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WHAT PREVENTS THE CRYSTALLIZATION OF MAGMA FROM THE ROOF DOWNWARDS IN LARGE BASALTIC MAGMA CHAMBERS?

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Abstract

A common feature of layered intrusions is the absence of the Upper Border Series (UBS)—a rock sequence that is expected to grow from the roof downwards in large basaltic magma chambers. This is surprising because magma cooling occurs predominantly through the roof of magma chambers. The lack of the UBS is thus indicative of some fundamental reason that prevents basaltic magmas from crystallizing at the chamber roof. Here, we propose that this could be attributed to a layer of anatectic granitic melt that develops on the top of evolving basaltic chambers. The layer may be formed by partial melting of silica-rich crustal rocks in response to the upward transfer of heat from the crystallizing magma. The heat transfer takes place through the initial UBS, resulting in this unit becoming suspended between two buoyant liquids: granitic melt above and basaltic melt below. This unstable position leads to the disruption of the UBS and its collapse onto the temporary chamber floor. A two-layer magma system thus forms, with a light granitic melt floating atop a denser basaltic magma. The granitic melt is expected to be superheated with respect to its liquidus temperature *via* heat transfer from the underlying basaltic magma. In the absence of a solid surface at the top of the basaltic magma layer, the growth of the UBS cannot resume due to the lack of a solid place for new crystals to attach. Further crystallization of basaltic magma may therefore only continue from the base upwards, producing a layered intrusion that consists of only floor rock sequences.

Keywords: basaltic magma chambers, layered intrusions, Upper Border Series, Layered Series, inward crystallization, roof country rocks, anatectic granitic melt, melt superheating.

Introduction

Modern igneous petrology has drawn many fundamental principles from mafic-ultramafic layered intrusions, which are widely considered as "fossilized" natural laboratories for various petrological studies (Wager & Brown 1968, Parsons 1987, Cawthorn 1996, Charlier *et al.* 2015, Latypov *et al.* 2024). These intrusions are commonly considered to result from basaltic magmas that slowly cooled and underwent fractional crystallization within crustal chambers (Naslund & McBirney 1996, Latypov *et al.* 2020, 2024). The modelling of the thermal history of a large sheet-like magmatic body indicates that the heat loss primarily occurs through its roof rather than the floor (*e.g.*, Irvine 1970, Frenkel' *et al.* 1988, Morse 1988). This is because of the larger thermal gradient at the top of the sheet-like body from the onset of its crystallization (Morse 1988). Consequently, magma crystallization is expected to prevail at the roof, resulting in the formation of a thick sequence of roof cumulate rocks [referred to as the Upper Border Series (UBS)] in most layered intrusions, as exemplified by the Kiglapait (Morse 1969) and Skaergaard (Wager & Brown 1968; Fig. 1a) intrusions. In some layered intrusions, such as the Sept Iles, the term UBS refers to roof cumulates formed by flotation of light plagioclase crystals (Namur *et al.* 2011). However, in reality, most layered intrusions have no UBS that extends from the roof downwards. In some cases, this may be attributed to the fact that the original roof rocks, together with the entire UBS, have been obliterated by erosion (*e.g.*, Kemi intrusion; Alapieti *et al.* 1989). Unroofing cannot, however, be the sole reason since many layered intrusions preserve their original roof rocks but still lack the UBS. Examples of such plutonic bodies include the Bushveld Complex (Fig. 1b; Eales & Cawthorn 1996, Cawthorn 2015), Fongen-Hyllingen intrusion (Wilson & Sørensen 1996),

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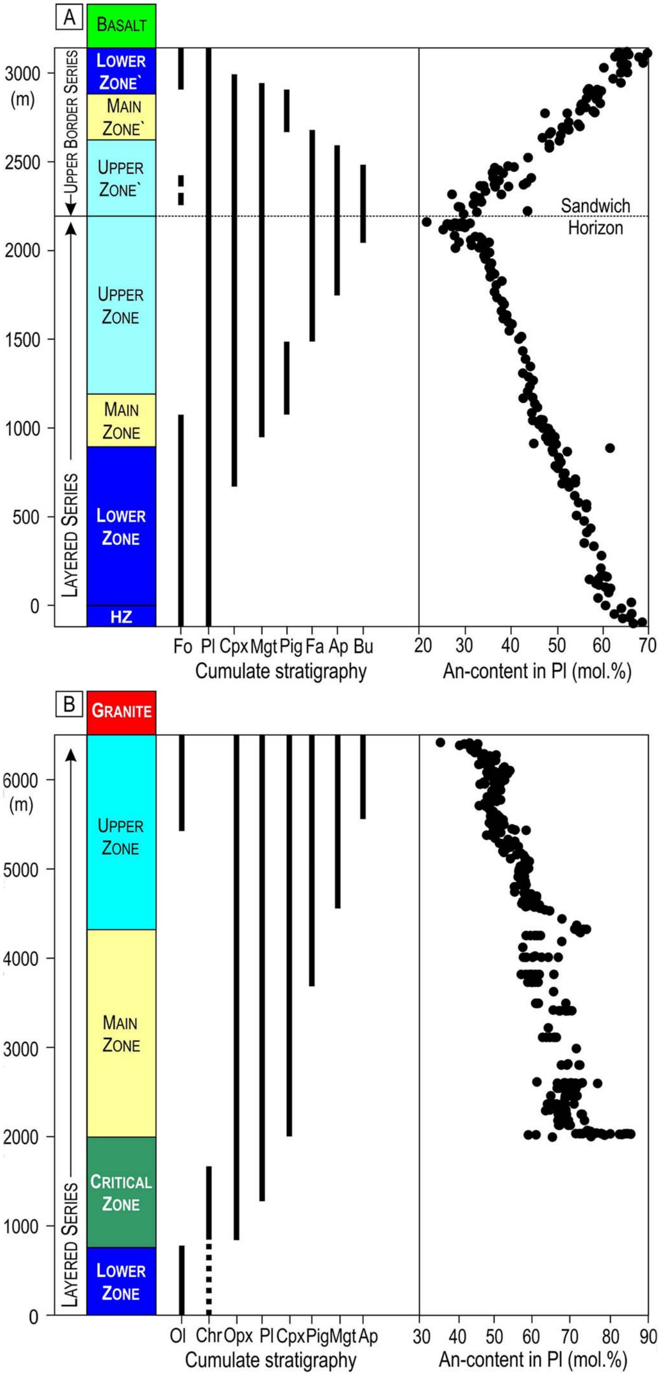

FIG. 1. Two layered intrusions with and without the roof sequence that grew downwards from the roof of basaltic magma chambers. (A) Simplified stratigraphic section and cumulate stratigraphy through the Skaergaard intrusion, East Greenland. The Skaergaard intrusion is composed of the Layered Series (LS) and Upper Border Series (UBS) that crystallized concurrently along essentially parallel trends of differentiation. The LS grew from the floor upwards, forming Lower, Main, and Upper Zones, while the UBS crystallized from the roof downwards, forming the same sequence of

Koillismaa intrusion (Karinen *et al.* 2022), Imandra intrusion (Egorova & Latypov 2012), Muskox intrusion (Irvine 1977), Sudbury Complex (Lightfoot 2016), and the Yoko-Dovyren intrusion (Ariskin *et al.* 2018), among others. At issue is thus: why is the UBS in these intrusions absent when theoretically it should be there? Our recent re-examination of this fundamental question led us to the conclusion that the initial UBS likely formed in all layered intrusions but was not preserved, instead experiencing destruction and collapse as angular blocks on the chamber floor (Latypov *et al.* 2019, 2024, Chistyakova & Latypov 2022). The separate blocks of the partly or completely demolished UBS are found scattered among the rocks of the floor sequences in many intrusive complexes (Fig. 2), including the Akanvaara intrusion (Mutanen 2005), the Stillwater Complex (Hess 1960), the Skaergaard intrusion (Irvine *et al.* 1998), the Windimurra Complex (Nebel *et al.* 2013), and the Sudbury Complex (Latypov *et al.* 2019). What remains to be understood, however, is the reason for (1) the common breakdown of the initial UBS as well as (2) a lack of significant UBS growth after this destructive event. This study aims to address these two fundamental issues in petrology of basaltic magma chambers.

A Difference in Composition of Roof Rocks that Overlie Layered Intrusions With and Without the Upper Border Series

Contrary to all other layered intrusions, the Skaergaard (Wager & Brown 1968, Nielsen 2004, Salmonsen & Tegner 2013, Thy *et al.* 2023) and Kiglapait (Morse 1969, 2015) intrusions demonstrate a prominent UBS that extends from the roof downwards. The crystallization sequences and mineral compositional trends in the UBS (*i.e.*, roof rock sequence) are mirror images of those observed in the underlying Layered Series (LS; *i.e.*, floor rock sequence) that grow from the base upwards (Fig. 1a). However, an important difference exists between these two intrusions and those lacking the UBS in terms of the nature and composition of the overlying roof rocks. Specifically, both the Skaergaard and Kiglapait intrusions are, or were, overlain by refractory rocks with a high melting point [*i.e.*, basaltic lavas in Skaergaard (Wager & Brown 1968) and massive anorthosite cumulates in Kiglapait (Morse 1969)] under which these magmatic bodies were emplaced. In contrast, most other layered intrusions with no UBS are overlain by layers of rocks of broadly granitic composition (Irvine 1975, Mutanen 1989, Egorova & Latypov 2012, Skursch *et al.* 2020, Karinen *et al.* 2022) that were likely produced by partial melting of silica-rich sedimentary or acid volcanic rocks (Irvine 1970, 1975, Campbell & Turner 1987, Huppert & Sparks 1988a, b). It is worth noting that the contamination of basaltic magma by this roof-located granitic melt has been considered a trigger for chromite formation in some layered intrusions (Irvine 1975, Kinnaird *et al.* 2002, Spandler *et al.* 2005). The granitic rocks commonly show little internal compositional variation (*e.g.*, Karinen 2010), indicating a crystallization from a well-mixed homogeneous granitic melt of nearly eutectic composition. As discussed below, we surmise that it is this layer of anatectic granitic melt that could be responsible for the absence of the UBS in most layered intrusions.

A Layer of Anatectic Granitic Melt Prevents Crystallization from the Roof Downwards in Magma Chambers

A typical layered intrusion starts to form with opening and inflation of a fissure in crustal rocks by forceful emplacement of mantle-derived basaltic magma (Fig. 3). The chilling of leading portions of the magma against the cold country rocks (Fig. 3a) is followed by its crystallization from both margins inwards with the formation of the initial roof and floor rock sequences, referred to as the UBS and LS, respectively (Fig. 3b). The upward heat transfer from the crystallizing basaltic magma (*via* the initial chill and roof rock sequence) may cause partial melting of the roof crustal rocks

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Fig. 1. (continued) Zones that are denoted with apostrophes. The two crystallization fronts converged at the Sandwich Horizon, as indicated by the mirror images of the cumulus phase arrivals and An-content of plagioclase in LS and UBS. The Hidden Zone (HZ) represents an unexposed portion of the Lower Zone. Note that the roof country rocks consist of basalts. Modified from Hagen-Peter *et al.* (2019). (B) Simplified stratigraphic section and cumulate stratigraphy through the Bushveld Complex, South Africa. The Bushveld Complex is composed of only a Layered Series that grew from the floor upwards, forming Lower, Critical, Main, and Upper zones. Only variations in An-content of cumulus plagioclase are shown in the figure. Note that the roof country rocks are generally granitic. The cumulate stratigraphy is based on many sources, including Eales & Cawthorn (1996), Cawthorn (2015), and Latypov & Chistyakova (2022). Plagioclase compositions are from Mitchell (1986), de Klerk (1991), and Tegner *et al.* (2006). The vertical continuous and discontinuous bars indicate cumulus and intercumulus minerals, respectively. Abbreviations: Ol – olivine, Fo – forsteritic olivine, Fa – fayalitic olivine, Opx – orthopyroxene, Pl – plagioclase, Cpx – clinopyroxene, Pig – pigeonite, Chr – chromite, Mgt – magnetite, Ap – apatite, Bu – (ferro)bustamite. An-content $= 100*An/(An + Ab)$.

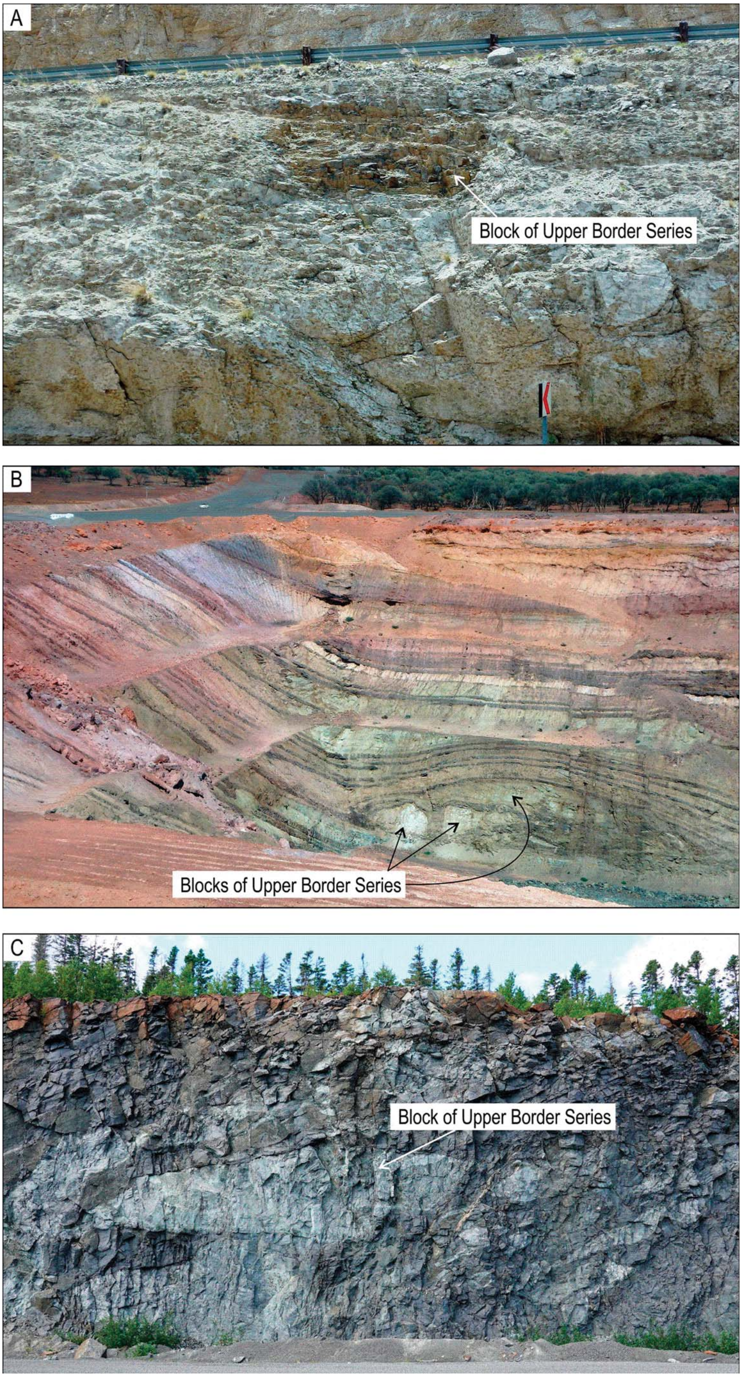

FIG. 2. Angular blocks that were likely dislodged from the Upper Border Series and deposited on the inward-growing chamber floor of the Layered Series. (A) A block of roof cumulates collapsed on the temporary chamber floor of the Layered Series in the eastern Bushveld Complex, South Africa. (B) Blocks of roof cumulates collapsed on the temporary chamber floor of the Layered Series in the Windimurra Complex, Western Australia. (C) A block of roof cumulates collapsed on the temporary chamber floor of the Layered Series in the Sept Iles Complex, Canada.

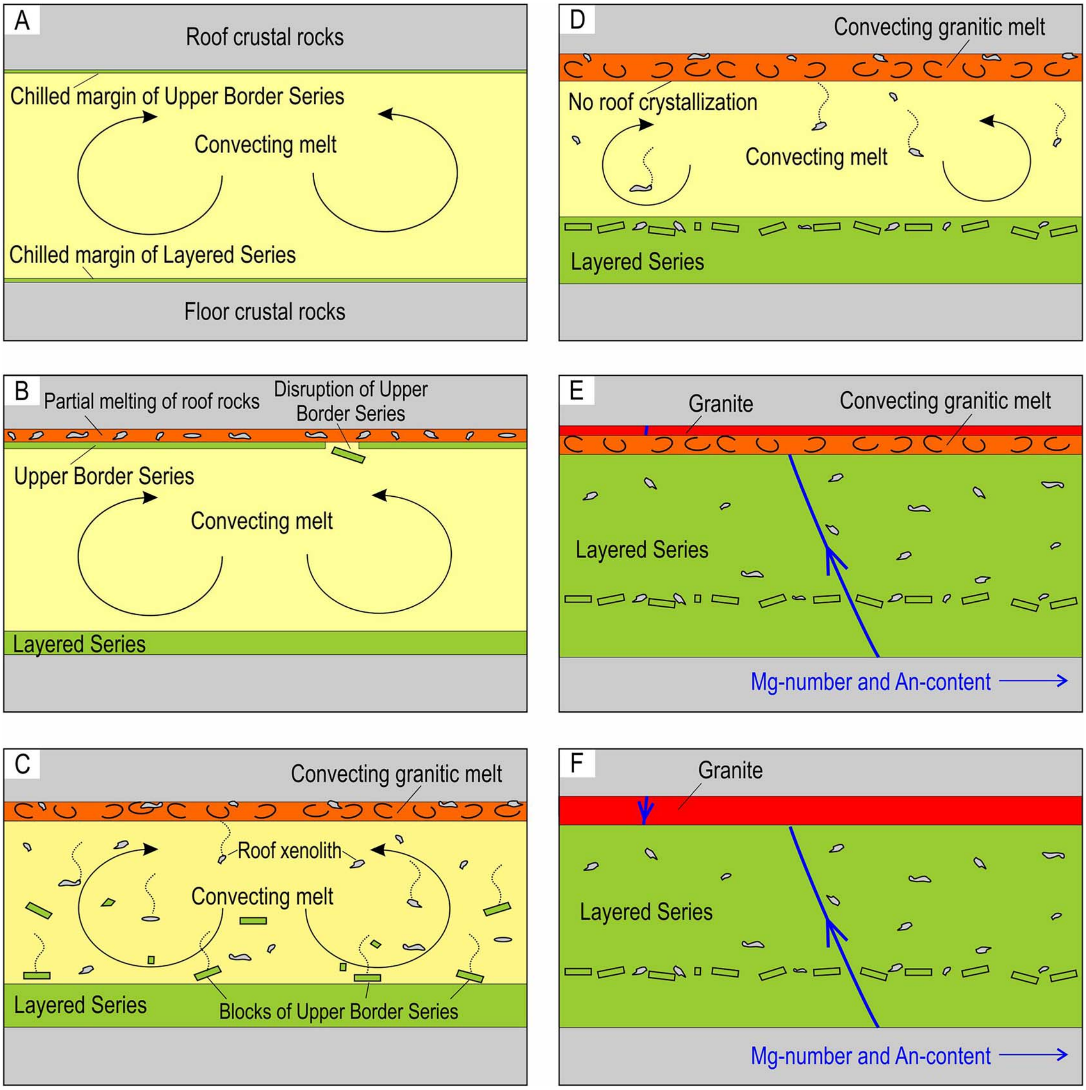

FIG. 3. A scenario to explain the absence of the Upper Border Series from the stratigraphy of layered intrusions. (A) Initially magma is chilled against cold country rocks and starts crystallizing from both margins inwards, forming the Layered Series (floor cumulates) and Upper Border Series (roof cumulates). (B) Heat transfer from the crystallizing magma causes partial melting of roof crustal rocks to form a layer of anatectic granitic melt above the Upper Border Series. (C) The Upper Border Series is tectonically disrupted and, together with restitic xenoliths from a zone of partial melting, sinks towards the upward-growing Layered Series (*i.e.*, chamber floor). (D) No new cumulates of the Upper Border Series form at the top of the basaltic magma because there are no solid roof rocks and therefore only the Layered Series advances from the base upwards, with some contribution from restitic xenoliths falling from the roof. (E) After the formation of the Layered Series, a granitic melt may start crystalizing from the roof downwards. (F) A resulting section of the intrusion only consists of the Layered Series in which minerals become increasingly more evolved, *i.e.*, show a decrease in Mg-number of olivine and pyroxenes and An-content of plagioclase, from the base toward the very roof. The former Upper Border Series is notably absent and only occurs as blocks scattered throughout the floor rock sequence of the Layered Series. Mg-number $= 100*Mg/(Mg+Fe)$, An-content $= 100*An/(An+Ab)$.

because the temperatures of basaltic magmas and the early-formed mineral assemblage crystallized from those magmas are typically higher than the liquidus temperature of most crustal rocks. The partial melting will be most effective in the chambers where the resident melt is kept under convection and replenished with new pulses of hot magmas, with or without phenocrysts. These two processes will contribute to the transfer of more heat from the chamber towards the roof crustal rocks. The resulting partial melts would be expected to be less dense than the parental basaltic magma in the chamber because (1) the average composition of the crust is andesitic or granodioritic, which causes these rocks to melt and produce partial melts less dense than basalts, (2) these partial melts will have higher water contents and be more buoyant than the intruding basaltic magma, and (3) rocks that melt to form light liquids (felsic rocks) have lower melting points than those which produce dense magmas (mafic and ultramafic rocks) (see Campbell & Turner 1987 for more details). The anatectic melt at the roof is expected to be of broadly granitic composition (Fig. 3c). This geological situation is analogous to partial melting of sedimentary rocks by heat transfer from basaltic/picritic dikes through the chilled margins, as documented and modelled by Hersum *et al.* (2007) and Barnes & Mungall (2018). As a result, a solid and dense sheet of the UBS finds itself suspended between two lighter and buoyant liquids: the overlying granitic melt and underlying basaltic magma. In most cases, this is not a gravitationally stable position for the dense solid rocks of the UBS and, therefore, any tectonic deformation may easily disrupt/dislodge these rocks, causing their collapse in the form of separate blocks on the temporary chamber floor (Fig. 3c). The initial UBS will thus be destroyed (partially or completely), with the blocks being scattered in a cumulate pile of the floor rock sequence. Such a nearly complete destruction of the initial UBS has been recently documented for the Sudbury Complex, with only minor remnants of the original UBS being preserved at the contact with the overlying country rocks (Latypov *et al.* 2019). In this complex, the roof-derived blocks of igneous rocks, some up to 700 m in length, appear to be quite abundant and may form ~15 vol.% of the overall thickness of its floor noritic/gabbroic sequence (Latypov *et al.* 2019, Chistyakova & Latypov 2022). In addition to the rocks from the UBS, dense restitic xenoliths of crustal rocks from the zone of partial melting may also be disrupted and sink towards the base of the chamber (Fig. 3c). Partial melting of crustal rocks and related disruption and settling of restitic xenoliths is expected to become even more effective after complete destruction of the UBS that was acting as an insulating layer (Fig. 3d). For this reason, some layered intrusions are nearly littered by blocks of partially digested crustal rocks fallen from the roof host rocks and scattered throughout their entire stratigraphies [*e.g.*, the Hasvik intrusion (Tegner *et al.* 1999) and the Bjerkreim-Sokndal intrusion (Nielsen *et al.* 1996)].

The destruction of the UBS is expected to culminate with the formation of a two-layer magma system consisting of a relatively light granitic melt lying on top of a denser basaltic magma. The low-density granitic melt will form a stable roof melt layer that, under normal conditions, will not mix with the underlying basaltic liquid due to significant contrast in their rheological properties (Annen *et al.* 2006, 2008). The relative proportion of granitic to basaltic magma may vary depending on many variables involved (nature of the roof country rocks, composition and temperature of parental basaltic melt, depth of emplacement, *etc.*). Campbell & Turner (1987) have experimentally examined such a two-layer system, indicating that the entire upper lighter granitic melt may begin to convect as a single layer, separated from the hotter convecting basaltic melt below, by a thin double-diffusive interface through which heat will be transmitted quite rapidly. Under these conditions, the upper granitic layer is expected to become superheated relative to its liquidus temperature (~1000 °C) by ~200–300 °C because it is maintained by thermal convection at a temperature close to that of the underlying basaltic melt (~1200–1300 °C). From this stage, magma crystallization at the top of the basaltic magma becomes impossible because of the lack of a solid substrate on which minerals can nucleate heterogeneously and grow downwards (Fig. 3d) (Campbell & Turner 1987). All crystals that happen to nucleate and grow homogeneously within the magma will thus settle towards the chamber floor, contributing to the growth of the floor rock sequence. As a result, further growth may only proceed from the floor upwards, with no UBS forming at all. In the most simplified scenario, a final section of such a layered intrusion will thus be exclusively composed of the floor rock sequence (*i.e.*, LS), with minerals becoming systematically more evolved (decrease in Mg-number of olivine and pyroxenes and An-content of plagioclase) from the base upwards (Figs. 3e, 1b). Campbell & Turner (1987) also indicated that no crystallization will occur at the roof contact itself during the early stages of the evolution of the chamber because the roof is in contact with a low melting point granitic melt. This granitic melt will likely only start crystallizing after or towards the end of the crystallization of a basaltic magma, when it will be cooled down to its liquidus temperature (Fig. 3f). Layered intrusions that show granitic rocks produced from such a roof-derived anatectic melt include the Muskox (Irvine 1975), Akanvaara (Mutanen 1989), Koillismaa (Karinen 2010, Karinen *et al.* 2022), Imandra (Egorova & Latypov 2012), Bushveld (Skursch *et al.* 2020, 2024), and many others. Further observational and numerical modelling studies are highly encouraged to clarify/validate details of this process (dynamics of crustal melting, cooling, convection and crystallization of an anatectic melt layer and differentiation processes in basaltic magma chamber, *etc.*).

Refractory Rocks Provide a Solid Surface for Crystallization of Cumulates from the Roof Downwards in Magma Chambers

In contrast to the above scenario, the Skaergaard and Kiglapait intrusions were not able to produce a layer of anatectic melt because the heat transfer from their basaltic chambers was not enough to warm the overlying basalt lavas/anorthosite cumulates above their solidus. This is because their solidus temperature is substantially higher (by ~200–300 °C) than that of silica-rich crustal rocks or acid volcanic rocks. Again, the situation is fully analogous to the case when basaltic/picritic dikes are emplaced into and chilled against host basaltic rocks. Thermal modelling of this scenario by Barnes & Mungall (2018) has shown that the basalts will not reach the temperature of their solidus during the cooling history of the dikes. As a result, the chilled margins of these dikes remain intact and strongly attached to solid basaltic rocks. In case of the Skaergaard intrusion, this would mean that the initial UBS will remain gravitationally stable likely for the entire period of magma chamber development because of its firm attachment to the overlying basalts. Even in this situation, some of the UBS may be still broken tectonically and fall on the temporary chamber floor, as observed in the Skaergaard intrusion (Irvine *et al.* 1998). The relative stability of the UBS allows magma crystallization in the chamber to occur from both margins inwards, forming simultaneously the roof and floor rock sequences. Following this process, the basal cumulate pile grows much faster than that of the roof. The slow growth of the UBS is commonly attributed to either crystal settling from the upper solidification front (Morse 1986, 1988, Frenkel' *et al.* 1988, Philpotts & Dickson 2000) or thermal convection that leads to higher heat flow through the roof, keeping the solidification zone thin (Worster *et al.* 1993, Jaupart & Tait 1995, Tait & Jaupart 1996). Thermal convection influences solidification in two ways. Initially, it raises the heat transfer from the melt to the roof, which can either slow down or prevent the growth of the UBS. Additionally, it accelerates the cooling of the melt, promoting the development of crystals internally, especially at the bottom of the chamber (Latypov *et al.* 2020). In such layered intrusions, the LS (*i.e.*, floor sequence) is typically 6–7 times thicker than the UBS (*i.e.*, roof sequence) (Fig. 1a; Jaupart & Tait 1995). The two series finally meet at the Sandwich Horizon, which is much closer to the roof than the floor, and show the same inward-directed rock succession and crystallization sequence (Fig. 1a).

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