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Large Igneous Provinces and Their Mafic-Ultramafic Intrusions

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Abstract. Here we provide an overview of the range of settings for mafic-ultramafic layered intrusions as part of the plumbing system of Large Igneous Provinces, and address the metallogenic implications.

1. Definition and Characteristics

LIPs have become an important focus for research in recent years due to their use in paleocontinental reconstructions [1], in exploration targeting [2-3], as planetary analogues [4-5], and as a result of their links to dramatic climate change [5]. LIPs represent large volume (>0.1 Mkm^3; frequently above 1 Mkm^3), mainly mafic (-ultramafic) magmatic events of intraplate affinity (based on tectonic setting and/or geochemistry) that occur in both continental and oceanic settings, and are typically either of short duration (<5 Ma) or consist of multiple short pulses that occur over a maximum of a few 10s of Ma. LIPs comprise volcanic packages (flood basalts) and a plumbing system of dyke swarms, sill complexes, layered intrusions, and a crustal magmatic underplate. LIPs can also be associated with major silicic magmatic events termed Silicic LIPs (SLIPs), as well as carbonatites and kimberlites. LIP events occur at a variable rate through time, averaging every 20–30 Ma, but with possible peaks associated with supercontinent breakup, back to at least 2500 Ma. The rate of LIP occurrences in the Archean is less certain due to its poorer preservation [5, 6].

1.1 Plumbing System of LIPs

Mafic-ultramafic (M-UM) intrusions are an important component of the plumbing system of LIPs, as outlined below. LIP-related regional mafic dyke swarms that can have linear (>2000 km long), radiating (up to >2500 km in radius), and giant circumferential (sub-circular or elliptical) geometries that form swarms up to nearly 2000 km in diameter [7-8]. While linear, radiating and circumferential swarms are all associated with mantle plumes, the linear swarms are uniquely linked to mantle plume-related triple junction rifting [6]. Dolerite sill provinces are common in sedimentary basins, such as the Karoo sills in the Karoo basin of southern Africa and the 2215 Ma Nipissing sills of the Huronian basin of the southern Superior craton of North America, but are also hosted in basement rocks, with the largest sill system being the 3000 km long Ferrar event of Antarctica/Tasmania/Australia [6, 9, 10].

2. Setting of Mafic-Ultramafic Intrusions in lips

Mafic-ultramafic (M-UM) intrusions are key exploration targets for a range of different mineral deposits (e.g. magmatic sulphide Ni-Cu-platinum group element (PGE) deposits, PGE “reef” style deposits) and many are linked to LIPs [11, 2, 5]. Key examples are large stratiform intrusions, such as the Bushveld and Stillwater, which can be the source of Ni-Cu-PGEs and Cr, amongst other commodities. Smaller mafic-ultramafic intrusions such as those with the geometry of chonoliths (e.g. Noril’sk) and giant dyke-like layered intrusions (e.g. the Great Dyke of Zimbabwe) have been proven to host significant amounts of Ni-Cu sulphide mineralization. There is also a link between LIPs and hydrothermal ore deposits, in which LIPs provide the necessary heat and fluids to facilitate hydrothermal circulation that leads to the concentration of desirable metals (e.g. native copper). The 5-part classification of Ernst and Jowitt [3] also identifies links between LIPs and additional types of ore deposits.

Here we provide an overview of the settings of mafic-ultramafic (M-UM) intrusions as part of the plumbing system of LIPs. We are not considering those layered intrusions associated with arc settings, nor those associated with spreading ridges. Instead, we are focussed on those that are linked to intraplate settings, and in particular, those inferred to belong to LIPs.

2.1 Magmatic underplate

The largest M-UM intrusions may correspond to magmatic underplates, located at the base of the crust. In LIP events, these are typically generated by partial melting of the underlying mantle plume head, yielding underplates that may be up to several-hundred-km across and 10-20 km thick [12; associated with the 130-90 Ma High Arctic LIP]. These underplates may be linked with the edge of circumferential swarms, as illustrated in Figure 13e from Makitie et al. [13], for example.

Geophysical studies support the presence of these deep crustal magma bodies, termed underplates, and magnetic maps processed as “pseudo gravity” [12] indicate their overall volume and importance within LIPs. Oakey and Saltus [12] identify a 17 million km^3 underplate associated with the High Arctic LIP (Canada).

The cooling history of these magmatic underplates is poorly understood, but an intriguing idea has been proposed by Xu et al. [14] whereby the final stage of crystallization of the magmatic underplate is associated with the release of metals and fluids into the overlying crust. Speculatively, cooling and crystallization of the magmatic underplate may release fluids and metals 30-100 myr after the LIP event occurs, leading to the formation of hydrothermal Cu and Pb-Zn deposits at shallow crustal levels [14, e.g. associated with the 260 Ma Emeishan LIP].

2.2 Mid-crustal intrusions circumscribing the plume centre region

Mafic intrusive units frequently exhibit geochemical evidence for crustal contamination. For instance, a geochemical/isotopic study in a portion of the Karoo province revealed multiple magma batches that could be related through the progressive AFC contamination of a staging chamber, from which there was periodic expulsion of magma batches (e.g. Fig. 18 in [15] It is generally interpreted that such contamination occurred in a staging magma chamber(s) located at greater depths within the crust, underlying the area where the contaminated units were emplaced [15]. However, the notion of large-scale lateral transport of magma through dykes [16, 6] and sills [9] suggests that such staging chambers are not necessarily located directly underneath the crustally contaminated units, but could be located hundreds of km or more away to the side.

One possible location for such chambers is surrounding the mantle plume centre at a distance of hundreds of km. For instance, the plume centre for the 1270 Ma Mackenzie LIP is surrounded by a ring of gravity/aeromagnetic anomalies [16] that represent mid-crustal M-UM intrusions 10s of km across and a few km thick [4]. These intrusions are located at the edge of a magmatic underplate and were likely generated from magmas ascending from the edge of that underplate [17]. The broader application of this model is being tested with geophysical studies around other plume centres [17].

One of the mid-crustal intrusions surrounding the Mackenzie plume centre is geophysically linked to the exposed Muskox layered intrusion that hosts Ni-Cu-PGE mineralization. The other mid-crustal intrusions that circumscribe the Mackenzie plume centre could therefore also be, hypothetically, linked to shallow bodies (as yet undiscovered) with economic magmatic sulfide potential [17].

2.3 Mid-shallow crustal intrusions within rift zones associated with LIPs

Separate intrusions aligned along rift zones: These are likely part of triple junction rift systems [17] and can spawn rift-parallel dyke swarms [18]. In the case of Greenland, there are lines of intrusions spaced along the rift margin. A similar case is associated with the Deccan, where the intrusions are alkaline in composition [17].

2.4. Sill-like (Stratiform) M-UM intrusions emplaced in sedimentary basins

This represents a class of dyke-like intrusions often emplaced at the base of supracrustal sequences. This class includes the exemplary 2060 Ma Bushveld and 2710 Ma Stillwater complexes, both of which host world-class PGE mineralization. The largest such stratiform M-UM intrusions are probably proximal to mantle plume centres, although smaller stratiform M-UM intrusions could also potentially be located more distally from the plume centre and fed via radiating dyke swarms.

2.5. Dyke-like M-UM

Dyke-like layered intrusions (e.g. the 2580 Ma Great Dyke of Zimbabwe, 2420 Ma Jimberlana dyke of western Australia, and the 2730 Ma Ahmeyim Great Dyke of Mauritania) and associated Ni-Cu-PGE mineralization can also be linked to LIP events [6]. For instance, the Jimberlana dyke is part of the widespread 2420-2400 Ma Widgiemooltha swarm of the Yilgarn craton, which can potentially be linked to a plume centre off the eastern margin of the craton [19]. The 2580 Ma Great Dyke of Zimbabwe has several companion dykes, but they are located close by and an overall fanning pattern has not been identified, so a plume centre cannot be currently linked to the Great Dyke of Zimbabwe event.

2.6. M-UM intrusions at a distance from the plume centre

Many LIPs have associated radiating dyke swarms that diverge from the plume centre and can channel magma laterally for distances of up to several 1000 km away from the plume centre [20, 6]. If the radiating dyke swarm intersects a sedimentary basin, the dykes may reorient and be emplaced as sills instead, some of which may be large and prospective hosts for mineralization [21, 6].

2.7. M-UM intrusions associated with giant circumferential dyke swarms

A new class of regional dyke swarms termed “giant circumferential” has now been recognized [22, 13, 23]. These dyke swarms circumscribe the plume centres of LIP events at distances up to more than 1000 km in radius, and are potentially fed vertically from the outer boundary of the plume head. We speculate that local M-UM intrusions may be associated with these giant circumferential swarms.

DISCUSSION

There are insights that arise from studying the plumbing system of LIPs including the role of mafic-ultramafic intrusions.

Range in geochemical composition

Geochemical studies of some LIPs reveal that the magmatism is very similar throughout the entire LIP, and in other cases, multiple compositions seem to be present [6]. Any variation in chemistry can result from different mantle sources, and mixing of these sources (plume, upper mantle asthenosphere, lithospheric mantle), variation in the depth of partial melting, and potential contamination as magma transects the lithospheric mantle and the crust, with especially significant modification if the magma sits in any chamber for a protracted period of time [24, 15].

Location of source mantle

The most important element related to the magma sources is the plume centre region. It has been established that giant radiating dyke swarms can transport magma from the plume centre region (about 500 km across) out to distances of more than 2000 km away from the plume centre, through laterally emplaced radiating dyke swarms. In such cases, the magma for the entire LIP is generated in the plume centre region rather than from the mantle underlying the entire swarm. This has particular significance when a radiating swarm feeds a sill province. An important example is the feeding of the Nipissing sill province in the Huronian basin by the Senneterre radiating swarm; it has been proposed that the Nipissing sill magmas were emplaced from laterally propagating dykes of the Senneterre radiating swarm and that the magma originated 1300 km to the NE of the Huronian basin, in the vicinity of the Ungava plume centre (at the focus of the Senneterre radiating swarm; [25, 6]). This means that mantle source for the Nipissing sills was not underlying the Huronian basin on the south side of the Superior craton, but was actually in the Ungava plume centre region on the NE side of the Superior craton, 1300 km away.

Integration with geophysics

In regional gravity and aeromagnetic maps, and on seismic cross surveys, there are typically many anomalous features observed. Knowledge of the LIP event units in the vicinity can provide a framework to interpreting the geophysical data, and in particular, to identifying those features which can be linked with LIP-related processes. For instance, plume centre regions can be located through giant radiating dyke swarms and such regions can then be interrogated using geophysics to identify the location of associated layered intrusions and the lower crustal magmatic underplate.

Distribution of associated ore deposits

Mafic-ultramafic intrusions are the host of most Ni-Cu-PGE ore deposits, and the question must be asked: Where are the most favourable locations for such deposits to form within LIP systems. As frequently noted, the footprint of an ore deposit is a very small fraction of the overall size of a LIP. For instance, the Norilsk deposits of the Siberian trap LIP represent a target that is less than 0.1% of the areal extent of the overall LIP itself [2]. It has been argued that proximity to the plume centre [2], along with association with translithospheric faults [26], are important criteria for mineralization potential. Other kinds of hydrothermal ore deposits can be spatially linked with regional extensive sill provinces, which may responsible for providing the heat to drive hydrothermal circulation that upgrade metal concentrations to produce these ore deposits.

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