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High-resolution insights into episodes of crystallization, hydrothermal alteration and remelting in the Skaergaard intrusive complex

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ABSTRACT

This paper presents a new high-precision zircon U–Pb geochronological view on the crystallization and assembly process of one of the most important and intensely studied intrusive bodies on Earth—the Skaergaard intrusion in East Greenland. With analytical uncertainties of a few tens of thousands of years, we were able to resolve several important events during cooling of this intrusion.

Initial cooling of the shallowly intruded $\sim$300 km^3 of tholeiitic basaltic magma from liquidus to zircon saturation at $\sim$1000 °C is recorded by a precise zircon crystallization age of 55.960 ± 0.018 Ma of an intercumulus gabbroic pegmatite in the lower portion of the intrusion. Based on this zircon crystallization age and a published cooling model we estimate the "true" age of emplacement to be $\sim$56.02 Ma. The last portions of Skaergaard appear to crystallize completely $\sim$100 ka after emplacement as recorded by abundant $\sim$55.91–55.93 Ma zircons in the Sandwich Horizon (SH), where lower and upper solidification fronts met. Intrusion of an isotopically distinct new magma batch, the $\sim$600 m thick Basistoppen Sill, into the solidified upper portion of Skaergaard, happened at 55.895 ± 0.018 Ma, suggesting close timing between crystallization of evolved rocks around the SH and intrusion of the Basistoppen Sill. The novel result of this work is the demonstration that zircons in the SH, $>$100 m below the Basistoppen contact, have a bimodal age distribution, with the youngest population of 55.838 ± 0.019 Ma postdating intrusion of the Basistoppen Sill by 57 ± 37 ka. Oxygen isotope analyses reveal that SH zircons are low and heterogeneous with respect to δ^{18}O. These results support the proposed conclusion that the SH crystallized twice: it was fully crystalline, then hydrothermally-altered by low-δ^{18}O surface waters and subsequently partially remelted, triggered by heat of the Basistoppen Sill. The low-degree partial melt generated during remelting partially migrated upward by intergranular compaction-driven flow, explaining the existence of the most incompatible trace element rich horizon, $\sim$100 m above SH.

As the Skaergaard intrusion is also the most classic example of a shallow meteoric hydrothermal system, this work documents the alternating processes in a life of an intrusion with periods of hydrothermal cooling, heating by new intrusions, and related remelting events, which cause the generation of low-δ^{18}O magmas.

Our precise temporal framework for intrusion crystallization also provides constraints for the timing of coeval flood basalt volcanism and its synchronicity with the Paleocene-Eocene thermal maximum.

1. Introduction

Chemically-zoned plutons have been the subject of intense research aiming to model the physical mechanisms of igneous differentiation (McBirney and Noyes, 1979; McBirney, 1995; Boudreau and McBirney, 1997; McKenzie, 2011). Most of these models concentrate on the efficiency of crystal-melt separation, the role of convection, and recently silicate liquid immiscibility (Jakobsen et al., 2005, 2010a; Veksler et al., 2007; Humphreys, 2011; Holness et al., 2011). When dealing with now solid plutonic bodies it is important to realize that there are many other time-integrated processes that are possible to unravel with new tools. It is particularly important to realize that even the simplest examples of igneous bodies may contain records of multiple

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refilling events and events of remelting of preexisting rocks that may be traced by radiogenic and/or stable isotopes and the timing of such events can be quantified using precise geochronological methods. In this study we investigate the late-stage evolution of the Skaergaard intrusion aiming to test proposed petrogenetic models and quantify time-scales of late-stage shallow crustal remelting and generation of low-δ^{18}O magmas (Bindeman et al., 2008).

Since its discovery in 1930, the Skaergaard intrusion has been a classic locality for the study of closed-system igneous differentiation (e.g., Wager and Deer, 1939; Wager and Brown, 1968; Brooks et al., 1991; McBirney, 1995; Irvine et al., 1998). After emplacement in the unconformity between the Precambrian basement and overlying Cenozoic basaltic lavas (Fig. 1), it evolved by fractional crystallization from primitive olivine gabbro to Fe-rich ferrodiorite with interstitial granophyre. Progressive crystallization from the floor, walls and roof of the intrusion produced the Layered Series (LS), the Marginal Border Series (MBS) and the Upper Border Series (UBS), respectively (Wager and Deer, 1939). The LS comprises the bulk of the volume and is further subdivided into zones and subzones (Fig. 1c) reflecting the appearance and disappearance of fractionating cumulus phases (Wager and Deer, 1939; Wager and Brown, 1968; Lindsley et al., 1969; Irvine et al., 1998). The upper and lower crystallization fronts coalesced around what is known as the Sandwich Horizon (SH), which contains the most evolved major element differentiation indices (e.g., highest Fe/Mg ratios). However, the highest incompatible trace element concentrations occur tens of meters above the SH, a layer called the secondary SH (McBirney, 2002), or following Bindeman et al. (2008), the "Brooks" Horizon, labeled after the paper by Brooks (1969) who first discovered this enrichment.

The Skaergaard intrusion is perhaps the simplest layered igneous body on Earth in the sense that $\sim$300 km^3 of tholeiitic basaltic magma formed and intruded in a single event into a shallow (ca. 1–2 km) rift zone during $\sim$56 Ma North Atlantic extension, and then differentiated from bottom and top by a closed system differentiation process without much mass loss to the surface, and without much assimilation of highly radiogenic Archean country rocks. Recent work has addressed the importance of crystal compaction vs. convective differentiation (Tegner et al., 2009; McKenzie, 2011), the role of igneous layering, and the role of liquid immiscibility (Jakobsen et al., 2005; 2010a; Veksler et al., 2007; Humphreys, 2011; Holness et al., 2011), but does not attempt to challenge the original views of Wager and Deer (1939) about top to bottom, and bottom to top, liquidus to solidus crystallization of Skaergaard.

2. Previous stable isotope studies and geochronology of the Skaergaard intrusion

These canonical differentiation trends observed in Skaergaard were the initial driving force to empirically understand changes of oxygen and hydrogen isotopic fractionation during magmatic differentiation (Taylor and Epstein, 1963). Subsequent studies, however, found that primary magmatic values were nearly

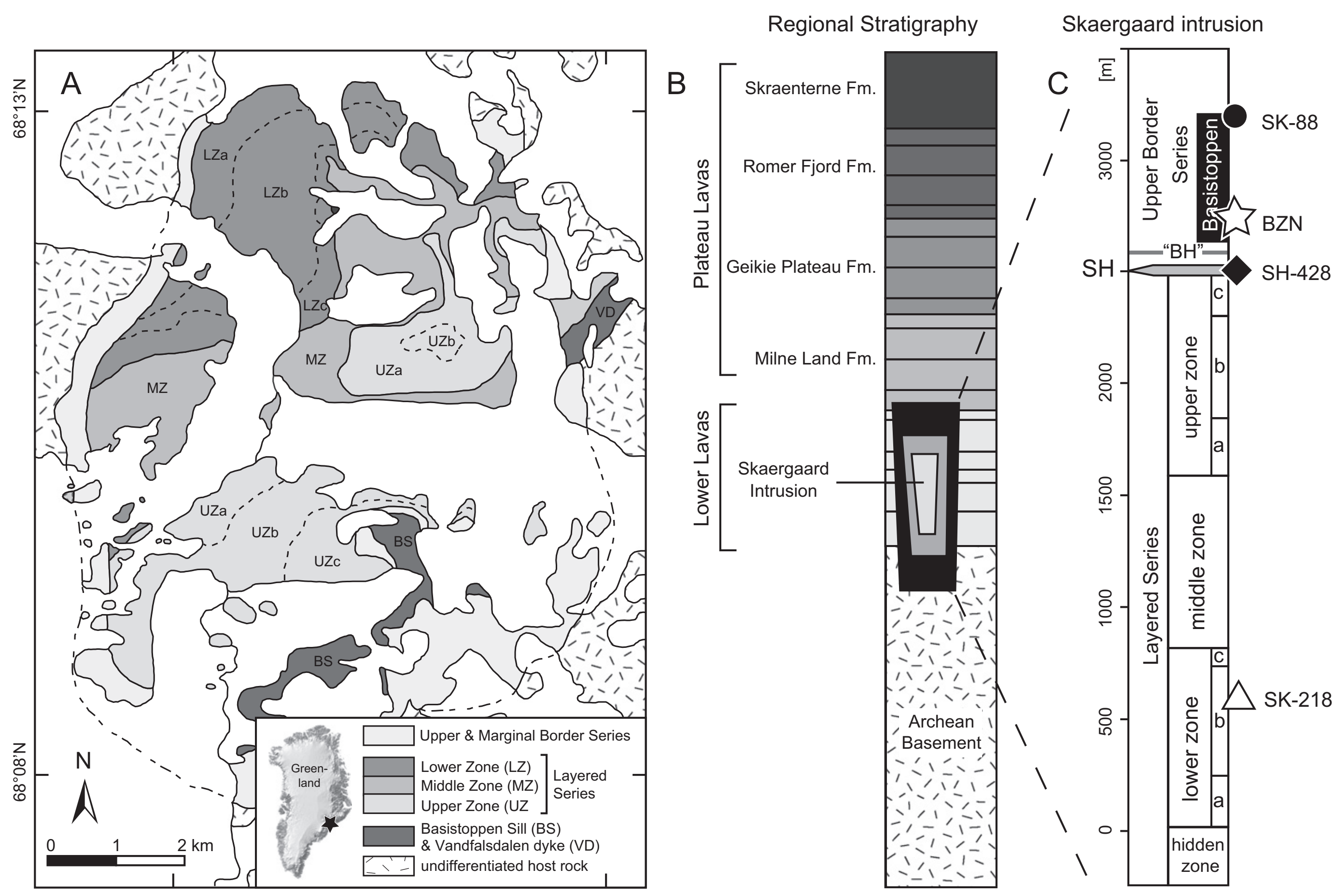

Fig. 1. (A) Geological map of the Skaergaard intrusive complex (McBirney, 1989), (B) regional stratigraphy showing stratigraphic relationship between the Skaergaard intrusion, the Precambrian basement and overlying basalts (after Jakobsen et al., 2010a,b) and (C) stratigraphic column of the Skaergaard intrusion (Wager and Brown, 1968) showing stratigraphic position of analyzed samples. Abbreviations: SH—Sandwich Horizon, BH—Brooks Horizon.