Crustal-Scale Magma Flow Networks and Magmatic Ore Deposits: Predicting Needles in Haystacks

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Intrusion-hosted Ni-Cu-PGE magmatic sulfide deposits accumulate within crustal-scale magma networks that transport mantle-derived mafic and ultramafic magmas from mantle sources to the surface. Magmatic sulfide mineralization within such networks occurs in a variety of traps that form due to a combination of structural and fluid-mechanical processes. Ore-hosting structures include tubular chonoliths (e.g., Nebo-Babel and Limoiera), ribbon-shaped sills (e.g., Noril'sk and Nkomati/Uitkomst), funnel-shaped jogs within conduits (e.g., Voisey's Bay Ovoid), elongate funnel-shaped flares within dike-like intrusions (Eagle, Tamarack), blade-shaped dikes (e.g., Expo-Ungava deposits in the South Raglan belt), and near the bases of layered intrusions, which often comprise stacks of sills, adjacent to the entry points of feeder dikes (e.g., Voisey's Bay Eastern Deeps). In all of these settings, economic accumulations of magmatic sulfides are thought to be associated with focused and channelized zones of high magma flux. Such mineralized zones make up only a tiny fraction of the system as a whole, so it is clear that explorers will need new tools and approaches to find new proverbial needles in magmatic haystacks. Although considerable research has been directed to the links between lithospheric architecture and Ni-Cu-PGE mineralization and the geochemical origins of the associated sulfide mineralization, far less work has focused on the physical processes involved in the transport of the host magmas, how and where high-flux channels develop in magma transport networks, and how and where sulfide liquids separate and accumulate to form high-value ore deposits.

Using a combination of theory and laboratory experiments, we examine the following four hypotheses that address these key questions: (1) Crustal-scale magma networks form by multiple transitions between dikes and sills, which are strongly controlled by preexisting structures. This suggests that structural traps for ore, such as funnel-shaped dike-sill transitions, are predictable. (2) Chonoliths and ribbons are preferred sites of mineralization, and they form by a combination of the development of mechanical instabilities at advancing dike/sill fronts, thermal erosion of country rocks and consequent widening of flow pathways, and concentration of magma flux through these pathways while crystallization occurs in the low-flux regions. (3) Magma flow within established networks is periodic and varies spatially over time as a partially solidified network is reactivated by new batches of hot magma. This leads to preferred linear channels within originally sheet-like bodies of flowing magma. (4) Mineralization within magma networks occurs when the separation of dense Ni-Cu-PGE sulfide liquids occurs within channels, transient eddies, and structural traps where magma flux is focused above a horizontal floor.

The signals of favorable host intrusions include high proportions of cumulate rocks; characteristic tube-like morphologies, forming a continuum with elongate canoe-shaped flared or blade-shaped dikes; evidence for strong interactions with country rocks such xenoliths, marginal breccias, and pegmatoidal marginal rocks ("taxites"); and proxies for anomalously slow magmatic cooling rates in relation to small size of intrusion, such as slow thermochronologic cooling rates and large thermal aureoles.