Copper and komatiitic magmatism – source of copper in the Sakatti Cu-Ni-PGE deposit in northern Finland

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Copper is an important commodity in most of the magmatic Ni-Cu-platinum group element (PGE) sulfide deposits. Several nickel camps and deposits, e.g. Noril'sk (Russia), Sudbury and Raglan (Canada), and Jinchuan (China), host individual mineralizations and mineralization types that are more enriched in Cu compared to Ni. Host rocks of these Cu-enriched Ni-deposits vary from mafic (derived from tholeiitic parental magmas) to ultramafic (derived from ferropicritic or komatiitic basaltic parental magmas) and they bear evidence of variable, but generally high silicate/sulfide mass ratios (R factor) from c. 100 to > 1000 during their formation [1.Important Cu-enrichment mechanisms also include mantle source with low Ni/Cu, fractional crystallization of segregated sulfide phase, assimilation of Cu from external source, and post-magmatic modification of sulfides by fluids.

Sakatti is a Cu-Ni-PGE deposit in the Paleoproterozoic c. 2.5-1.8 Ga Central Greenstone Belt (CLGB) in northern Finland with total reported resources of 44.4 Mt @ 1.9% Cu, 0.96 % Ni, 0.05% Co, 0.64 g/t Pt, 0.49 g/t Pd and 0.33 g/t Au [2]. The deposit was discovered by Anglo American Plc in 2009 and can be sub-divided into six distinct ore types: 1) Ni-rich massive ore, 2) Cu-rich massive ore, 3) Ni-Cu interstitial ore in gabbronorites, 4) Cu-rich disseminated ore, 5) Cu-PGE-rich stockwork vein ore, and 6) Py-rich massive ore. The mineral assemblage consists of chalcopyrite, pyrrhotite, pentlandite, pyrite and Ni-Pt-Pd tellurides of the melonite-merenskyite-moncheite series. The sulfide phase shows evident fractionation from Ni-rich monosulfide solid solution (mss) to Cu-rich intermediate sulfide solid solution (iss) [3, 4]. Bulk of the sulfides in Sakatti show narrow range of $\delta^{34}S$, between +2 and +4 ‰, indicating non-magmatic source of sulfur for much of the deposit. The Sakatti sulfide deposit is underlain by argillaceous sediments with thick anhydrite-gypsum intervals, some of which, are in direct contact with the cumulates and show prominent magma-country interaction.

The sulfide ores in Sakatti are hosted by chonolith-style magma conduit composed of ortho-, meso- and adcumulates, pegmatoidal gabbronorites and fine-grained komatiitic rocks. These are derived from a komatiitic parental magma in equilibrium with Fo_{92-93} olivine (c. 19–21 wt. % MgO). Olivine in the Sakatti deposit contains relatively high Ni contents (2500–3500 ppm), which can be due orthopyroxene fractionation in the lower crust en route to surface [5]. Typical mineral assemblage contains olivine + chromite ± orthopyroxene ± clinopyroxene ± plagioclase. All host rocks show one to two orders of magnitude enrichment in LREE compared to that of chondrite. The age of the ultramafic magmatism is constrained to c. 2054 Ma [6], which corresponds to a global Ni-Cu-PGE mineralizing event with coeval ages in e.g. Bushveld (South Africa), Mirabela (Brazil) and Elanskii (Ukraine) complexes, related to the final break-up of the supercontinent Kenorland.

With R factor modelling it is not possible to achieve the observed low Ni/Cu ratio at Sakatti. The same is true also with the N factor (zone refining) or with the multistage upgrading modelling. Therefore, four other processes that could account for the anomalously high Cu-content and low Ni/Cu of Sakatti are discussed: 1) Magma generation from Cu-enriched metasomatized mantle source 2) removal of Ni-rich mss at depth, 3) Assimilation of copper from country rocks, and 4) post-magmatic upgrade of the Cu grades.

[1] Cu-enriched mantle source is commonly attributed to metasomatized mantle. Uncontaminated CLGB komatiites have MREE-enriched hump-shaped patterns, reflecting limited marks of metasomatized source at the time of their separation [7]. Mantle source alone contributing the copper contents in Sakatti is doubtful, as the degrees of partial melting for parental melts are high (c. 15-25 %) [5, 7].

[2] Brownscombe et al. [3] proposed that the primary mss was segregated at earlier stage and the Cu-rich portion of it was re-assimilated and injected into the current host cumulates by later magmas that did not equilibrate with the sulfides, possibly due to a kinetically controlled process, similar to that proposed for varying metal tenors in the Raglan deposits [8]. However, the most primitive olivine cumulates also host the most primitive mss, indicating that host magma took part to the sulfide segregation to some degree. R factors for Sakatti are generally low (50–100) and the modelled Ni/Cu values are generally much higher than the ones observed, therefore indicating that there must be additional processes contributing to the varying Ni/Cu ratios. However, an alternating option could arise from computational simulations, where Ni/Cu ratios between 1.9 and 0.4 ratios can be produced for sulfides during closed fractional crystallization scenario depending on the initial sulfur content of the parental magma [5].

[3] Magma-sulfate interaction textures, positive $\delta^{34}S$, elevated Fe^{3+} contents in chromite [9] and similarity in REE-patterns between cumulates and sulfate rocks indicate that Sakatti host rocks have assimilated their sulfate-bearing country rocks during ascent and/or in-situ. However, most of the seemingly unaltered sulfate sediments bear very low Cu contents, and besides, regionally potential assimilants have Cu contents typically below 150 ppm [10, 11]. Yet copper collection during assimilation could be facilitated by oxidized magma, coexisting magmatic fluid(s) [12] and formation of xenomelts [13], which would form as a response to assimilation of carbonate-sulfate sediments.

[4] Re-Os [14], U-Pb [6], Pb-Pb, and Cu isotope results [15] point towards later remobilization of the Cu-rich portions of the ore. However, no obvious alteration patterns resulting from late hydrothermal fluids are found in the deposit. Age constraint for post-magmatic modification spans from c. 1.9 to 1.8 Ga [6, 14], which include ages of the numerous Au and IOCG (Iron-Oxide -Copper-Gold) deposits within the CLGB [16], suggesting mobility of copper during this period. Massive sulfide ores, however, pose a strong chemical buffer, which means they are not easily extensively affected by fluid activity.

The discussed processes are not mutually exclusive and could have contributed to the high Cu budget. The available data indicates that processes 2) and 4) were the dominant controls of Cu.

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