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The effect of crustal xenolith-kimberlite reaction on host kimberlite classification: The Pionerskaya case

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Introduction

Primary volcanic rocks mined for diamonds have historically been classified as Group I or Group II kimberlites. Orangeites, olivine lamproites, and carbonate-rich olivine lamproites collectively make up Group II kimberlites. The vast majority of economic diamond mines throughout the world are hosted by kimberlites, while lamproites and orangeites generally have lower diamond potential (Kjarsgaard et al. 2022). This study reclassifies the Pionerskaya pipe from orangeite to kimberlite and shows that the previous erroneous classification relates to the presence of crustal xenoliths and their metasomatic reactions with the host rock.

Results

Twenty-seven samples from depths between 378-1042m from the Late Devonian Pionerskaya pipe (Arkhangelsk diamond province, NW Russia) were examined in this study. The pipe is part of the mined Lomonosov diamond deposit and contains pyroclastic kimberlite (PK) and hypabyssal kimberlite (HK) at depths below 900 m. Pionerskaya, and other pipes in the Zolotitsa field, have historically been classified as orangeites due to the presence of groundmass clinopyroxene as well as high modes of phlogopite with compositions that are atypical of kimberlitic phlogopite. The PK contains subspherical to amoeboid melt-bearing pyroclasts and abundant broken olivine pyrocrysts. Many melt-bearing pyroclasts contain multiple olivine crystals and others form thin selvages around olivine crystals or xenoliths. The HK is coherent with a fine-grained groundmass composed of patchy serpentine and carbonate and ~25 modal % of medium to coarse grained olivine macrocrysts which are typically fresh and subhedral in shape. The Pionerskaya pipe contains granite, amphibole-biotite schist, and diorite xenoliths (collectively called silicate xenoliths) that were altered through reactions with the host kimberlite. The silicate xenoliths observed in the PK samples are typically less reacted than those in the HK samples, i.e. the original mineralogy and texture of the xenoliths is better preserved in the PK. The silicate xenoliths have reaction rims with distinct sequences of minerals from the xenolith rim to the kimberlite groundmass. The mineralogy of the reaction rims are unique for each type of xenolith (Fig. 1). The reacted xenoliths contain phlogopite (Phl), clinopyroxene (Cpx), serpentine (Serp), hydrogarnet (HGrt), chlorite (Chl), calcite (Cc), and pectolite (Pec). The relative proximity of the silicate xenoliths impacts the abundance, size, shape, inclusion content, and composition of the phlogopite in the groundmass. The phlogopite closest to the xenoliths is small (<100μm), stubby, and does not contain inclusions. The phlogopite furthest from the xenolith has laths up to 300 μm in size that are heavily embayed and included, with one fresh monticellite inclusion that was not pseudomorphed by serpentine. The intermediate phlogopite has large laths up to 400 μm in size that are moderately included.

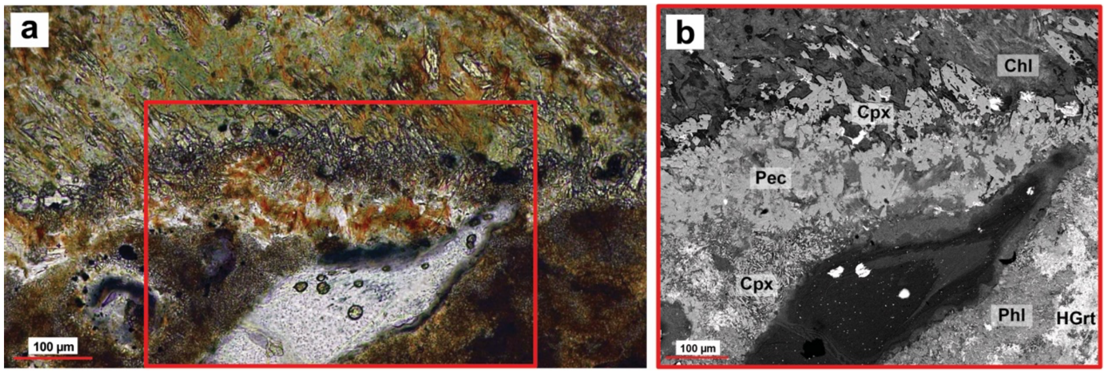

Figure 1: Diorite xenolith reaction rim and kimberlite reaction halo with an olivine macrocryst pseudomorphed by serpentine and chlorite. a) Photomicrograph (PPL) of the xenolith rim and reaction halo. b) SEM image of reaction rim with the sequence: Chl→Cpx→Pct→Cpx→Phl. See text for mineral abbreviations.

Electron microprobe analysis (EMPA) was carried out on the groundmass phlogopite and clinopyroxene. The phlogopite exhibits various compositional trends which are dependent on the proximity to the silicate xenoliths. Phlogopite in the reaction rim closest to the xenoliths shows very little change in composition from core to rim and doesn't have a clear trend (Fig. 2). Further away from the xenolith, in the halo, the phlogopite shows more change in core to rim composition and follows a phlogopite-tetraferriphlogopite orangeite groundmass trend. The outer phlogopite, furthest away from the xenolith, has a significant compositional change from core to rim and follows a phlogopite-tetraferriphlogopite kimberlite groundmass trend. The cores of the outer phlogopite typically plot inside of or near the groundmass kimberlite core compositional fields (Mitchell 1995; Kjarsgaard et al. 2022). The correlation between the distinct phlogopite compositional zoning trends and the proximity to the silicate xenoliths indicates that the reaction between the xenoliths and the kimberlite is affecting the composition of the phlogopite. The Pionerskaya groundmass kimberlite and reacted xenoliths also contain up to 16 vol% clinopyroxene, which by composition does not match Cpx in orangeites or kimberlites (Mitchell 1995).

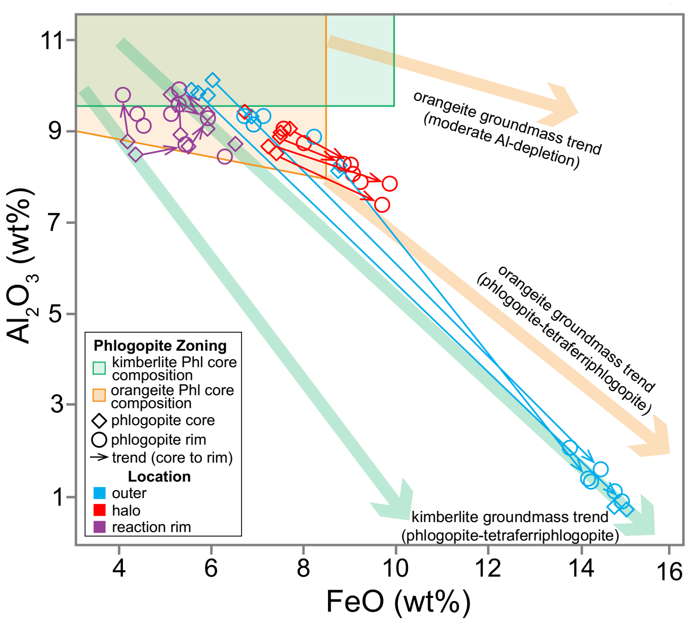

Figure 2: EPMA compositions of phlogopite (Phl) cores and rims. Small arrows show the trends from cores to rims of the Pionerskaya Phl. The markers are coloured by location which indicates the proximity to the silicate xenolith (reaction rim-closest, halo-intermediate, groundmass-furthest). The shaded areas are the compositional fields of Phl cores for kimberlites (green) and orangeites (orange). The large arrows show the Phl composition trends from core to rim for kimberlites and orangeites.

Thermodynamic phase equilibria models at 250-1450°C and 300 bar were created in Perple_X using X-ray fluorescence (XRF) bulk rock data from both fresh country rock (analyzed by Samsonov et al. 2008) and reacted silicate xenoliths including amphibolite, biotite amphibole schist, diorite, and granite (Fig. 3). The fresh country rock samples are modeled under fluid saturated conditions and the modelled mineralogy matches the observed mineralogy. Fluid saturated conditions did not produce garnet in the models for the reacted xenoliths, which is a key phase observed in all samples. The observed mineralogy, including garnet, is accurately reproduced only when H_2O and CO_2 are modelled as components controlled by the kimberlite composition. Initially, the modelled mineralogy did not match the observed mineralogy at any temperature for the raw bulk composition of the reacted silicate xenoliths alone. Therefore, a hybrid bulk composition of 20% unreacted country rock plus 80% reacted silicate xenolith is used to accurately model the mineralogy of the reacted xenoliths. The models of the reacted silicate xenoliths produce solidus temperatures ranging from 1030-1330°C, with reactions that continue from solidus temperatures to <250°C. While the modeled phases between the solidus temperatures and the lowest modeled temperature of 250°C are different for each xenolith type, there are multiple phases that are consistent between them. Grossular appears at moderate temperatures (500-700°C) and continues to form at the lowest modeled temperatures. Clinopyroxene appears at the solidus and continuously forms throughout the entire temperature range. The late stage, low-temperature formation of clinopyroxene is also observed petrographically where hydrogarnet is replaced by microcrystalline clinopyroxene. Pectolite also occurs as a major low temperature phase below 500°C in the granite and diorite xenoliths.

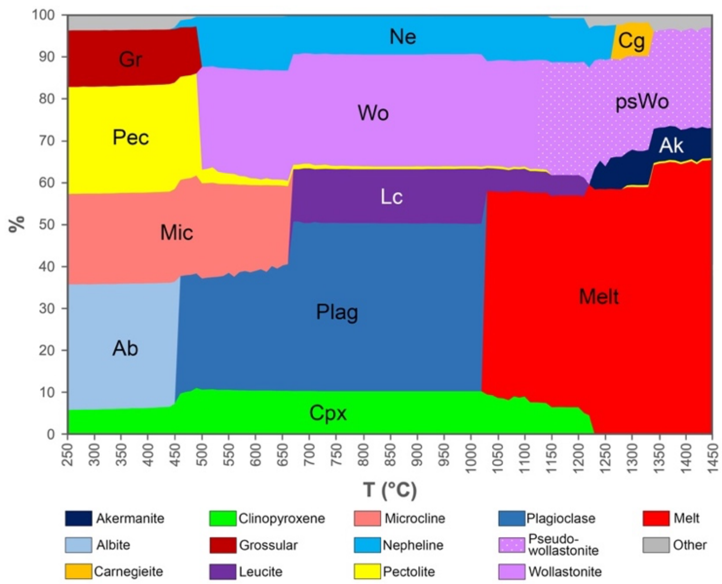

Figure 3: Modal mineralogy of a strongly reacted granite xenolith from Pionerskaya pipe. Modeled using a hybrid bulk composition and measured H_2O and CO_2 values.

Discussion

There are multiple lines of evidence in support of a metasomatic, rather than magmatic (as expected in orangeites and olivine lamproites) origin of groundmass clinopyroxene and phlogopite in Pionerskaya. Both phlogopite and clinopyroxene were modelled as subsolidus, low-T (<500°C) phases. Clinopyroxene was observed replacing hydrogarnet, another low-T (250-700°C) phase. There is evidence of element mass transfer between the silicate xenoliths and the kimberlite. The reacted silicate xenoliths are higher in MgO and CaO, and lower in SiO_2 and Al_2O_3 when compared to the equivalent unreacted country rocks. The mass transfer is shown to continue through several stages of thermal history and be significant even below the closure temperature of the thermodynamic equilibration (~ 200°C). The changes in texture and compositional zoning trends in phlogopite with proximity to silicate xenoliths further demonstrates the effect of xenolith contamination in the kimberlite groundmass. Monticellite is very rare in orangeites and its presence is strong evidence of a kimberlitic magmatic origin. The results of this study indicate that Pionerskaya should be classified as a Group I kimberlite, supporting its significant diamond potential.

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