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Millennia of magmatism recorded in crustal xenoliths from alkaline provinces in Southwest Greenland

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ABSTRACT

Mantle-derived CO_2-rich magma ascends rapidly through the lithospheric column, supporting upward transport of large mantle-xenoliths and xenocryst (>30 vol%) loads to the (sub-)surface within days. The regional magmatism during which such pulses occur is typically well characterized in terms of general duration and regional compositional trends. In contrast, the time-resolved evolution of individual ultramafic dyke and pipe systems is largely unknown. To investigate this evolution, we performed a geochemical and speedometric analysis of xenoliths from ultramafic (aillikite) dykes in two Neoproterozoic alkaline provinces in West Greenland: 1) Sarfartôq, which overlies Archean ultra-depleted SCLM and yielded ultra-deep mineral indicators, and 2) Sisimiut, where the SCLM is refertilized and deep xenoliths (>120 km) are lacking. We focused on the rare and understudied crustal xenoliths, which preserve a rich record of melt injection. The xenoliths are derived from 25–36 km depth and were transported to the sub-surface within 4 ± 1 h (Fe-in-rutile speedometry), during which they were exposed to the magmatic temperature of $1{,}015 \pm 50$ °C (Zr-in-rutile thermometry). Garnet major-element speedometry shows that before the xenolith-ascent stage the lower crust had already been exposed to a variety of magmas for 700 (Sarfartôq) and 7,100 (Sisimiut) years. The Sisimiut samples contain exotic carbonate- and sulfide-rich assemblages, which occurred during the early stages of melt infiltration. Absence of such exotic assemblages and the faster magmatic development at Sarfartôq are tentatively linked to higher decarbonation kinetics in the more depleted SCLM at this location. The data reveal the so far unrecognized pre-eruptive development of ultramafic systems. This stage involves non-steady state melt-silicate interaction between ascending magmas and the immediate SCLM wall-rock, during which the composition of both is modified. The progress and duration of this interaction is strongly influenced by the composition of the SCLM. Kinetics factors describing this interaction could thus be used to model the chemistry of aillikite and similar ultramafic magmas.

1. Introduction

Aillikite and its less potassic equivalent kimberlite represent carbonate-rich asthenosphere-derived magmas contaminated by material assimilated from the lithosphere (SCLM; Mitchell, 2008; Nielsen et al., 2009; Malarkey et al., 2010; Pilbeam et al., 2013). The melts typically contain a large (>30%) volume fraction of dense mantle xenoliths and xenocrysts, which provide unique insight into the composition and evolution of the continental lithosphere. This cargo ascends through the lithospheric column within a few days (Canil and Fedortchouk, 1999; Costa and Dungan, 2005; Peslier et al., 2008), which enables it to survive exposure to the corrosive magma. Individual magmatic pulses involve: 1) ascent of CO_2-rich parental melt from the asthenosphere during an episode of regional magmatism; 2) chemical differentiation and devolatilization of these melts during SCLM silicate assimilation, 3) influx into the crust through vapor-filled crack propagation, and 4) intrusion or eruption, followed by super-cooling and solidification (e.g., Sparks et al., 2006; Wilson and Head, 2007; Mitchell, 2008; Russell et al., 2012; Pilbeam et al., 2013).

Detailed analyses of ultramafic rocks have provided a leap forward in our knowledge of the chemistry and timing of ultramafic magmatism, and large-scale spatial and temporal trends therein. In contrast, the evolution of individual magmatic pulses as reflected by single dykes, sheets and other such systems is only poorly char-

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acterized. Such systems are hypothesized to reflect single-stage assimilative melting in chemically buffered conduit wall-rock during a very short period of a few days or less. Continuous fractional crystallization with simultaneous digestion of orthopyroxene xenocrysts during ascent could explain the rapid development of such process (Russell et al., 2012) and is at least consistent with the chemical variation as observed among xenocrystic olivine in type-1 kimberlite (Pilbeam et al., 2013). The uniform importance of such single-stage process can however be scrutinized on the basis of fluid-assisted differentiation and deformation within the lithospheric source *before* the eruption of aillikitic magma (Cordier et al., 2015). Such new insights demonstrate that SCLM conduits feeding ultramafic systems may be chemically and physically preconditioned by processes that have so far been overlooked. This general uncertainty compromises efforts to reliably model the evolution of ultramafic systems.

Much of the research devoted to the development of kimberlites and aillikites focused on mantle-derived xenoliths scavenged from the SCLM wall-rock and their immediate melt host (e.g., Griffin et al., 1999; Pearson et al., 2003; Tappe et al., 2011). However, the petrological record of these materials is typically complex and may only represent the final xenolith-transport stage. Lower-crustal samples are typically better preserved due to short magma residence time and may act as better recorders for magmas emanating from the SCLM. However, in spite of this expectation, such rocks are typically only poorly studied. In this study, we focus on such samples to study the magmatic history of the shallow lithosphere in West Greenland. To investigate the effects from SCLM architecture and composition, we analyzed samples from ultramafic lamprophyre dykes in two alkaline provinces: Sarfartôq, which is situated over ultra-depleted Archean SCLM of the North Atlantic Craton (NAC), and Sisimiut, where the SCLM was re-enriched during the Paleoproterozoic (Nielsen et al., 2009; Tappe et al., 2011). We performed geochemical analyses to constrain: 1) ambient temperature (T) and pressure (P) of the source areas, 2) the nature, temperature and chemical evolution of metasomatic agents, 3) the duration and rate of xenolith ascent, and 4) the duration of crustal metasomatism.

2. Geological setting and sample description

The Sarfartôq and Sisimiut alkaline provinces are part of an extensive belt of epizonal ultramafic dykes and sheets, which resulted from the interaction between asthenosphere-derived carbonate-rich melts and variably metasomatized SCLM (Nelson, 1989; Larsen and Rex, 1992; Nielsen et al., 2009; Tappe et al., 2011; Pilbeam et al., 2013). The magmatic bodies originated during a prolonged period of regional magmatism during the Late Neoproterozoic (590–550 Ma; Tappe et al., 2012); they intruded into the heterogeneous gneiss-dominated basement that extends from the Archean NAC in the south, across the Ikertooq shear zone, to the c. 1.8-Ga Nagssugtôqidian Orogen in the north (Fig. 1). Nagssugtôqidian reworking involved tectono-magmatism and – following Van Gool et al. (2002) – southward subduction of terranes north of the Ikertooq boundary. Metasomatism and refertilization of the SCLM is most intense north of the Ikertooq boundary, but also affected the deepest sections of the NAC margin (Nielsen et al., 2009).

The Sarfartôq location is on the northernmost margin of the NAC. Magmatism at this location ended with the simultaneous emplacement of dykes and sheets comprising aillikite – technically aillikite straddling the kimberlite field based on groundmass paragenesis (Nielsen et al., 2009) – calcite-kimberlite and REE-rich carbonatite (Larsen and Rex, 1992; Mitchell et al., 1999; Hutchison and Heaman, 2008; Hutchison and Frei, 2009; Tappe et al., 2012). Sarfartôq mantle xenocrysts and xenoliths locally include high-Cr/Ca 'G9' and 'G10' pyrope, chromite, and sporadic

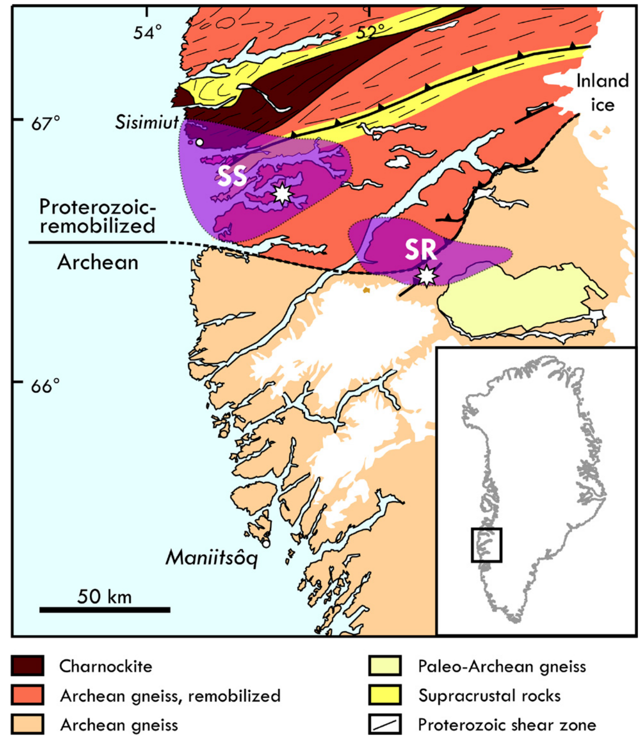

Fig. 1. Geological map of SW Greenland after Mengel et al. (1998), showing the location of the Sisimiut (SS) and Sarfartôq (SR) alkaline provinces and the Archean–Proterozoic terrane boundary from Nielsen et al. (2009). Sample locations are noted with a star.

diamond, all indicative of deep derivation (170–200 km; Bizzarro and Stevenson, 2003; Sand et al., 2009). Mineral compositions and P–T data indicate a stratified SCLM during the Late Neoproterozoic, with depleted harzburgite dominating down to 180 km depth and the lower 70 km being relatively fertile and lherzolite-rich (180–250 km; Bizzarro and Stevenson, 2003; Griffin et al., 2004; Sand et al., 2009). Refertilization of the lower layer could be attributed to Nagssugtôqidian subduction and is possibly the reason for the prevalence of aillikite in this part of the NAC (Mitchell et al., 1999; Nielsen et al., 2009).

In contrast to the Sarfartôq locality, the igneous province at Sisimiut north of the Ikertooq boundary 1) lacks carbonatite and calcite-kimberlite, 2) yielded fewer mantle xenoliths and appear to lack harzburgite altogether, 3) shows lower maximum xenolith derivation depth (120 km), 4) provided no ultra-deep mineral indicators, and 5) occurs among the Paleoproterozoic-reworked gneisses of the Nagssugtôqidian Orogen rather than in the NAC (Mitchell et al., 1999). The aillikites at Sisimiut define a compositional end-member for ultramafic rocks in the region; their mineral and bulk-rock geochemistry reflect a particularly strongly metasomatized mantle source. The rocks resemble those of the Torngat Province in northern Québec and Labrador, which are sourced in a refertilized SCLM rich in MARID-metasomes (mica–amphibole–rutile–ilmenite–diopside; Tappe et al., 2008). In contrast, Sarfartôq aillikites represent compositional intermediates between the Sisimiut aillikites and the bonafide group-1 kimberlite at Maniitsôq in the core of the NAC (Nielsen et al., 2009). Extensive geophysical surveying and xenolith studies demonstrated an average crustal thickness of 40–50 km (Dahl-Jensen et al., 2003) and a relatively consistent geothermal gradient of 40–42 $mW\,m^{-2}$ throughout the region (Griffin et al., 2004; Sand et al., 2009).

Crustal xenoliths comprise 2–5% of the total xenolith population at both locations. They are generally small (0.5–5 cm in diameter) and elliptic (Fig. 2). Three crustal xenoliths (SR-44, SR-45, and SR-47) were recovered from the Sarfartôq dykes. The rocks are