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PLUME-GENERATED 90° STRESS CHANGE LINKED TO TRANSITION FROM RADIATING TO CIRCUMFERENTIAL DOLERITE DIKE SWARMS OF THE SIBERIAN TRAPS LARGE IGNEOUS PROVINCE AND TO EMPLACEMENT OF THE NORILSK-TALNAKH ORE DEPOSITS

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Abstract

A 90° change in stress orientation has been previously proposed as the trigger for the final emplacement of the world-class Norilsk-Talnakh magmatic sulfide mineralization via the migration of accumulated sulfide melts from elsewhere within the plumbing system of the Siberian Traps large igneous province (LIP). We propose that this stress change does not require and was not triggered by a distal change in plate boundary stresses, but instead can be explained both temporally and spatially by stress changes recorded in the dike swarm patterns of the Siberian Traps LIP, namely the transition from a giant radiating dike swarm (associated with mantle plume uplift) to a giant circumferential swarm (linked to flattening of the plume head). The mantle plume stress-related changes recorded by these dike swarms, rather than distal plate boundary stress changes, were therefore most likely the trigger for the emplacement of the Norilsk-Talnakh mineralization. Other LIPs that have both giant radiating and circumferential dike swarms most likely reflect similar major and rapid changes in stress orientation, indicating that mantle plume-induced stress changes revealed by dike swarms should be considered an additional tool in magmatic sulfide exploration.

Introduction

Role of stress changes in emplacement of magmatic sulfide mineralization

Ni-Cu-platinum group element (PGE) magmatic sulfide deposits are a globally important source of Ni and PGE production; the most significant of them are associated with plume-generated large igneous province (LIP) magmatic events (e.g., Pirajno, 2000; Schissel and Smail, 2001; Naldrett, 2010; Ernst and Jowitt, 2013). There is already a significant body of literature on the magmatic processes involved in the generation of Ni-Cu-PGE-sulfide deposits (e.g., Naldrett, 1997, 2004, 2010; Lesher and Keays, 2002; Barnes and Lightfoot, 2005; Cawthorn et al., 2005; Lightfoot and Keays, 2005; Maier and Groves, 2011; Lightfoot and Evans-Lamswood, 2015; Robertson et al., 2015; Begg et al., 2018); as such, this paper will not focus on the processes involved in the generation of this style of mineralization. Instead, this paper focuses on the role of plume-generated stress changes in the formation of magmatic sulfide mineralization events.

It has been proposed that the emplacement of magmatic sulfide mineralization is associated with changes in stress orientation that can trigger the release of accumulated massive sulfide melts from other deeper or laterally located portions of the magmatic plumbing system (e.g., Begg et al., 2018; see also Lightfoot and Evans-Lamswood, 2015). Examples of major deposits associated with LIP events where such stress changes have been identified (shown in fig. 1.3 of Begg et al., 2018) include the 252 Ma Norilsk-Talnakh ore deposits of the Siberian Traps LIP in Siberia, for which the stress change was from NNE-SSW to ESE-WNW; the 1333 Ma Voisey's Bay deposits of the Nain LIP of eastern Canada, for which the stress switch was from northwest to west; and the 1070 Ma deposits of the West Musgraves (Nebo-Babel) of the Wara-

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kurna LIP of central Australia, for which the stress transition was from east to northeast. Begg et al. (2018) propose that these stress changes are linked to changes in plate dynamics distal from the focal areas of magmatism associated with these LIP events.

However, this study presents an alternative model using the Norilsk-Talnakh case that does not require the influence of distal plate boundary changes. Instead, we propose that mantle plume dynamics and resulting associated local stresses are key triggers in magmatic sulfide transport and deposition, as recorded by variations in the orientations of dike swarms of the LIP. It should be noted that stresses due to the arrival of a mantle plume can locally dominate over plate boundary stress, and even cause changes in plate motion (e.g., Goldfarb et al., 2007; van Hinsbergen et al., 2021). As such, changes in mantle plume dynamics and resulting stress regime changes may be a significant driver of the generation of magmatic sulfide mineral deposits within LIP systems and should be considered during exploration for this style of mineralization.

Stress change in plume-generated LIPs

The arrival of deeply sourced mantle plumes at the base of the lithosphere on Earth (as well as on Mars and Venus) is typically associated with domal uplifts, with radii of up to ~1,200 km (Campbell, 2007). This uplift typically produces giant radiating dolerite dike swarms that can extend in some cases up to >2,000 km away from the plume center (Halls, 1982; Fahrig, 1987; Baragar et al., 1996; Ernst and Buchan, 2001; Buchan and Ernst, 2021; El Bilali et al., 2023). Buchan and Ernst (2018, 2019, 2021) also identified another class of giant subcircular dolerite dike swarms that are circumferential around the plume center, with radii of up to >1,000 km. LIPs containing both giant circumferential and radiating dike swarms have circumferential swarms that are typically younger, suggesting a link with spreading of the mantle plume head beneath the lithosphere over time. Giant circumferential swarms may also be analogous to abundant giant circular tectonomagmatic features on Venus, termed "coronae," that are often coupled with giant radiating dike swarms (e.g., Buchan and Ernst, 2019, 2021).

Dolerite dike swarms are aligned along maximum compressive stress directions, and as such are precise monitors of crustal stress orientation (e.g., Pollard, 1987; Fahrig, 1987; Ernst, 2014). This means that the existence of giant radiating dike swarms is indicative of a radial σ1 stress configuration associated with uplift above mantle plume head regions. Giant radiating dike swarms are only affected by regional plate stress when they extend beyond the edge of the plume head (e.g., Baragar et al., 1996; Ernst, 2014), suggesting that local stresses are more important than distal plate boundary stresses within LIP systems up to a radial distance of ~1,200 km. The circumferential stress state (marked by the formation of circumferential dikes) can also be explained by a change in mantle plume dynamics as the plume flattens and spreads after arrival at the base of the lithosphere (Buchan and Ernst, 2019).

Thus, the 90° stress change associated with the transition from radiating to circumferential dike swarms in plume-generated LIPs is purely due to stress changes induced by underlying plume dynamics , rather than being the result of any distal processes such as plate tectonic reconfiguration. The duration of this plume-induced stress transition is not well constrained, but is thought to occur over a few million years at most and perhaps over only a few hundred thousand years. This temporal constraint is based on available U-Pb and high-resolution Ar-Ar geochronology of the overall short duration of many LIP events, including the Siberian Traps LIP (e.g., Kasbohm et al., 2021; Jiang et al., 2023), and models of how plume heads arrive and spread at the base of the lithosphere (e.g., Campbell, 2007; Friedrich et al., 2018).

As noted above, in this study we propose that the stress changes associated with magmatic sulfide deposits are caused by plume dynamics, as expressed by the transition from radiating to circumferential dike swarms, rather than by more distal plate kinematics as proposed by Begg et al. (2018). We apply our model to the Norilsk-Talnakh ore deposits of the Siberian Traps LIP (Fig. 1) and its associated radiating and circumferential dyke swarms (Fig. 3a). This world-class Ni-Cu-PGE mineralization ranks among some of the highest-value mineralization known anywhere on Earth (e.g., Barnes et al., 2020), with Mudd and Jowitt (2022) reporting 2018 resources (inclusive of reserves) of 2.15 billion tonnes (Bt) of mineralization at a grade of 0.73% Ni, 1.4% Cu, 1.02 g/t Pt, and 3.70 g/t Pd, containing some 15.7 million tonnes (Mt) Ni, 30 Mt Cu, 2,189 tonnes (t) of Pt, and 7,943 t of Pd.

Dramatic change in stress orientation associated with the Norilsk-Talnakh mineralization of the Siberian Traps LIP

The relationship between the mineralization of the Norilsk-Talnakh volcanic sequence and changes in regional stress patterns was examined by Begg et al. (2018). The volcanic formations of the Norilsk-Talnakh sequence have been grouped into three assemblages (Fig. 2; e.g., Fedorenko, 1981; Begg et al., 2018). Begg et al. (2018) note that the thickness isopachs of the

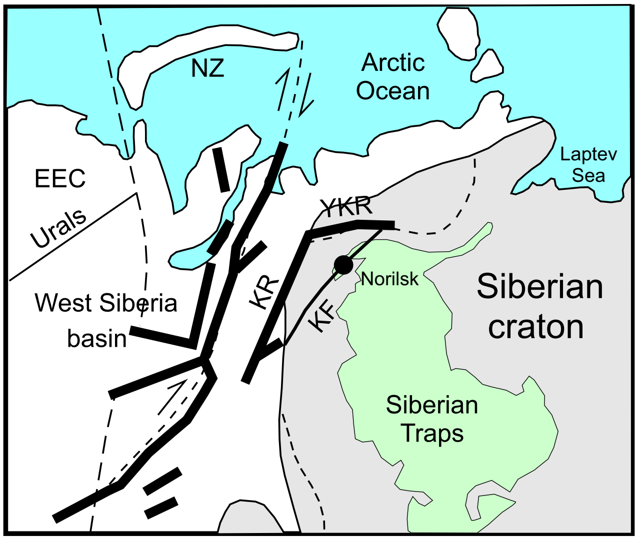
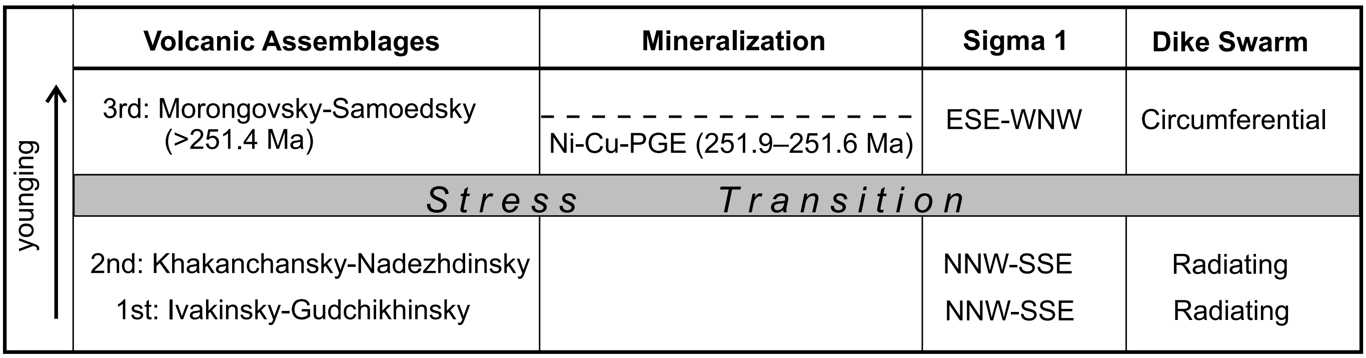


Fig. 1. Geologic and geodynamic setting for the Norilsk-Talnakh ore deposits of the Siberian Traps large igneous province (LIP). Thick black lines = Late Permian-Early Triassic rifts (transtensional fault zones) beneath the Jurassic-Tertiary West Siberia basin; EEC = East European craton; KF = Norilsk-Kharaelakh fault; KR = Khudosei Rift; NZ = Novaya Zemlya; YKR = Yenisei-Khatanga Rift. Modified after northern portion of figure 1.3A in Begg et al. (2018).



Volcanic Assemblages	Mineralization	Sigma 1	Dike Swarm
3rd: Morongovsky-Samoedsky (>251.4 Ma)	Ni-Cu-PGE (251.9–251.6 Ma)	ESE-WNW	Circumferential
Stress Transition			
2nd: Khakanchansky-Nadezhdinsky		NNW-SSE	Radiating
1st: Ivakinsky-Gudchikhinsky		NNW-SSE	Radiating

Fig. 2. Timing of volcanic assemblages in the Norilsk region (younging upward), compared with the stress orientations after Begg et al. (2018) and with the matching dike swarm pattern from the present paper. The mineralized Norilsk intrusions have high-precision ages of U-Pb 251.64 ± 0.010, 251.813 ± 0.065, and 251.907 ± 0.067 Ma (Burgess and Bowring, 2015), with the younger age preferred in the discussion of Latyshev et al. (2020). The timing has been specifically correlated with the lower Morongovsky-Samoedsky assemblage (Begg et al., 2018) on the basis of a geochemical match with the Morongovsky formation (e.g., Fedorenko, 1994). The timing is also supported by a paleomagnetic match with the Morongovsky and Mokulaevsky formations (Pavlov et al., 2019; Latyshev et al., 2020). The minimum age for the Morongovsky-Samoedsky assemblage is given by the U-Pb age of 251.376 ± 0.050 Ma for the Daldykansky intrusion, which crosscuts the entire lava stratigraphy and the Ni-bearing Noril'sk-type intrusions (Burgess and Bowring, 2015). The Ivakinsky-Gudchikhinsky assemblage consists of the Ivakinsky, Syverminsky, and Gudchikhinsky formations, with the Khakanchansky-Nadezhdinsky assemblage comprising the Khakanchansky, Tuklonsky, and Nadezhdinsky formations, and the Morongovsky-Samoedsky assemblage comprising the Morongovsky, Mokulaevsky, Kharaelakhsky, Kumginsky, and Samoedsky formations. PGE = platinum group element.

first two volcanic assemblages of the Siberian Traps LIP (Ivakinsky-Gudchikhinsky and Khakanchansky-Nadezhdinsky) are parallel with the trend of the overall NNE-SSW–trending Norilsk-Kharaelakh Trough, which parallels the Norilsk-Kharaelakh fault (Fig. 3b). However, the thickness isopachs for the third (youngest) Morongovsky-Samoedsky assemblage are at an angle of 90° to the trough (Fig. 3c). This led Begg et al. (2018) to suggest that this is indicative of a change in regional stress orientation from approximately NNE-SSW to ESE-WNW, and that the change was due to distal plate stresses. Furthermore, Fedorenko (1994) notes that the Ni-Cu-PGE mineralizing intrusions formed during the early stages of the youngest (Morongovsky-Samoedsky) assemblage. This interpretation is supported by paleomagnetic data that indicate that emplacement of the ore-bearing intrusions coincides with the timing of the Morongovsky and Mokulaevsky volcanic formations (Latyshev et al., 2020). Begg et al. (2018) indicate that this timing is consistent with an interpretation that a sudden change in regional stress was the trigger for release of Siberian Traps magmas containing magmatic sulfide melts from deeper within the magmatic plumbing system. It should also be noted that more recent research (e.g., Barnes et al., 2023) suggests that the magmatic sulfides of the Norilsk-Talnakh system were generated within the ~2-km-thick sequence of anhydrite-bearing evaporites of the region, with sulfides being moved laterally to locations of deposition and mineral deposit formation rather than ascending from deeper within the LIP plumbing system. However, independent of whether sulfides migrated from depth or laterally to the location of deposition around Norilsk-Talnakh, the main factor is that some change in stress regime was most likely needed to initiate the migration of these significant volumes of sulfide from elsewhere in the LIP system toward the eventual location of deposition and mineral deposit formation.

Below, we develop our alternative model to explain the driver of the 90° stress change associated with the Norilsk-Talnakh mineralization as related to the transition from a giant radiating to a giant circumferential dike swarm, rather than being related to distal plate boundary stresses as proposed by Begg et al. (2018).

Results

Radiating and circumferential dike swarms of the Siberian Traps LIP

A coupled giant circumferential and radiating dike system for the Siberian Traps LIP (Fig. 3a) was originally proposed by Ernst and Buchan (1997, 2001; see also Buchan and Ernst, 2019). The radiating swarm comprises the Ebekhaya and Maimecha (Maymecha) subswarms (Ernst et al., 1996 and references therein) and the linear "feeder zones" to volcanic flows of the Norilsk area (Fedorenko et al., 1996). The Siberian Traps flood basalts have been removed by erosion on their eastern side, exposing underlying Riphean rocks crosscut by the E- to ESE-trending Ebekhaya and SE-trending Maimecha subswarms. The Norilsk area feeder zones trend NNE to SSW and correlate with major faults (Figs. 1, 3), with these magma-filled fractures (including the major Norilsk-Kharaelakh translithospheric fault) being analogous to dikes and forming part of the overall radiating intrusion pattern within the LIP (Ernst and Buchan, 2001). Note that, although matching in name, the mafic Maimecha dikes (Fig. 3a) do not belong to the Maimecha-Kotui meimechite igneous province of the northern Siberian platform (Sobolev et al., 2009).

The Kochikha circumferential mafic dike swarm (Fig. 3a; Ernst et al., 1996; Ryabov et al., 2014) has a pronounced elliptical shape (maximum and minimum outer diameters of ~600 and 350 km) and shares a common center with the radiating

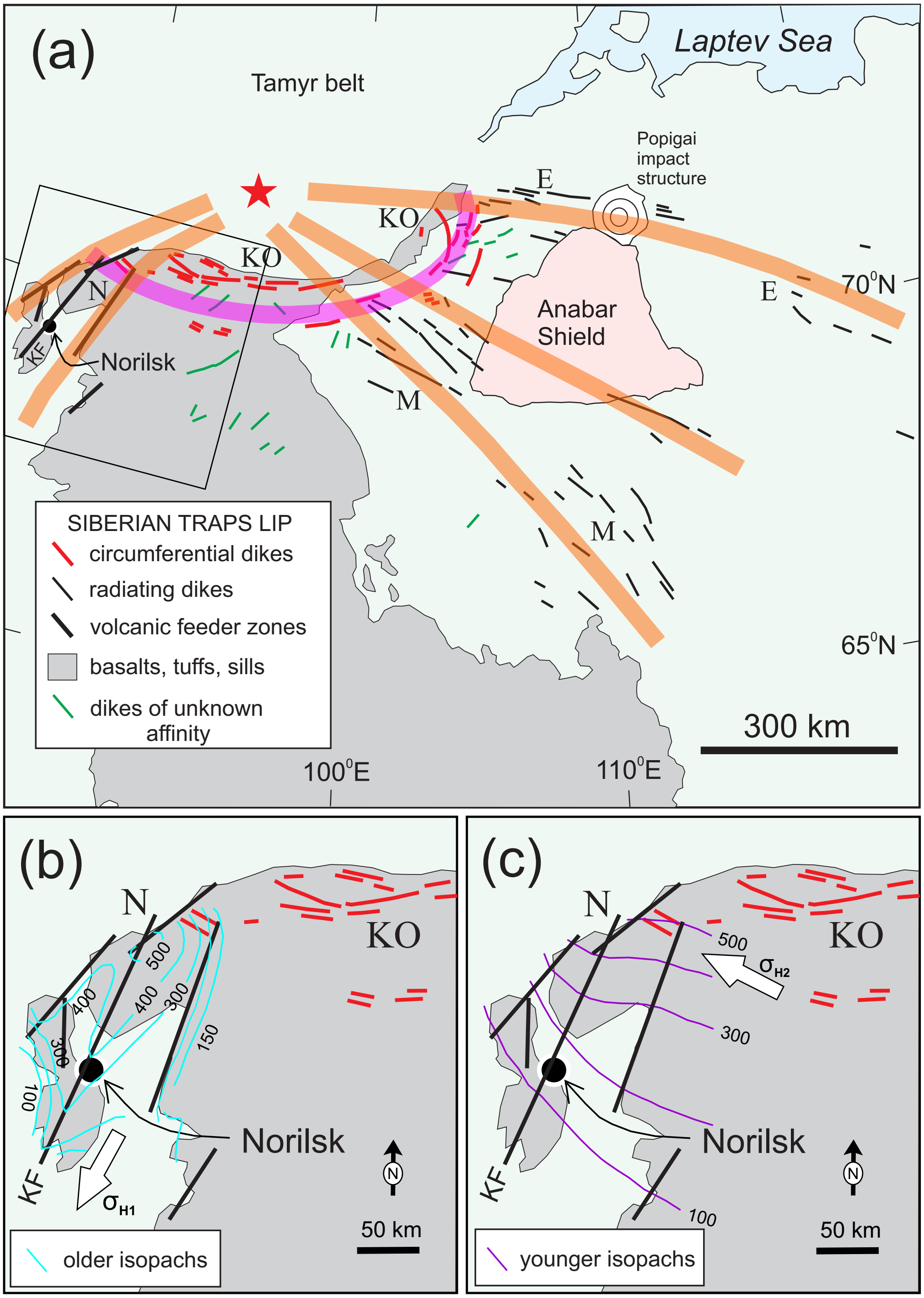


Fig. 3. (a) Distribution of dike swarms and volcanic feeder zones associated with the Siberian Traps large igneous province (LIP), modified after Buchan and Ernst (2019). A generalized version of the overall radiating system of dikes and feeder zones is superimposed in orange, and a generalized version of the circumferential dikes is in pink. The red star locates the approximate focus of the radiating swarm and the center of the circumferential swarm. Dike sets: E = Ebekhaya dikes; KO = Kochikha dikes; M = Maimecha dikes. The red circumferential dikes cut the volcanic rocks, whereas the black radiating dikes do not. Green dikes represent a linear swarm that is younger than the volcanic rocks and has unknown affinity. N = Norilsk feeder zones to volcanic flows (Fedorenko et al., 1996), which correlate with major fault zones, including the prominent Norilsk-Kharaelakh fault (KF). These feeder zones are interpreted to be part of the radiating dike system (see text). The box shows the location of Figures 3b and 3c. (b) Thickness isopachs (in meters) for the oldest volcanic assemblage (from fig. 15.3a in Fedorenko, 1994) parallel the NNE-SSW–trending Norilsk feeder zones. Thickness isopachs for the middle volcanic assemblage (not shown; see fig. 15.3b in Fedorenko, 1994) also parallel the Norilsk feeder zones. White arrow = interpreted stress orientation σ_{H1} (following Begg et al., 2018). (c) Thickness isopachs for the youngest volcanic assemblage (from Fedorenko, 1994; fig. 15.3c) are perpendicular to the NNE-SSW–trending Norilsk feeder zones. White arrow = interpreted stress orientation σ_{H2} (following Begg et al., 2018).

swarm. It spans an arc of ~150° and crosscuts the Siberian Traps flood basalts. Based on crosscutting relationships of the dike swarms and volcanic flows, the circumferential dike swarm is interpreted to be younger than the radiating swarm, as is the case for most LIPs with both radiating and circumferential dike swarms (Buchan and Ernst, 2019). Ryabov et al. (2014) group the circumferential dikes based on their differing characteristics, with dikes of the Daldykansky and Avamsky Complexes described as dolerite and trachydolerite. The largest Avamsky dikes have widths of 40 to 50 m and lengths >10 km. Smaller dikes of the Kamensky and Ust'-Del'kansky Complexes are described as syenite–mela-nephelinite and lamprophyre, respectively (Ryabov et al., 2014).

Association of transition from radiating to circumferential dike swarm with stress orientation changes associated with Norilsk ore emplacement

The NNE to SSW trend of the feeder zones of the radiating swarm in the Norilsk area (Figs. 3b) is indicative of a σ1 stress direction that is parallel to the elongated basins of the area and consistent with the stress direction estimated by Begg et al. (2018) from the thickness isopachs of the first two (oldest) volcanic assemblages. In comparison, the ESE to WNW trend of the circumferential dike swarm in the Norilsk area (Fig. 3c) records an ESE to WNW σ1 stress direction that is consistent with the stress direction estimated by Begg et al. (2018) from the thickness isopachs of the third (youngest) volcanic assemblage. We propose that this 90° shift in stress direction associated with the emplacement of the Norilsk-Talnakh mineralization (Begg et al., 2018) was caused by the transition from a giant radiating to circumferential stress pattern (revealed by the dike swarms; Figs. 2, 3) above the Siberian Traps plume head; in other words, the change in stress regime was driven by a proximal change in mantle plume dynamics rather than any distal plate boundary driver. This stress transition brackets two important steps in the generation of these Norilsk-Talnakh ores. The first of these is the eruption of the Nadezhdinsky volcanic rocks, which are chalcophile-element–depleted and have been proposed to have lost their metals in the source staging chamber for the Norilsk-Talnakh ores (e.g., Lightfoot and Keays, 2005), although there is evidence that these magmas do not necessarily record the chalcophile element enrichment processes associated with the formation of the Norilsk-Talnakh ores (see discussion in Barnes et al., 2023). However, these volcanics are emplaced at the end of Assemblage 2 (i.e., prior to the stress transition). This precedes the final emplacement of the Norilsk-Talnakh ores in the early stages of the subsequent Assemblage 3 (Fedorenko, 1994; Begg et al., 2018) after the stress change has occurred. This indicates that although the magmatic sulfides may have been generated during the time of Nadezhdinsky volcanism, they may have remained in a staging magma chamber/conduit system, perhaps as a result of the dynamics of the magmatic system at this time being unfavorable for the transport of large volumes of magmatic sulfide melt (e.g., Lesher, 2019). Alternatively, as mentioned above, the sulfides that eventually formed the Norilsk-Talnakh mineralization is likely to have been generated in shallower parts of the same system close to the time of the stress change outlined above. Irrespective of the direction of magma and magmatic sulfide migration, a stress change either during the time of formation of the Nadezhdinsky volcanics or shortly after may be important for the transport of the significant volumes of magmatic sulfides deposited within the Norilsk-Talnakh area.

The gap in time between the Nadezhdinsky volcanic rocks (and the potential associated profound loss of chalcophile elements in some magma reservoir) and the final emplacement of ore-bearing intrusions could represent a time of protracted upgrading of tenor of the segregated ores (Barnes et al., 2016), an idea that is consistent with new Ni isotope data for the ores (Chen et al., 2023), or as mentioned above, could reflect the formation of magmatic sulfides between the deposition of the Nadezhdinsky volcanics and the stress change discussed in this paper. Considering the first of these models, upgrading have occured until the time of late-stage injection to shallower chambers (Barnes et al., 2016; Yao and Mungall, 2021). This model is consistent with the proposal that "a sudden regional tectonic stress switch served as the trigger for release of magmas rich in magmatic sulfide melt from deeper within the magma conduit network" (Begg et al., 2018), which we herein interpret to be due to the change from radiating to circumferential stress patterns associated with a mantle plume (proxied by the dolerite dikes), rather than the original interpretation of Begg et al. (2018) that required a distal plate boundary influence. In the case of lateral migration being triggered by the stress change outlined above, the upgrading could have happened within dynamic parts of the LIP system before migrating laterally towards the Norilsk-Talnakh area; in either case, the stress change caused an end to upgrading and began the process of sulfide and silicate melt migration toward the eventual site of deposition.

It has also been suggested that strike-slip movement on the Norilsk-Kharaelakh fault opened pathways for ascending or laterally migrating ore-bearing magmas (e.g., Lightfoot and Evans-Lamswood, 2015). The addition of new magmas into a staging magma chamber or elsewhere within the LIP system could have increased the dynamism of the system, increasing R-factors but also potentially leading to the breakup of larger, less-mobile sulfide melt droplets (e.g., Robertson et al., 2015). This would have allowed the movement of large masses of sulfide as a result of a change to a more dynamic magma regime, potentially allowing the lateral intrusion of the mineralized magmas that formed the Norilsk-Talnakh deposits (e.g., Yao and Mungall, 2022). In the context of our model, our proposed stress change due to Siberian Trap plume dynamics affects a large extent of the northern Siberian craton and could well have locally reactivated the Norilsk-Kharaelakh fault (or activated it in a different orientation). This would have created increased space for magma flow and potentially increased flow rates, enabling magmas to break up and thus carry dense sulfides (e.g., Robertson et al., 2015), as well as changing the dynamics of intrusions within the system as noted above.

Broader Implications

An increasing number of LIPs around the world are now recognized to have both radiating and circumferential swarms (Buchan and Ernst, 2019, 2021), with the radiating stage typically preceding the circumferential stage (although more complicated scenarios apply in some cases). The proposed link between stress changes associated with the transition from radiating to circumferential dike swarms and emplacement of magmatic sulfide mineralization in the case of the Siberian Traps plume/LIP indicates that favorable time periods and locations for magmatic sulfide mineralization in other LIPs may well be associated with the plume-driven transition from radiating to circumferential stress states rather than any distal plate boundary stress change. A change in stress within a magmatic system can also cause changes in pressure, volatile release, and potentially overpressure-related explosive injection of magmas, all of which may play a role in the formation of LIP-related magmatic sulfide deposits (e.g., Yao et al., 2019). A further speculative idea to consider is whether stress changes like that documented within the Siberian Trap system above have any role in contributing to the formation of the tube-like chonoliths that are the main intrusive host for magmatic sulfide mineralization at Norilsk-Talnakh and other important magmatic sulfide deposits (Barnes et al., 2016). A factor that could be relevant is that the 90° swapping of σ1 and σ3 trends during the transition from radiating to circumferential swarm must pass through a time period when the horizontal stresses would be isotropic. This change could cause the formation of an entirely different style of intrusion, going from what may be considered “normal” LIP magmatism and plumbing system formation to the formation of the chonoliths commonly associated with magmatic sulfide systems. A detailed analysis of this is beyond the remit of this paper but should certainly be considered in future research.

Further research is also needed on other LIPs with both giant radiating and circumferential systems (e.g., the 130–95 Ma High Arctic LIP, the 370 Ma Yakutsk-Vilyui LIP of Siberia, and the 1110 Ma Umkondo LIP of Kalahari craton; Buchan and Ernst, 2019) to assess the spatial and temporal relationship between the stress changes recorded by variations in dike swarm orientation and magmatic sulfide-bearing intrusions. This should also include the broader development of exploration targeting strategies based on the distribution of coupled radiating and circumferential swarms in LIPs.

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