
1Centre for Planetary Science and Exploration / Dept. of Earth Sciences, University of Western Ontario, London ON.

Introduction: The Offset Dykes are impact melt-bearing dykes that formed as a part of the ~1850 Ma (Krogh et al. 1984) Sudbury impact event. They occur concentrically around – and radiating outwards from – the Sudbury Igneous Complex (SIC), the remnants of a differentiated impact melt sheet from which the Offset Dykes originated [2,3]. They consist of two phases: an inclusion- and sulfide-rich quartz diorite (IQD) in the centre of the dyke, and an inclusion- and sulfide-poor quartz diorite (QD) along the margins of the dyke [4]. A third Offset Dyke lithology that is often overlooked is the so-called metabreccia, which consists of a recrystallized heterolithic breccia that is unique to the Offset Dykes north of the SIC in the North Range [5]. However, some details regarding the origin and emplacement of the Offset Dykes remain uncertain. In this study we evaluate the current understanding of the North and East Range Offset Dykes (Hess, Trill, Ministic, Cascade, Pele, Foy, Parkin, and Whistle dykes) and identify a coherent emplacement model that is consistent with the geological, mineralogical, and geochemical observations.

Potential Emplacement Methods: The most common hypothesis for the formation of the Offset Dykes involves two intrusion events: an early emplacement of clast- and sulfide-poor melt from the SIC, followed by emplacement of an inclusion- and sulfide-rich melt after the melt sheet became sulfur-saturated (c.f., Worthington [6], Copper Cliff [7], Trill [8], Whistle and Parkin dykes [5]. Although cross-cutting relationships between QD and IQD (e.g., enclaves of QD in IQD at the Foy dyke [9]) are consistent with the concept that QD must have been at least partially solidified when IQD emplaced, there are some spatial relationships that are not explained by multi-stage emplacement model(s). For example, these studies provide no explanation as to why a second intrusion of IQD is often, but not always located in the centre of QD, and it is not clear what physical process of melt sheet re-adjustment was responsible for a second phase of injection of mineralized inclusion-bearing quartz diorite. An alternate hypothesis is that a single injection of clast- and sulfide-bearing melt occurred, and that flow differentiation was responsible for separating out clasts, forming a clast-rich phase in the middle (IQD) and a clast-poor marginal phase (QD) [10].

Methodology: Fieldwork was conducted in the summer months from 2013 – 2018 on property owned by Wallbridge Mining Company Limited covering the distal regions of the Hess, Trill, Cascade, Ministic, Pele, Foy, and Parkin dykes, as well as the Whistle Pit, owned by Glencore and Vale, and North American Nickel Post Creek site. Updated regional field maps of the Trill and Parkin Offset Dykes were created at 1:2,000 and 1:5,000 scale [11], and detailed trench maps were created at 1:100 scale at the Hess, Trill, Pele, Foy, and Parkin dykes [10-12]. Samples were analyzed using optical microscopy, wavelength (WDS) and energy dispersive spectrometry (EDS), and chemical analysis via inductively coupled plasma optical atomic emission spectroscopy (ICP-AES) and mass spectrometry (ICP-MS).

Geochemical Variation of the North Range Offset Dykes: The majority of the North Range Offset Dykes have very similar geochemical properties suggesting they were emplaced at around the same time, relative to the differentiation of the SIC. Minor variations in chemistry between the dykes can be explained by the effects of their host rocks, which altered both the original composition of the impact melt and subsequently altered the melt through the assimilation of local clasts. For example, subtle differences between the Parkin dyke and the other North Range dykes (e.g., lower Sr, TiO2, Ba, and Rb) can be attributed to the effect of the Huronian metasedimentary rocks that host the dyke. Similarly, Foy and Whistle Offset Dykes exhibit minor variations in terms of their REE profile, and the ratios of incompatible elements (e.g., high Th/U and La/Y ratios). This is potentially due to assimilation of Levack Gneiss material that hosts sections of both dykes, and exhibits similar REE profiles and incompatible element ratios to the dykes [13]. An exception is the chemically evolved nature of the Pele dykes, which suggests that the dykes were emplaced later than the other North Range dykes, from a portion of the SIC melt sheet that was more chemically evolved and devoid of clasts.

Emplacement mechanisms of IQD and QD: In the multiple emplacement model, dykes consisting of only QD or only IQD would be expected. There is one instance of a QD-only dyke (Pele), which suggests there was at least one late injection of clast-poor melt. However, the lack of an IQD-only dyke is inconsistent with the multiple emplacement model. The cross-cutting relationships between QD and IQD have commonly been cited as evidence for multiple emplacements. However, enclaves of QD and IQD within IQD are possible in the flow differentiation model as well,
and only requires that portions of the dyke begin to crystallize while the majority of the dyke continues to flow. For this reason, the QD / IQD cross-cutting relationships are consistent with either model and should not be considered as evidence to support one over the other. The variable nature of the QD / IQD contact could also be the result of either model. In the flow differentiation model, minor differences in the immiscibility between the clast-poor and clast-rich melts (affected by clast content, viscosity, density, and temperature) would change the nature of the contact over short distances. In the multiple emplacement model, this implies that some portions of the dyke are not fully crystalline prior to emplacement of IQD. Finally, the presence of primary sulfides in QD and IQD imply that both must have been emplaced after sulfides began to concentrate at the base of the melt sheet. This is inconsistent with many emplacement models that suggest an early QD emplacement and a later IQD emplacement.

**Metabreccia formation:** Metabreccia shares many similarities to footwall breccia, and does not appear to be related to QD or IQD. The footwall breccia is also composed of quartz and feldspar and shows diffuse matrix-clast contacts. The texture of the matrix of both breccias is characterized by poikilitic to poikiloblastic textures and signs of partial melting and local recrystallization features are also present in footwall breccia. Geochemical data suggests that metabreccia is not genetically related to QD or IQD, but instead shares a closer resemblance to footwall breccia [14]. Based on the petrographic and geochemical similarities, footwall breccia is considered to be the closest analogue to metabreccia, and it seems likely that metabreccia is metamorphosed and thermally overprinted footwall breccia (as was proposed by [15]), and that this hypothesis likely holds true for metabreccia found throughout the North Range Offset Dykes.

**A model for the emplacement of the North Range Offset Dykes:** In summary, the following working hypothesis is presented for the timing relationship of the North Range Offset Dykes, the relationship between QD and IQD, and the formation of metabreccia. The impact event produced a fractured and brecciated footwall (footwall breccia) and an impact melt sheet that was initially stratified with a clast rich bottom and top. As the melt sheet cooled, it started to become sulfur saturated and sulfides formed and settled towards the base (e.g., [2,3]). Late-stage adjustments in the floor opened dilatant fractures (cf., [6]) into which the clast- and sulfide-rich melt was emplaced. The first melt is clast rich but as the base of the melt sheet drains locally the melt available becomes less clast rich. It is believed that the Hess Offset Dyke was emplaced into a concentric fault system that would correspond with the terrace of the crater. The exact timing of this emplacement is not clear; however, relationships between the Foy and Hess indicate that both were liquid at the same time [10]. During emplacement, clasts of the brecciated footwall rock material were ripped up and included into the dyke. The heat of the Offset Dykes recrystallized the breccias resulting in pods of metabreccia. The Hess dyke, having been emplaced from the collapsed terrace and not directly beneath the melt sheet, would not have ripped up the same brecciated material as the radial dykes, explaining why it lacks metabreccia. As the dykes continued to flow, clasts and sulfides moved away from the walls of the dyke, starting to concentrate in the centre, resulting in a clast-poor marginal phase (which crystallized to form QD) and a clast-rich central phase (that crystallized to form IQD) [10]. The above is believed to have occurred for the Hess, Trill, Ministic, Cascade, Foy, Parkin, and Whistle dykes, at approximately the same time – geologically speaking. After these dykes solidified, the remaining melt sheet began to differentiate. After some differentiation had occurred, the chemically-evolved clast-poor melt was emplaced to form the Pele Offset Dykes.