BLADE-SHAPED DIKES AND NICKEL SULFIDE DEPOSITS: A MODEL FOR THEEMPLACEMENT OF ORE-BEARING SMALL INTRUSIONS

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Abstract

Most of the world’s major deposits of nickel and copper were formed as accumulations of magmatic sulfide liquid within small mafic-ultramafic intrusions. Ore-hosting intrusions exhibit a variety of forms but typically show greater horizontal than vertical extents, occurring as tube-shaped chonoliths, narrow elongate sills, boat-shaped bodies, or sword blade-shaped dikes with originally horizontal principal axes. Sulfide accumulation at the downward termination of blade-shaped dikes is noted in a number of deposits worldwide. Based on evidence from continental dike swarms, Icelandic fissure eruptions, and active shield volcanoes, we suggest that these blade-shaped bodies formed by magma migration within vertical fractures that propagated laterally rather than vertically. Some examples, notably the bladed dikes of the South Raglan trend, have contact relationships indicating processes of active erosion, assimilation, and replacement of country rock. Where such dikes are injected into mixed volcanic-sedimentary sequences, thermal modeling of interaction with nonrefractory country rock predicts repeated formation and collapse of transient chilled margins against narrow zones of partially molten wall rock. Where the wall rock is sulfide-rich sediment, this generates a slurry of sulfide liquid, country-rock xenoliths, and chilled margin fragments that flows down the wall to accumulate at the bottom edge of the dike. This type of mixture is commonly seen as “sulfide-matrix ore breccias” in intrusion-hosted deposits. Widening of the conduit along zones of easily eroded country rock may result in a transition from a dike-like to a tubular chonolith geometry. Multiple magma pulses within the same magma conduit may give rise to complex superimpositions of ore zones, further complicated by formation of sulfide-silicate melting-infiltration fronts. Hence we argue that the bladed-dike geometry is an end-member type that commonly serves as a precursor form to a range of eventual geometric forms; recognition of this basic geometry provides general insights into the origins of other important deposits.

Introduction

Many of the world’s major Ni-Cu-platinum group element (PGE) sulfide deposits, including those at Noril’sk (Russia), Voisey’s Bay (Canada), Jinchuan and the Kalatongke-Huangshan nickel province in China, and the Midcontinent rift of the USA, are hosted by small mafic or mafic-ultramafic intrusions thought to have developed as conduits within magmatic plumbing systems (Naldrett and Lightfoot, 1999; Lightfoot and Evans-Lamswood, 2015; Barnes et al., 2016). Between them, such intrusions host the bulk of the potentially mineable sulfide Ni-Cu resources worldwide and contain some of the world’s most valuable individual orebodies (Barnes et al., 2017a). Typically only a very small proportion (about 1 ppm in the case of the Noril’sk-Talnakh intrusions in the Siberian large igneous province) of the total volume of the host magmatic province is taken up by ore-bearing intrusions (Naldrett and Lightfoot, 1999). Their origin remains enigmatic, and as mineral exploration targets they are difficult to detect, hence the need for genetic models to predict their location and geometry. Most of these intrusions fall along a spectrum from tubular chonoliths through boat- or funnel-shaped bodies to zones of widening within dike complexes (Barnes et al., 2016). Many sill-like bodies have contacts that truncate or even replace layering in the country rock, indicating processes of active erosion and assimilation as opposed to emplacement by extensional space filling (e.g., Uitkomst; Gauert, 2001). Some deposits form at the basal edge of sword blade-shaped dikes or within downward-terminating dike-like projections forming keels at the base of apparently boat shaped intrusions (Fig. 1). In this contribution, we consider the origin of mineralized bladed dikes and show how this model can be generalized to understand the origin of a large part of the spectrum of intrusion-hosted Ni-Cu ores.

Examples of Dike-Hosted Ores

Bladed-dike morphologies have been recognized in a number of different deposits in a range of settings, including the ~1883 Ma shallow subvolcanic intrusions of the South Raglan trend in Quebec (Mungall, 2007) (Fig. 1A), the ~2735 Ma subvolcanic Eagle’s Nest intrusion in the Superior province, Ontario (Mungall et al., 2010) (Fig. 1B), and the ~1840 Ma deep crustal Savannah (Sally Malay) deposit (Fig. 1C) in the convergent Halls Creek orogen in the Kimberley region of Western Australia (Sproule et al., 2000; Hicks et al., 2017). We describe these in turn, then show how these geometries form an end member of a continuum leading to tube-like chonoliths.

A hallmark feature of several of these intrusions is the presence of a mixture of exogenous and endogenous xenoliths in semimassive ore. This feature is shared by a number of other conduit-hosted deposits, including Voisey’s Bay (Li and Naldrett, 2000; Lightfoot et al., 2012; Barnes et al., 2017b),
Fig. 1. Examples of Ni-Cu orebodies within bladed dike or boat-keel shaped intrusions (see text for data sources). Legend refers to all frames except where specifically labeled. (A) Mequillon; (B) Eagle's Nest; (C) Savannah; (D) Kalatongke; (E) schematic geometry of funnel-dike or flared-dike geometry with a downward closing termination based on composite of Kalatongke and the Central Asian orogenic belt (CAOB) intrusions; (F) Huangshandong (CAOB); (G) Huangshanxi. Abbreviations: $ = matrix, bx = breccia.
several of the small mafic-ultramafic intrusion-hosted deposits in central Finland (Makkonen, 2015), Radio Hill (De Angelis et al., 1987) and Nebo-Babel (Seat et al., 2007) in Western Australia, and the Aguablanca deposit in southwestern Spain (Tornos et al., 2001; Piña et al., 2006).

**Raglan South—Expo Intrusive Suite**

Probably the best-preserved examples of Ni-Cu sulfide ores hosted within dike-shaped intrusions are those of the Expo Intrusive Suite in the hypabyssal feeder complex beneath the Raglan deposits of the Proterozoic Cape Smith belt in the New Quebec orogen. These bodies form part of the Chukotat Suite within the extensive 1.88 Ga circum-Superior large igneous province (Ernst and Jowitt, 2013). The Expo Intrusive Suite comprises a group of originally vertical ultramafic dikes that were emplaced into a layered sequence of basalt and sediment on the northern margin of the Superior province, with long-axis orientations approximately parallel to the regional strike. Postemplacement regional tectonics deformed the dikes into a series of open folds with wavelengths and amplitudes of several kilometers and fold axes perpendicular to the strike such that the dikes are now exposed over several kilometers of structural relief. The dimensions of the dikes are of the order of 100 km in strike length, 3 km in vertical extent, and tens to hundreds of meters wide. The dikes were emplaced laterally within the basalt-sediment pile, such that their lower terminations rest on massive basalt of the lower Beauparlant Formation, and their upper terminations are geometrically complex dike-sill transitions where they open up into an overlying sequence of turbiditic metasediments of the Nuvilik Formation before continuing upward as ultramafic dikes up to 1 km wide within the Nuvilik Formation turbidites. Where they are enclosed by massive basalt of the upper Beauparlant Formation, they have sharp chilled margins and have not undergone any discernable contamination or differentiation. The resulting rock is a coarse-grained ophitic melagabbro-norite with bulk composition similar to that of its chilled margins. The chilled margins against basalt are less than 1 m thick and are mantled by narrow pyroxene hornfels aureoles that are also less than 1 m thick. Where dikes are in contact with nonrefractory sedimentary rocks, they become much broader, show clear signs of partial melting and assimilation of their host rocks, and are filled with ultramafic cumulates. This is true for the midsections of the dikes, where they are in contact with interlayered sulfidic clastic sediments and basalts of the middle Beauparlant Formation, and in their uppermost extensions, where they are surrounded by turbidites. Chilled margins are effectively absent, with medium- to coarse-grained ultramafic cumulates sitting adjacent to partially melted country rocks except against refractory country rocks like quartzites. In some notable examples the refractory host rocks persist as relict beds extending tens of meters into ultramafic bodies, suggesting that much of the ultramafic rock has removed and replaced fusible metasediments while leaving refractory rock types intact. Below the broadened peridotitic portions of the dikes, the dikes narrow downward into the underlying massive basalts of the lower Beauparlant Formation, showing broad transitions from coarse-grained gabbroic marginal facies through coarse-grained sanidinite-facies metabasalt with pockets of pegmatic partial melting through pyroxene hornfels out into host basalts. Even experienced core loggers commonly cannot pick an intrusive contact in these transitions. Inside the margins, the lower terminations of the dikes are filled with a characteristic sequence from bottom to top of massive sulfide, net-textured sulfide in a pyroxenitic cumulate, followed by pyroxenite and peridotite with interstitial and locally globular disseminated sulfide mineralization (Barnes et al., 2017c). In some localities (e.g., Mequillon) the pyroxenite and peridotite cumulates are packed with xenoliths and autoliths of a variety of clast types including fragments of fine-grained melagabbro-norite, dunite, and possibly country rock. These xenoliths diminish overall grade, because the disseminated sulfides are only present in the matrix of the breccia. The base of each dike is typically rounded like the hull of a boat but in many cases is cut by a much narrower downward-propagating dike filled with comngled barren and net-textured pyroxenite and massive sulfide. Typically, this narrower dike has carried away all or most of the massive sulfide from the trough structure at the base of the original broader dike.

Because of the regional folding of the dikes, their basal portions are exposed on the flanks of anticlines, and their uppermost portions sit in synclines; at surface the deposits are therefore all located at the tips of exposed dike segments. Where such dike segments are relatively short, exposed only near the axes of synclines, they appear boat-shaped and are apparently isolated from other parts of the complex due to the removal of the intervening sections in the anticlines. In one instance a massive sulfide keel dike is the only remaining portion of the system, which makes it exceptionally hard to detect.

**Eagle’s Nest**

The Eagle’s Nest deposit (Mungall et al., 2010) forms part of the Ring of Fire in the Superior province of northeast Ontario, constituting part of a complex of mafic-ultramafic intrusions within the Archean McFaulds Lake greenstone belt. The deposit is hosted by a N-striking blade-shaped body that intersects the bedrock surface over approximately 500 × 75 m and plunges vertically for about 1.5 km before being truncated and offset by a major fault at depth. Massive and net-textured mineralization resides at the northern tip of the dike, commonly immediately in contact with the enclosing tonalites and always within the northernmost 150 m of the structure (Fig. 1). It is interpreted to have been a sword blade-shaped dike similar to the Expo dikes, with its long axis close to horizontal and its intermediate 500-m axis vertical at the time of its emplacement; in this configuration the sulfide mineralization all sits on the basal termination of the dike. It has been rotated through 90° during subsequent deformation of the host greenstone belt. The southern (i.e., uppermost) tip of the dike shows extensive brecciation and stoping of the host tonalite. Autolithic breccias, including blocks of mineralized peridotite enclosed in a barren matrix, are observed within the intrusion, possibly indicative of emplacement into an active fault system subject to multiple episodes of both tectonic and magmatic reactivation.

**Savannah, Western Australia**

The Savannah (formerly Sally Malay) deposit (Thornett, 1981; Sproule et al., 2000; Hicks et al., 2017), located within
the Halls Creek orogen in far northeastern Western Australia (Tyler et al., 2012; Kohanpour et al., 2017) comprises an accumulation of sulfide matrix breccias along the basal contact of an originally subvertical blade-shaped dike, now tilted through 90° about an axis normal to the dike wall such that its outcrop pattern reflects its original cross-sectional geometry (Fig. 1). The main body of the dike is occupied by interlayered peridotite (poikilitic olivine orthocumulate) and troctolite in the lower part, with a fringe of strongly orthocumulate olivine norite and cumulate norite in the upper part. The peridotite unit is locally layered, with the layering normal to the dike walls subvertically dipping in an orientation parallel to the plunge of the main axis of the orebody. The lower margins of the dike (where not occupied by sulfide) consist of a contaminated noncumulate norite unit with abundant inclusions of partially digested country-rock paragneiss. The sulfide ores themselves contain a polymict assemblage of paragneiss and other country-rock xenoliths and xenocrysts up to decimeters in size and also endogenous norite inclusions from the host intrusion (Fig. 2).

In the case of Savannah and Eagle’s Nest, the dikes are part of locally voluminous suites of mafic-ultramafic intrusions but not (as far as we know) parts of recognized regional dike swarms. Their emplacement controls appear to be local stress regimes rather than large-scale regional far-field plume-related extension as in the case of typical continental-scale mafic dike swarms (Halls, 1982; Fahrig, 1987).

Other intrusions with transitional boat-dike morphologies

Examples of other intrusions having geometries combining boat-shaped intrusions with downward dike-like keels are shown in Figure 1D-G. Numerous intrusions in the Central Asian orogenic belt, of which Huangshandong (Fig. 1F) (Gao and Zhou, 2012; Gao et al., 2013) and Huangshanzhixi (Fig. 1G)
Bay deposits (Lightfoot et al., 2012; Saumur and Cruden, 2016, 2017) and in lateral pinch-out features at Kambalda (Staude et al., 2016). In some cases, as at Savannah, Eagle’s Nest, and in the South Raglan deposits, these features have localized subsequent shearing and hence display durchbewegung breccia fabrics, but textural and structural evidence implies the breccias had an original magmatic origin overprinted by shearing. Sulfide-filled dikes provide further constraints on emplacement mechanisms of the ores and their host intrusions.

**Emplacement Mechanisms**

Traditionally, emplacement of mafic dikes has been regarded as primarily by upward propagation driven by the buoyancy of the mafic magma relative to the wall rocks. However, two lines of evidence—anisotropy of magnetic susceptibility (AMS) in large continent-scale dike swarms (Ernst et al., 1995; Ernst, 2007; Haste et al., 2014) and real-time seismic observations of dike propagation under actively erupting shield volcanoes (Ericsson et al., 2014; Orr et al., 2015; Sigmundsson et al., 2015)—show that in many cases dike propagation is as much (or more) lateral than it is vertical, and dikes emplaced in this way have downward and lateral as well as upward propagation fronts and terminations (Kavanagh et al., 2015). Considering continental dike swarms with lateral extents of thousands of kilometers (Fahrig, 1987), it is obvious that the principal axis of elongation of most dikes is horizontal, with intermediate vertical axes. Real-time determination of earthquake foci in Iceland also demonstrates that mafic dikes feeding fissure eruptions propagate laterally as sword blade-shaped structures from magmatic centers (http://hraun.vedur.is/ja/quakes3d/). This may be the key to understanding ore formation in bladed dikes.

In a detailed study of the South Raglan dike-hosted deposits, Mungall (2007) showed that the magmas had undergone as much as 50% contamination by country-rock metasediments and that ore formation was a consequence of the addition of country-rock sulfide. This interaction was the result of the emplacement of picritic to komatiitic melts through a high-flux conduit and selective erosion of nonrefractory sedimentary layers within a predominantly basaltic country-rock succession. Figure 3B illustrates the process based on a simple model of conductive heat flow (Crank, 1975; model parameters chosen by Chung and Mungall, 2009) through the wall of a static picritic dike (Fig. 3A) against either basaltic (Fig. 3C-E) or sedimentary (Fig. 3F-H) host rocks. The temperature distribution through the region of the contact is shown in Fig. 3B for three different times, compared to the solidus temperature of both sediment and basalt, and the temperature at which 50% of the picrite would be crystallized, which we take to be the rheologically solid chilled margin at any given time. After one day (solid gray curve in Fig. 3B) the chilled margin is about 20 cm wide. Where the host rock is basalt, it never reaches a temperature above its solidus during the cooling history of the dike. However where the host rock is sediment, the chilled margin is immediately separated from the solid host rock by a narrow zone of melted sedimentary rock. This contact configuration may initially be stable, but as time passes and both the melted sediment and the solid chilled margin thicken, the chilled margin will be unstable because it is a thin dense solid sheet suspended between two buoyant
liquids. Collapse of the chilled margin (Fig. 3G) allows mixing of the melted host rock into the main body of the dike, promoting melt contamination and crystallization of olivine. Sulfide introduced to the magma from the melted host rock will join the olivine and the fragments of chilled margin in a dense slurry that descends to collect at the base of the dike. Where the melted host rock has moved away from the contact, fresh picrite will once again be in contact with cold sedimentary rock on a surface that has retreated somewhat (Fig. 3H), and the process will occur again until the contaminated magma reaches a point of saturation with multiple silicate minerals and has cooled sufficiently that the sedimentary rock will not melt in the contact zone. The dike therefore enlarges itself by replacing fusible host rocks with ultramafic magma and cumulates. The eventual form of the dike may be dramatically altered by this fortuitous expansion into favorable host rocks, masking its origin as a blade-shaped dike. Depending on the way the resulting intrusion is intersected by the subsequent erosion surface, the geometry so formed may evolve into an apparently boat shaped intrusion. Resistant beds may remain within the volume of the ultramafic dike, propped up on ultramafic crystal mush and appearing as isolated layers of refractory sediment entirely surrounded by peridotite.

The major conclusion is that interaction with nonrefractory country rock causes repeated formation and collapse of transient chilled margins against narrow zones of partially molten wall rock. Where the wall rock is sulfide-rich sediment, this generates a slurry of sulfide liquid, country-rock xenoliths, and chilled margin fragments that flows down the wall to accumulate at the bottom edge of the dike, giving rise in ideal circumstances to a basal zone of sulfide-matrix ore breccia as seen at Savannah. A sludge of cumulus silicate crystals, xenoliths, and disseminated sulfide develops down the lower side walls and along the base, modified by subsequent percolation of dense, low-viscosity sulfide liquid through the pore space between cumulus crystals and rock fragments (Barnes et al., 2017b). The time and length scales of the evolution of an ore-forming conduit system (Barnes and Robertson, 2018) depend...
upon the extent to which it is kept hot by continuing flow of magma. Where flow is continuous and prolonged, the geometry evolves toward a widening tube-like sill where the country rock is least refractory. Erosion of the country rock then proceeds through stoping of the roof as well as lateral erosion of the side wall. This process will be favored where the magma exploits zones of structural weakness; in the case of the Voisey’s Bay system, these weaknesses take the form of intersections between subhorizontal shear zones and steep faults that initially localize the dikes (Saumur et al., 2015; Barnes et al., 2016; Saumur and Cruden, 2016). Tubular sill-like bodies could then develop along the preferred horizons, giving rise to chonolith geometries as seen in deposits such as Kalatongke. Depending on regional stress regimes and volume of magma supply, such systems could potentially evolve into layered intrusions (Ernst and Buchan, 1997).

The basic mechanism for wall-rock assimilation proposed here could operate just as well at the margins of intrusions propagating laterally as sills with flat sword-blade morphologies. Such intrusions could initiate as finger-like lobes at the edges of propagating sills (Hansen and Cartwright, 2006; Schofield et al., 2012). The ore-hosting intrusions at Noril’sk-Talnakh (Lightfoot and Zotov, 2014) and Uitkomst (Dewaal et al., 2001; Gauert, 2001; Yudovskaya et al., 2015) could have formed in this manner.

**Intrusion propagation aided by sulfide infiltration**

Accumulation of semimassive sulfide at the lower edge of bladed dikes could serve to enhance the erosion and propagation process (Fig. 4E). This could occur initially through a process whereby hot, low-viscosity, dense sulfide liquid invades fractures that form part of the process zone (Dewaney et al., 1986), the system of mainly dike parallel fractures that characteristically develops ahead of propagating dikes. The process is self-enhancing to a degree through the mechanism described by Staude et al. (2017), whereby the sulfide melt penetrates fractures in the country rocks and causes localized melting along those fractures. The driving pressure for the downward sulfide migration gets larger as the vertical extent of the sulfide network increases, giving rise to the development of melt-infiltration fronts and in some cases sulfide-filled veins into the country rock (Saumur and Cruden, 2017) at scales of meters to tens of meters. The ultimate examples of such migrating sulfide vein-dike networks are the kilometer-scale offset dike systems at Sudbury (Lightfoot, 2016), where the localizing fracture network was produced by the impact event; in the model presented here the cause is different and the scale is smaller, but the processes are analogous.

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**Fig. 4.** Stages in propagation of a transitional dike to chonolith transition. (A, B) Lateral propagation of crack-filling dike, initiation of selective melting, and intrusion along a favorable horizontal stratum in country rock. (C) Continuing lateral propagation along favorable horizon, aided by suitable stress regime and preexisting structural grain caused dike to transition into tube-like chonolith. (D) Idealized geometry of a Kalatonge-like funnel-tube intrusion (Barnes et al., 2017a). (E) Detail of lower edge of dike showing formation of sulfide matrix breccias and sulfide vein forming at infiltration-melting front into fractured process zone at dike tip.
Conclusion

All of the processes alluded to above—lateral propagation of dikes, widening of conduits due to preferential thermal erosion of country rocks, gravity flow of sulfide-silicate-xenolith slurries, and self-enhancing propagation of sulfide vein-dike networks into process zones in country rocks—coupled with postemplacement tilting and random intersection with present-day erosion surfaces, could work together to create the spectrum of mineralized intrusion geometries highlighted in Figure 1: sword blade-shaped dikes, boat-shaped intrusions with downward terminating keels, funnel-dike transitions such as Kalatongke (Fig. 1D), and potentially tube shaped chonoliths. This model also accounts for the commonly observed association of small intrusions and breccia-textured semimassive ores. Furthermore, it suggests that the unexposed bottom edges of sulfide-bearing dikes, such as the Paleogene East Greenland macrodikes (Holwell et al., 2012), which like the Raglan dike suite contain globular sulfides frozen into their chilled margins, should be regarded as potential exploration targets. More generally, the morphology and internal structure of small mafic and/or ultramafic intrusions should be considered as part of the set of criteria used in prioritizing exploration targets, bearing in mind the effects of postemplacement deformation.

Acknowledgments

We thank Panoramic Resources Ltd. for access to Savannah, Canadian Royalties Inc. for access to the Raglan South deposits, Noront Resources Ltd. for access to Eagle’s Nest, various colleagues—particularly Sandy Cruden, Tony Naldrett, Peter Lightfoot, Yajing Mao, and Greg Dering—for discussion, Marco Fiorentini and Valentina Taranovic for reviews of early drafts, and Benoit Saumur and Richard Ernst for perceptive reviews of the submitted manuscript.

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