



New insights from field observations of the Younger giant dyke complex and mafic lamprophyres of the Gardar Province on Tuttutooq island, South Greenland

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Abstract

The Gardar Province of south Greenland is defined by the products of alkaline igneous magmatism during the Mesoproterozoic. The most laterally extensive Gardar intrusions are a series of giant dyke complexes best exposed on the Tuttutooq archipelago. We present new field observations and a geological map of north-east Tuttutooq island that provide fresh insights into the temporal evolution of the Younger giant dyke complex and two associated ultramafic lamprophyres. Our data demonstrate that distinctive crystallisation regimes occurred in different sectors of the dyke complex, leading to the formation of marginal gabbros and ovoid pod-like domains displaying lamination, modal layering and/or more evolved differentiates. We infer that at least two pulses of magma contributed to the formation of the Younger giant dyke complex. In addition, the relative ages of two ultramafic lamprophyre diatremes are constrained and attributed to two distinct phases of rifting in the Gardar Province.

Introduction

Determining how magmas intrude and crystallise in the crust using structural data and textural features provides fundamental insights into the processes inherent in the construction of igneous intrusions. Despite decades of research, the mechanisms that control layer formation, magma transport and storage, and *in-situ* magma evolution in magma chambers remain elusive (e.g. Cashman & Giordano 2014). The Younger giant dyke complex (YGDC) is an elongate igneous intrusion that extends for over 145 km across southern Greenland (Upton 2013). The YGDC contains regions in which igneous layering, foliation and/or differentiated compositions are observed (Upton 1962). It therefore provides a unique opportunity to study these enigmatic magmatic processes. This study presents a detailed field analysis of eastern Tuttutooq island, focusing on the sections of the YGDC exposed on the island and two ultramafic lamprophyre intrusions. We use these data to elucidate the structural and crystallisation history of the YGDC magma and associated lamprophyres, and thereby gain insights into the processes that controlled the formation of these spectacular intrusions.

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Abbreviations:

BFD: Big feldspar dykes

OGDC: Older giant dyke complex

TIN: Tuttutooq-Ilimmaasaq-Narsarsuaq

YGDC: Younger giant dyke complex

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Geological background

The Tuttutooq–Ilímaasaq–Narsarsuaq (TIN) Zone is the southern of two ENE-orientated rift zones that comprise the Gardar Province. Rifting occurred during the break-up of the Columbia supercontinent, and magmatism was confined to two distinct periods: early (1320–1250 Ma) and late (1200–1140 Ma) Gardar (Upton 2013). Today, the TIN Zone is composed of a granitic basement (Juliane-håb batholith), a fault-bound sedimentary and extrusive volcanic sequence (Eriksfjord Formation), and a range of intrusive bodies, of which those exposed on Tuttutooq are presented in Table 1.

Apart from minor occurrences of brown dykes, Gardar magmatism on Tuttutooq began with the emplacement of the Older giant dyke complex (OGDC) – a composite giant dyke with syenogabbroic margins and a central zone grading from augite syenite in the west, to peralkaline sodalite-nepheline syenite in the east. This predates a suite of subvertical dykes, obtaining widths of up to 800 m, known as the YGDC. The YGDC is dominantly troctolitic but encloses several large ovoid pods of layered and/or more evolved rocks aligned parallel to the strike of the dyke (Upton 1962; Upton *et al.* 2003). Following the giant dykes, the main Gardar dyke swarm was emplaced throughout the TIN Zone (Upton 2013). Relatively small occurrences of ultramafic lamprophyre, occasionally associated with breccia pipes and carbonates, are thought to have been emplaced throughout rifting. Two of these are preserved on Tuttutooq (Upton *et al.* 2006). The latest known igneous events were the emplacement of large central complexes along the rift axis c.1160–1140 Ma, including the Tugtutôq Central complex and Ilímausaq complex (Waight *et al.* 2002).

After rifting ceased, the Gardar Province remained remarkably well preserved. Block faulting, erosion and uplift have set present day exposure at an estimated depth of 3–4 km below the contemporary land surface (Upton 2013). It is thought that Tuttutooq sits structurally below the nearby Ilímausaq complex (Upton 2013), and hence the island provides an opportunity to study deeper rift plumbing systems below economically critical deposits.

Results

A new geological map produced during the current work is presented in Fig. 1. Mapping was conducted at the 1:5000 scale, and a full resolution copy can be found in the supplementary files. In the following section, we provide a summary of field relationships within the YGDC and two ultramafic lamprophyre diatremes in the study area.

Younger giant dyke complex YGDC facies description

The basis for subdivisions of lithological units used in this study is provided later.

YGDC marginal gabbro. The YGDC marginal gabbro is a fine- to medium-grained gabbro. Dendritic plagioclase (<3 cm) and leucocratic melt segregate lenses are observed; the long axis of both are perpendicular to the contacts between host rock and YGDC at several localities (Figs. 2b, d). Rounded host rock xenoliths up to 15 cm are also observed sporadically within this facies (Fig. 2a).

YGDC central troctolite. A coarse-grained troctolite comprised of predominantly olivine and plagioclase primocrysts. Minor oxides and interstitial clinopyroxenes are also present. Four variations of the YGDC central troctolite exist: (1) a texturally homogeneous facies typically with <1% anorthosite xenoliths; (2) an anorthosite xenolith facies with 50–80% anorthosite xenoliths (0.1–150 m) surrounded by a troctolite matrix; (3) a glomerocrystic facies comprising a framework of 2–3 cm ‘snowflake’-like plagioclase aggregates; (4) a layered facies, which has modal layering and/or a foliation defined by a plagioclase crystal framework.

YGDC syenogabbro. Alkali feldspar-bearing gabbro with primocrysts of clinopyroxene. Assortit syenogabbro has characteristic dendritic clinopyroxene (<30 cm). Krydssø syenogabbro grades from modally layered through foliated, to texturally homogeneous (L3, Fig. 1).

Table 1 Gardar intrusions on Tuttutooq

Name	Rock Unit	Trend	Age (Ma)	± (Ma)	Reference
Brown dykes (BD0)	Dolerite	WNW–ESE	1279	1.3	Upton 2013
Older Giant Dyke	Nepheline syenite	E–W	1184	5	Heaman (unpublished data)
Younger Giant Dyke	Troctolite	ENE–WSW	1163	2	Heaman (unpublished data)
Gardar dyke swarm	Various, including big feldspar dykes (BFDs)	ENE–WSW	1163–1160	-	Upton 2013 (Relative age)
Tuttutooq ultramafic lamprophyre	Mela-aillikite	N/A	<1163	-	Upton <i>et al.</i> 2006 (Relative age)
Tuttutooq Central Complex	Quartz Syenites, Granites	N/A	1143	36	Blaxland <i>et al.</i> 1978

See Upton 2013 for original references and isotopic systems in detail.

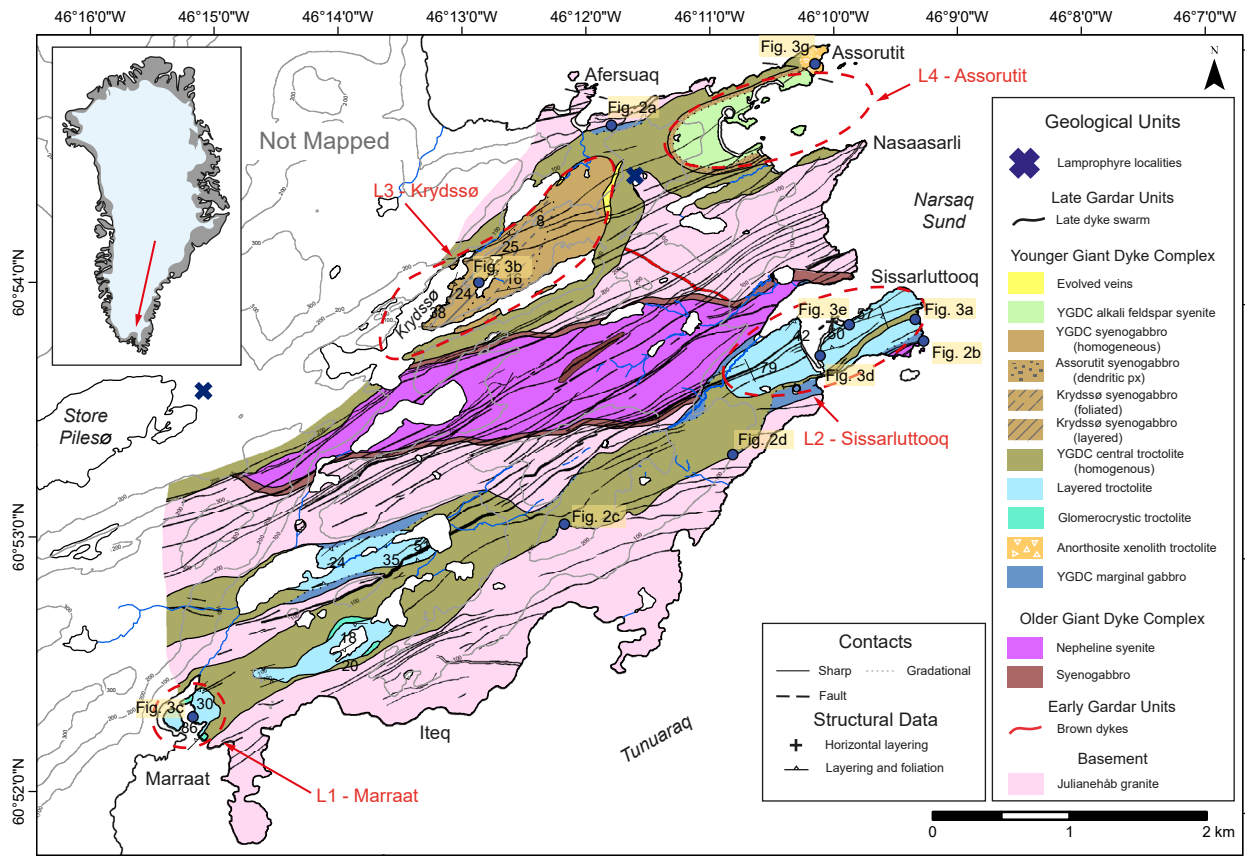


Fig. 1 Composite map of the studied area, with location identified by a red arrow in the inset map. Lamprophyre locality maps are presented in Fig. 4. Localities 1–4 (circled in red) refer to select evolved or layered ‘pods’ and are discussed in the text.

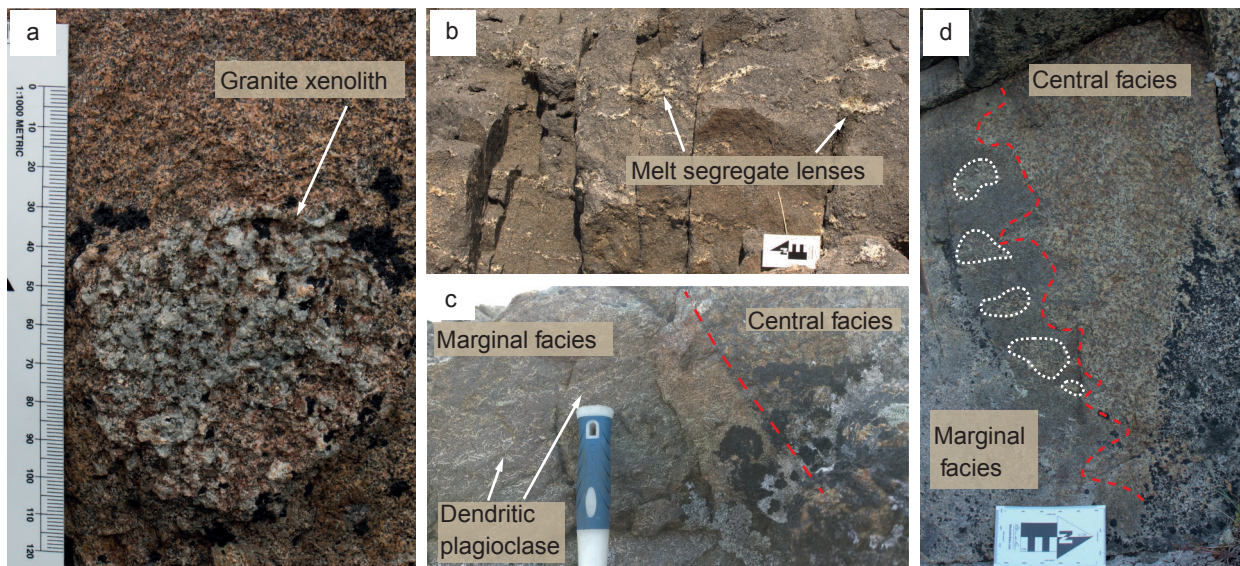


Fig. 2 Selected photographs of key exposure within the YGDC. **a:** Granite xenolith incorporated in the YGDC marginal gabbro. **b:** Melt segregate lenses in the marginal gabbro perpendicular to contact at Sissarluttooq. **c:** Dendritic plagioclases within the marginal gabbro sharply truncated against the central facies troctolite. **d:** Wavy contact between marginal gabbro and central troctolite. The north arrow is 15 cm, and the hammer handle is 10 cm. Location of each image can be found in Fig. 1.

YGDC alkali feldspar syenite. Alkali feldspar-dominated syenite with clinopyroxene, quartz (<5%), amphibole, olivine, and calcite. Evolved veins (commonly <1 m wide) are similar but contain more quartz (up to 20%) and are occasionally pegmatitic.

YGDC facies relationships

Two sections (henceforth limbs) of the YGDC are present in the study area. Both have subvertical, sharp contacts with the basement granite. They have wider (up to 800 m) and narrower sections (minimum 150 m), and trend ENE–WSW.

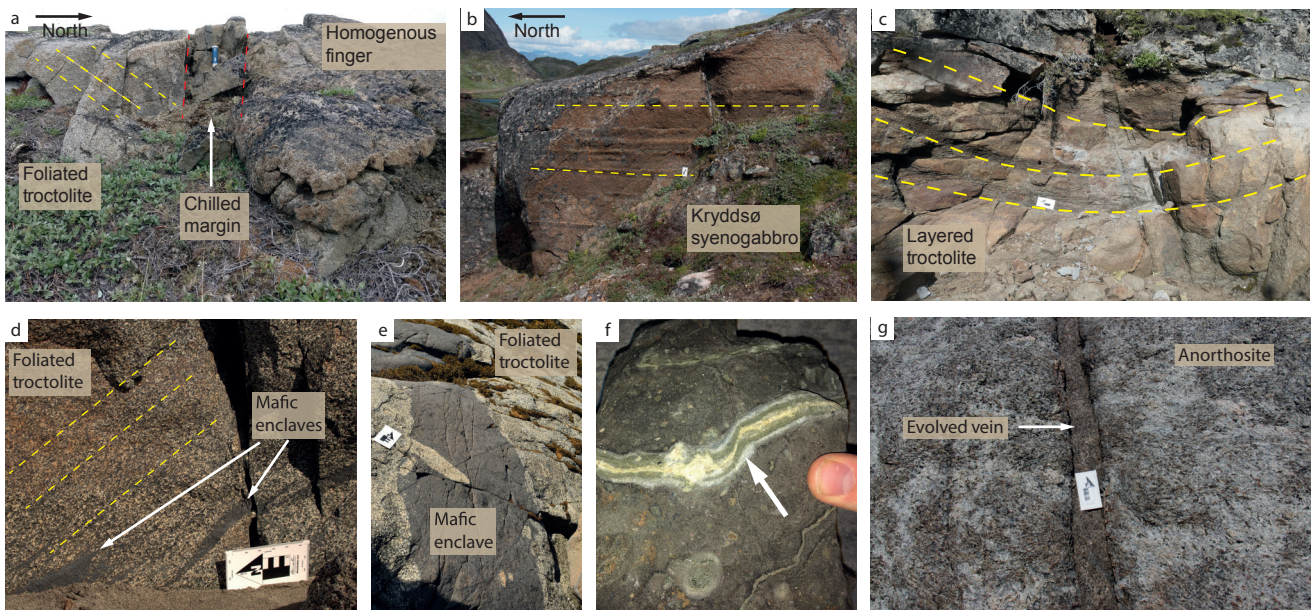


Fig. 3 **a:** Contact between a 'homogenous finger' and foliated troctolite at Sissarluttooq. **b:** Modal layering in the Kryddsø pod. **c:** Overview of layered synform in the Marraat pod. **d:** Foliated troctolite and parallel mafic enclaves in the Sissarluttooq pod. **e:** Large mafic enclave entraining portions of foliated troctolite in the Sissarluttooq pod. **f:** Bilateral veins (e.g. white arrow) within mafic lamprophyres. **g:** Evolved vein cross-cutting anorthosite at Assorutit. The north arrow is 15 cm, and the thumb is 2 cm. Location of each image can be found in Fig. 1.

The outermost 2–100 m of each limb consists of the YGDC marginal gabbro, which shares a lobate or diffuse contact with the homogeneous facies troctolite (Figs. 2c, d). The gross morphologies of the limbs are therefore equivalent.

Several petrographically distinct ovoid pods occur in the centre of the widest parts of the YGDC (Fig. 1). Contacts between the homogeneous facies troctolite and the pods are not exposed. Where pods are concentrically zoned, internal contacts are gradational over c. 3 m. Four individual pods are discussed in detail later.

Marraat pod (L1)

The Marraat pod is 300 m wide, is composed of layered troctolite and in places sheathed with glomerocrystic troctolite (L1, Fig. 1). Contacts between the two facies are complex, and occasional 'glomerocrysts' are found within layers. Within the layered troctolite, alternating picritic and thicker troctolitic layers dip towards the centre of the pod, defining a synformal structure. Layers are laterally continuous and typically thicker at the axis (up to 30 cm) than the edges (1 cm). Contacts between layers are generally gradational over 1 cm; however, some sharp boundaries are observed to the south of the pod where the layers steepen to near vertical. Feldspar crystals define a weak layer-parallel foliation within the troctolite and a non-pervasive, layer-parallel foliation in the picrite that is most apparent at the southern margin. Pegmatitic autoliths of the

YGDC central troctolite (up to 30 cm) occur in the southern section of the layered pod.

Sissarluttooq pod (L2)

The Sissarluttooq pod is dominated by a layered troctolite that is best exposed along the eastern coast of Tututooq, where the YGDC attains a width of 800 m (L2, Fig. 1). A well-developed foliation is persistent throughout the pod defined by a framework of plagioclase. Foliations dip concentrically inwards and shallow from 50° at the edge towards a horizontal central point, defining a canoe-shaped morphology. Crystal size is uniform throughout the pod. Modal layering is observed at only one locality where decimetre-scale picritic layers alternate with foliated troctolite across a 5 m interval.

Elongate mafic enclaves composed of olivine-magnetite cumulates (60–40%) with interstitial plagioclase are observed both aligned with (up to 6 m long) and cross-cutting the foliation (0.15–1 m long). Magnetite crystals are often aggregated and have poikilitic textures enclosing rounded olivine and/or plagioclase crystals. Enclave margins are cusped against the troctolite, are not chilled (Fig. 3), and entrain ellipsoidal autoliths or individual phenocrysts from the neighbouring-foliated troctolite.

A thin (4–50 m) sheet of homogeneous facies troctolite dissects the YGDC through the Sissarluttooq pod (Fig. 3a). It has a fine-grained chilled margin and terminates bluntly outside of the pod (Fig. 3a).

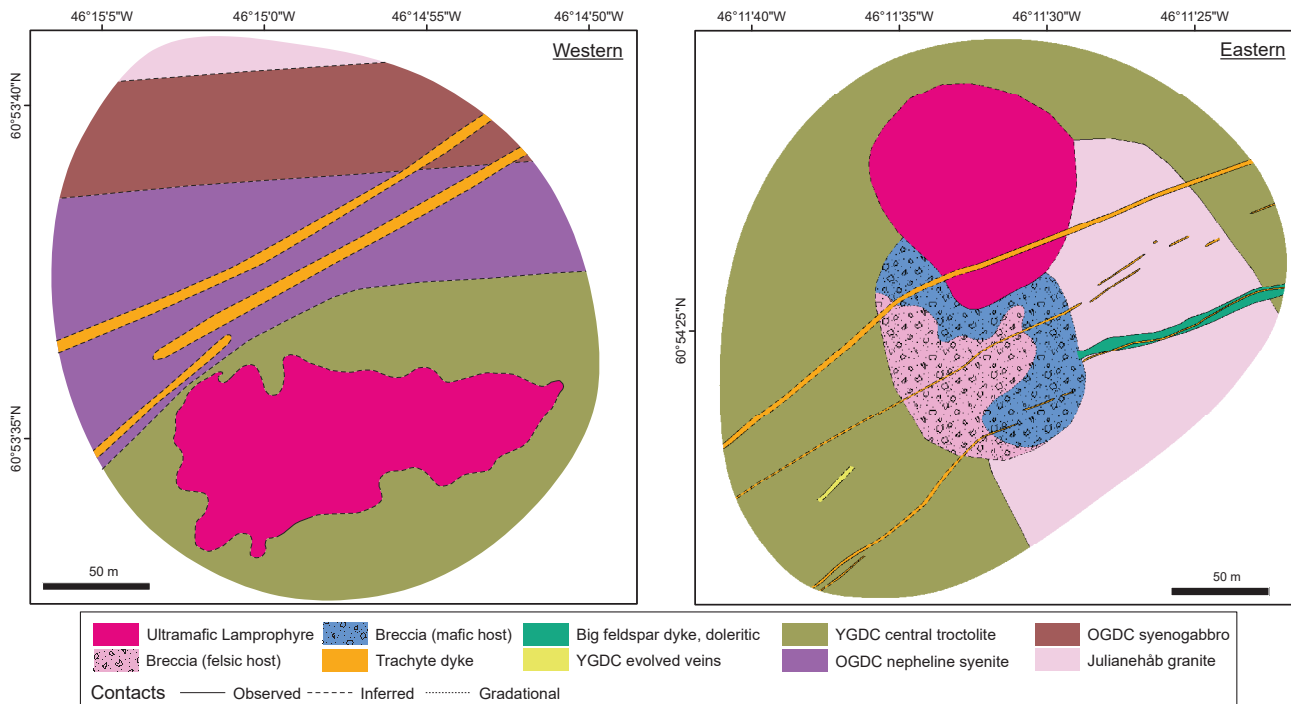


Fig. 4 Focus maps of the western and eastern lamprophyre bodies (see Fig. 1 for locations).

Krydssø pod (L3)

Exposed c. 1 km SSW of Assorutit (L3, Fig. 1), this pod is composed of Krydssø syenogabbro. Thick modal layering (5–15 cm) of laterally continuous feldspar-rich (<80% mode) and feldspar-poor (>40% mode) layers is exhibited in the western third of the pod. To the east, layering grades into a foliation defined by euhedral aligned 2–10 mm pyroxene (c. 20% mode), before diminishing into texturally homogeneous Krydssø syenogabbro. Layering and foliation both dip from c. 40° at the margins towards the centre of the pod and define a central synformal axis plunging 10° towards the north-east. Two large evolved veins (up to 60 m wide) have been identified near the Krydssø pod.

Assorutit pod (L4)

The Assorutit pod (L4, Fig. 1) grades concentrically from the homogeneous facies troctolite through 50–100 m of Assorutit syenogabbro to a core of Alkali feldspar syenite. Towards the tip of Assorutit peninsula, an anorthosite xenolith troctolite is juxtaposed against the pod by a WNW–ESE fault marked by a 2–5 m wide zone of brecciated troctolite. Pegmatitic (0.5–10 cm) evolved veins cross-cut and radiate outwards from the YGDC alkali feldspar syenite facies and can be observed on either side of the fault. The veins also cross-cut the large anorthosite xenoliths (Fig. 3g).

Ultramafic lamprophyre

Two ultramafic lamprophyres are associated with the northern limb of the YGDC (Fig. 4).

Eastern lamprophyre and breccia

The eastern lamprophyre and an associated breccia diatreme outcrop at the apex of a narrowing in the YGDC, both are circular in map view with diameters of c. 100 m (Fig. 4). The lamprophyre's mineralogy consists of olivine, pyroxene, phlogopite and garnet, and occasional phlogopite pegmatitic segregations. Cross-cutting, sinuous and bilateral veins (Fig. 3) are observed radiating from the centre. The breccia pipe comprises clasts with rounded edges and a matrix that grades from a felsic to mafic composition. Clasts include quartzite, a fine-grained mafic lithology and coarse granite.

The lamprophyre cross-cuts the breccia pipe causing further brecciation but no contact between either unit with the YGDC is exposed. Dykes from the main Gardar dyke swarm have variable relationships with the units. Trachytic dykes cross-cut both the lamprophyre and breccia. However, a doleritic dyke with large feldspar xenocrysts (i.e. a big feldspar dyke; BFD) is traceable for less than a metre into the breccia before it becomes indistinguishable from the surrounding breccia matrix (Fig. 4). The matrix at this point is mafic in composition. Cross-cutting relationships that nearby indicate the doleritic BFDs were some of the earliest members of the main Gardar dyke swarm, emplaced prior to the trachytic dykes.

Western lamprophyre

The western lamprophyre is found wholly within the YGDC near the northern contact with the OGDC. Exposure is limited, but the unit appears to have an

irregular shape. The mineralogy can be divided into two groups: (1) oikocrysts consisting of 2–10 mm plagioclase, amphibole and biotite in the south and <2 mm biotite crystals in the north and (2) uniformly sized mafic chadacrysts that are enclosed by group 1. The northern contact with the YGDC is sharp and curvilinear, whereas the southern contact displays a complex melange of troctolite and lamprophyre. In one outcrop, orbicular minerals (potentially pseudo-leucite) are present.

Discussion

Origin of layering

The layered pods of the YGDC have previously been interpreted as regions where convective overturn was vigorous enough to produce dynamic layering (Upton 1962, 2013). However, we find the structural, mineralogical and textural differences between the Marraat and Sissarluttoq pods sufficient to warrant the presence of two different layer-forming processes. The synformal structure with layers thickening towards the centre at Marraat may be explained by crystal-laden density currents originating from gravitational instabilities at the walls, implying convection may not be required. A similar process has been suggested to occur in parts of the Skaergaard intrusion (Irvine 1980), as well as other regions of the YGDC (Upton 2013). This process is inconsistent with the uniform crystal size and concentric structure at Sissarluttoq; instead, we hypothesise layering occurs here through gravitational settling below a convective cell.

Petrogenesis of YGDC magmas

Assorutit and Krydssø magmas

The presence of evolved rocks at the Krydssø and Assorutit pods has been attributed to either *in-situ* fractionation of the troctolitic melt (Upton 1962) or the emplacement of distinct later injections of magma (Upton & Thomas 1980). Field results presented here are not exclusive to either process. However, the layering mechanisms discussed earlier could fractionate a melt by mechanically separating crystals (i.e. dynamic fractional crystallisation). This process could occur during layer formation in the Krydssø and Sissarluttoq pods, driving the fractionation of the YGDC to more evolved compositions.

Furthermore, the presence of cross-cutting evolved veins within the anorthosite xenolith troctolite, known to be a part of the YGDC roof zone (Upton 2013), indicates that silicic melt migrated within the YGDC along vein networks. This presents a process by which the central complexes of the TIN Zone could be fed by evolved melts fractionated at depth. The silica-saturated nature of the Assorutit pod, in otherwise undersaturated lithologies, has been postulated to be the result of crustal assimilation (Upton 2013). Granite xenoliths found in this study provide direct evidence that this process was occurring.

Mafic enclaves

We interpret the mafic enclaves at Sissarluttoq to be cogenetic with the YGDC, and not later melt injections, due to the lack of chilled margins. Such enclaves may be the result of the YGDC melt crossing into the Fe-immiscibility field during fractional crystallisation. The resulting dense, Fe-rich melts sank through the crystal mush below, whilst the lighter melts ponded at the top of the intrusion, forming the anorthosite. A similar process has been suggested to occur in the Isortôq Giant Dykes (Rosa *et al.* 2020).

Homogeneous sheet

The presence of central facies troctolite that cross-cuts the Sissarluttoq pod (L2) indicates that minor troctolitic injections occurred over a prolonged time period. Both injections of YGDC melt are thought to have the same source due to their mineralogical and textural similarities.

Timing of lamprophyre magmatism

The gradational change of a felsic to mafic matrix in the breccia diatreme at the eastern lamprophyre pipe is interpreted to record mixing between a primary felsic material and a mafic magma. We suggest that the felsic material formed through the melting of Julianehåb granite and the mafic host was sourced from the BFD and possibly the lamprophyre. This requires the emplacement of these bodies before the breccia's matrix had fully crystallised, which provides a tight relative age on the emplacement of the lamprophyre – contemporaneous with the emplacement of the BFDs at the start of the main Gardar dyke swarm.

The equigranular ultramafic mineralogy present in the western lamprophyre implies a consistent crystallisation regime. In contrast, the variable size of the enclosing poikilitic mineralogy suggests that the minerals crystallised within a high thermal gradient. The textural differences between the north and south contacts of this lamprophyre support the presence of a high thermal gradient, which may be explained by the proximity to the external contact of the YGDC. In addition, the complex southern contact of the lamprophyre provides no evidence of a liquid–liquid contact between the lamprophyre and the YGDC. We suggest this body is a xenolith of an ultramafic lamprophyre emplaced just before the YGDC, producing an equigranular mafic mineralogy. Density differences have led it to sink through the YGDC post-emplacement, generating the poikilitic mineralogy due to the interaction with the host magma.

Conclusion

Our field results lead to several conclusions: (1) density currents and/or convection developed the Marraat and Sissarluttoq pods; (2) the YGDC melts were available

for a prolonged time period; (3) magmatic fractionation drove the formation of the Assorutit and Krydssø pods as a result of crystal settling under dynamic conditions; (4) the presence of evolved veins radiating from the Assorutit pod demonstrates that there was mobilisation of magmatic differentiates within the YGDC; (5) the two ultramafic lamprophyres on Tuttutooq are of two distinct ages in the late Gardar (>1163 and 1163–1160 Ma). Targeted geochemical, anisotropy of magnetic susceptibility and spatial analyses will enhance our understanding of the YGDC petrogenesis presented here and further study the associated lamprophyre intrusions.

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Author contributions

LK, RW, RC, LM and AM: fieldwork, sample collection, drafting and editing of the manuscript. WM and AF: research supervision and revision of the manuscript.

Competing interests

The authors declare no competing interests.

Additional files

A high-resolution geological map and a methods description can be found at <https://doi.org/10.22008/FK2/NAX2IT>

References

- Blaxland, A.B., Van Breemen, O., Emeleus, C.H. & Anderson, J.G. 1978: Age and origin of the major syenite centers in the Gardar province of south Greenland: Rb-Sr studies. *Bulletin of the Geological Society of America* **89**(2), 231–244. [https://doi.org/10.1130/0016-7606\(1978\)89<231:AAOTM>2.0.CO;2](https://doi.org/10.1130/0016-7606(1978)89<231:AAOTM>2.0.CO;2)
- Cashman, K.V. & Giordano, G. 2014: Calderas and magma reservoirs. *Journal of Volcanology and Geothermal Research* **288**, 28–45. <https://doi.org/10.1016/j.jvolgeores.2014.09.007>
- Irvine, T. 1980: Magmatic density currents and cumulus processes. *American Journal of Science* **280**(A), 1–58.
- Rosa, D., Sandrin, A., Nielsen, T.F.D. & Vesturklett, H. 2020: Petrography, geochemistry and magnetic susceptibility of the Isortoq fe-ti-v deposit, Isortoq Giant Dykes, South Greenland. *GEUS Bulletin* **44**, 1–8. <https://doi.org/10.34194/geusb.v44.4626>
- Upton, B.G. 2013: Tectono-magmatic evolution of the younger Gardar southern rift, South Greenland. *Geological Survey of Denmark and Greenland Bulletin* **29**, 1–24. <https://doi.org/10.34194/geusb.v29.4692>
- Upton, B.G.J. 1962: Geology of Tugtutoq and neighbouring islands, South Greenland, Part 1. *Meddelelser Om Gronland* **169**(8), 1–60.
- Upton, B.G.J., Craven, J.A. & Kirstein, L.A. 2006: Crystallisation of mela-aillikites of the Narsaq region, Gardar alkaline province, South Greenland and relationships to other aillikitic-carbonatitic associations in the province. *Lithos* **92**(1–2), 300–319. <https://doi.org/10.1016/j.lithos.2006.03.046>
- Upton, B.G.J., Emeleus, C.H., Heaman, L.M., Goodenough, K.M. & Finch, A.A. 2003: Magmatism of the mid-Proterozoic Gardar Province, South Greenland: Chronology, petrogenesis and geological setting. *Lithos* **68**(1–2), 43–65. [https://doi.org/10.1016/S0024-4937\(03\)00030-6](https://doi.org/10.1016/S0024-4937(03)00030-6)
- Upton, B.G.J. & Thomas, J.E. 1980: The Tugtutôq Younger Giant Dyke Complex, South Greenland: Fractional crystallization of transitional olivine basalt magma. *Journal of Petrology* **21**(1), 167–198. <https://doi.org/10.1093/petrology/21.1.167>
- Waight, T., Baker, J. & Willigers, B. 2002: Rb isotope dilution analyses by MC-ICPMS using Zr to correct for mass fractionation: towards improved Rb-Sr geochronology? *Chemical Geology* **186**(1–2), 99–116. [https://doi.org/10.1016/S0009-2541\(01\)00420-X](https://doi.org/10.1016/S0009-2541(01)00420-X)