternatively, we may speculate that Sudbury-type magmatic sulphides could have fractionated from one or more compartments of sulphur-oversaturated melts like that which fed the pyrite-pentlandite-pyrrhotite-chalcopyrite-bearing dyke described above.

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