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Crystallisation of mela-aillikites of the Narsaq region, Gardar alkaline province, south Greenland and relationships to other aillikitic–carbonatitic associations in the province

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Abstract

Aillikites (carbonated, melilite-free ultramafic lamprophyres grading to carbonatites) are minor components of the Gardar alkaline igneous province. They occur principally as minor intrusions and as clasts in diatremes, but more voluminous aillikitic intrusions crop out near the Ilímaussaq Complex, which they predate by a few million years. These larger intrusions were emplaced at 1160 ± 5 Ma. They are essentially carbonate-free and, consisting almost wholly of ferromagnesian silicate and oxide minerals, are mela-aillikites. Typically the mela-aillikites are fine-grained rocks composed largely of olivine, clinopyroxene, phlogopite and magnetite that crystallised in open systems, permitting loss of volatile-rich residues. The petrography is highly complex, involving at least 28 mineral species. Pyroxenitic veins were emplaced while the host-rocks were still at high temperatures and represent channels through which fluorinated silico-carbonatitic residual melts escaped, with exsolving CO_2 as propellant. Precipitation of Ca-rich minerals including monticellite, perovskite, vesuvianite, wollastonite and cuspidine was a result of dissociation of the calcium carbonate in the residual melts. Late-stage crystallisation was in a highly oxidising environment in which the 'common minerals' attain extreme compositions (almost pure forsterite, ferrian-diopside, highly magnesian ilmenite, Ba–Ti-rich phlogopite and Sr-rich kaersutite). Spatially associated diatremes may be vents through which CO_2-rich gases erupted. The whole-rock compositions are considered to be well removed from those of co-existing melts: compaction and expulsion of highly mobile residual melts is inferred to have left the mela-aillikites as aberrant cumulates.

The mela-aillikites are a late-Gardar manifestation of the aillikitic magmatism that occurred intermittently in the province for over 120 Ma. Repetitive formation of metasomite vein systems in the deep lithospheric mantle is postulated. These readily fusible metasomites had short residence histories, experiencing either adiabatic melting or thermal melting as a result of plume activity. The abnormally large volumes of ultramafic lamprophyre magma, from which the mela-aillikites crystallised, may denote the culmination of metasomatic processes in the closing stages of the evolution of the Gardar Province.

Keywords: Ultramafic lamprophyre; Mela-aillikite; Carbonatite; Alkaline province; Mantle metasomatism

1. Introduction

The Gardar Alkaline Igneous Province comprises a Mesoproterozoic (1350–1140 Ma) suite of alkalic intrusions in southern Greenland (Upton and Emeleus, 1987;

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Upton et al., 2003). Although best known for its syenite and nepheline syenite plutons including the celebrated Ilímaussaq Complex, the province also includes some enigmatic ultramafic lamprophyres of the aillikite suite characterised by high contents of carbonate and incompatible elements. A continuum between aillikite and carbonatite magmas has been postulated (Upton and Fitton, 1985; Rock, 1986; Coulson et al., 2003).

The Gardar activity involved repetitive rifting and magmatism related to incipient break-up of the Palaeopangaea continent (Upton et al., 2003). Syn-rift volcanic and sedimentary strata composing the Eriksfjord Formation are preserved as a consequence of faulting and relatively superficial erosion. Up to 3.4 km thickness of this Formation is preserved, approximately half of which is represented by lava successions in three principal units or members. These (Mussartût, Ulukasik and Ilímaussaq) members represent magmatic episodes during which large volumes of transitional olivine basalt (and their differentiates) were erupted.

Extensive Gardar dyke swarms, mainly comprising (mildly alkalic) olivine dolerites, developed through repetitive mantle melting events. Magmas of intermediate to salic compositions are also represented in these swarms, although salic rocks are mainly confined to central-type plutons. The salic magmas are inferred to have been derived by fractional crystallisation from basaltic magmas, in conjunction with variable degrees of crustal interaction, during times of transtensional tectonics (Upton et al., 2003).

2. Geological setting

Gardar magmatism was principally concentrated into three ENE-trending zones: (A) within the border of the Archaean craton, (the Arsuk-Ivigtut Zone), (B) to the south-east of the Archaean craton, in the northern part of the Palaeoproterozoic Ketilidian (Julianehåb) Batholith, (the Nunarssuit-Isortoq Zone) and (C) co-axial with the batholith (Fig. 1). This latter, Tugtutôq-Ilímaussaq-nunatak Zone (or TIN Zone), hosts large nepheline syenite intrusions that include the Ilímaussaq Complex and a group collectively known as the Igaliko syenites (Emeleus and Upton, 1976). Two intrusions of this

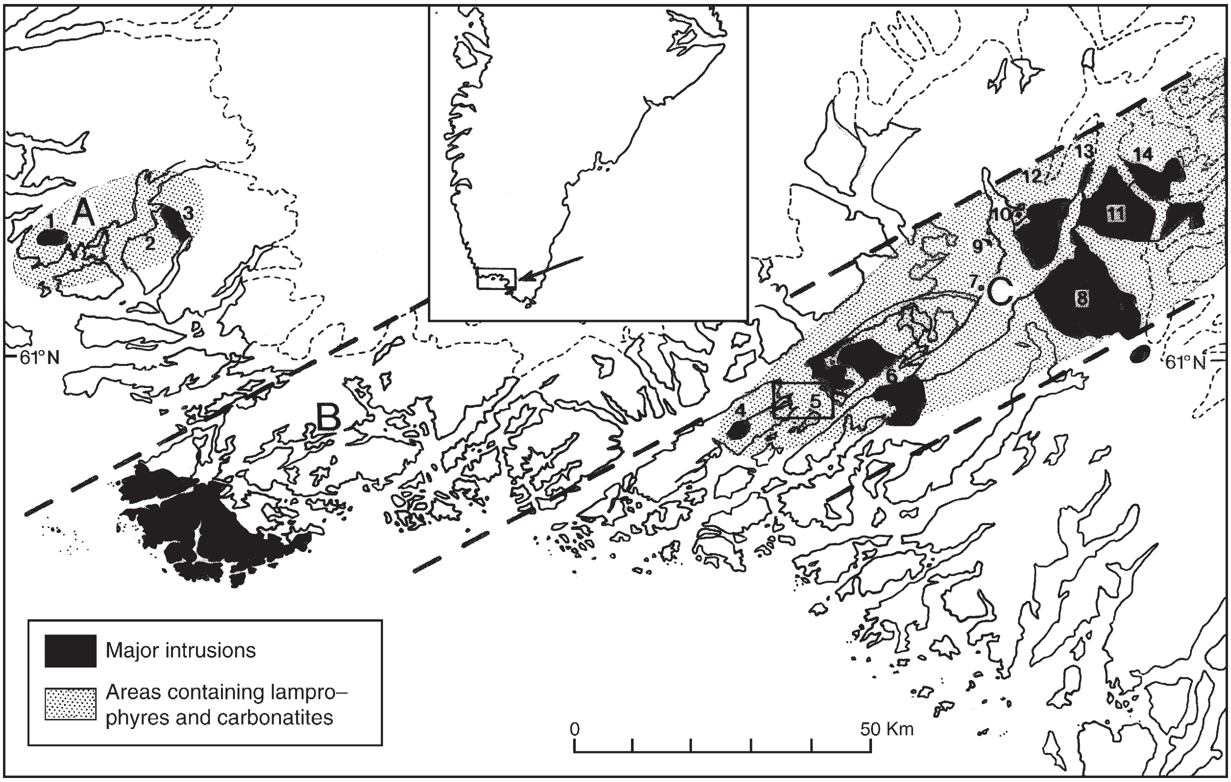

Fig. 1. Map of the Gardar Province showing the Arsuk-Ivigtut Zone (A), the Nunarssuit-Isortoq Zone (B) and the Tugtutôq-Ilímaussaq-nunatak Zone (C), the distribution of major intrusions and the areas in which carbonatites and lamprophyres occur. (1) Kûngnât; (2) Ivigtut; (3) Grønnedal-Ika; (4) Tugtutôq; (5) Narsaq; (6) Ilímaussaq; (7) Sidlisit; (8) Igdlerfigssalik; (9) Qassiarsuk; (10) Narsarsuaq; (11) Motzfeldt; (12) Johann Dahls Land; (13) Mellem Land; (14) G.F. Holm nunatak. The box around '5' shows the area covered in Fig. 3.

group, Motzfeldt and Igdlerfigssalik, are identified in Fig. 1. Intrusions in the Arsuk-Ivigtut Zone have ages in the interval 1350–1260 Ma, whereas activity persisted in the Nunarssuit-Isortoq and TIN Zones to around 1160 Ma.

Small volumes of lamprophyric and carbonatite magmas were generated beneath both the Arsuk-Ivigtut and TIN Zones. Relatively little attention has been paid to the lamprophyres of the Arsuk-Ivigtut Zone but several detailed studies have been made of those in the TIN Zone where the melilite-free and typically carbonated ultramafic lamprophyres 0(UML) will be referred to as aillikites (cf. Rock, 1986; Tappe et al., 2005). This paper focuses on some extraordinary ultramafic intrusions that crop out a few kilometres SE of the Ilímaussaq complex, in the more easterly parts of Tugtutôq island and near Narsaq (Fig. 1). These, containing >80% of ferromagnesian silicates and oxide minerals, conferring a colour index >90, have formerly been referred to as biotite pyroxenites (Upton and Thomas, 1973) but here, following Rock (1986) and Tappe et al. (2005), are described as mela-aillikites.

The extreme alteration which typifies the majority of the aillikitic rocks is attributed to deuteric reaction between early crystallising phases and residual carbonate-rich fluids (Upton and Emeleus, 1987). The Tugtutôq-Narsaq mela-aillikites are, however, exceptional in being largely unaffected: they are inferred to have undergone loss of a volatile phase while still at relatively high temperatures, thus preventing deuteric alteration. The mela-aillikites merit special study on account of (a) their complex petrography involving at least 28 mineral species, reflecting extensive disequilibria, (b) the extreme compositions of some of the common mineral species composing them and (c) the occurrence of minerals rarely found in igneous associations.

Carbonatites have a close space/time relationship with nepheline syenites in the Arsuk-Ivigtut Zone (at Grønnedal-Ika) and with those in the Igaliko group. They were accordingly inferred to have been derived from carbonated phonolitic magmas (Emeleus, 1964; Emeleus and Harry, 1970; Pearce, 1988; Bedford, 1989). While Pearce et al. (1997) subsequently refuted this, claiming that the carbonatites were related to the lamprophyres through liquid immiscibility, a cognate relationship between phonolite and carbonatite magma at Grønnedal-Ika has since been re-affirmed by Halama et al. (2005). The Nunarssuit-Isortoq Zone, while otherwise richly endowed with Gardar intrusions, has no nepheline syenites, lamprophyres or carbonatites.

Within the TIN Zone, UML and carbonatites crop out within an area some 100 km ENE–WSW by 50 km NNW–SSE, embracing eastern Tugtutôq, the Ilímaussaq peninsular, the whole Igaliko region, Mellem Land and the nunataks north of Igaliko (Fig. 1). Field relations, petrography and geochemistry of these rocks have been described by Walton (1965), Stewart (1970), Emeleus and Harry (1970), Martin (1985), Upton and Fitton (1985), Pearce (1988), Coulson (1996), Pearce and Leng (1996), Pearce et al. (1997), Finch et al. (2001) and Coulson et al. (2003). Whereas the close relationship between the aillikitic lamprophyres and carbonatites is most clearly observed at Qassiarsuk (Stewart, 1970), evidence such as the existence of 'mixed' carbonatite–silicate/oxide dykes (Fig. 2), the observation of calcio-carbonatite clasts in lamprophyric dykes, their typical low-temperature carbonation and the compositional convergence of the aillikite and carbonatites can all be cited in support of a co-magmatic relationship.

2.1. Timing

In the Arsuk-Ivigtut Zone lamprophyres, including some UML varieties, occur as small, ENE- to NE-trending dykes (Berthelsen and Henriksen, 1975). Some pre-date the Kûngnât alkaline complex (~ 1275 Ma) and also the pre-Kûngnât dolerite dykes (Upton et al., 2003). Lamprophyric activity also predated the Grønnedal-Ika Complex (1299 ± 17 Ma; Emeleus, 1964; Berthelsen and Henriksen, 1975). The younger and more widespread dolerite dykes of this zone are commonly >5 m wide, many exceeding 20 m. Assuming that dyke widths and abundances bear some positive relationship to volumes, the lamprophyric magmas were volumetrically insignificant in comparison to the basaltic/hawaiitic magmas responsible for the bulk of the subsequent mafic dyke swarms. The lamprophyre magma genesis in this Zone was largely or wholly restricted to a single initial episode heralding much larger mantle melting events.

While the aillikites and carbonatites are mainly seen as minor intrusions, there are some extrusive occurrences within the Eriksfjord Formation. UML lavas are very rare (Rock, 1991) and the aillikitic lavas in the Formation may be globally unique. East of Narsaq, basal arenites of the Eriksfjord Formation pass up into tuffaceous horizons overlain by volcanic breccia containing quartzitic blocks in a fine-grained matrix. Allaart (1973) noted the similarity of the latter with an aillikitic sill in Eriksfjord Formation quartzites adjacent to the western margin of the Ilímaussaq Complex at Nunarsarnaussaq.

Outcrops to the east of Narsaq have been previously regarded as of basalts within the Mussartût Member of

Fig. 2. Part of a 3-m-wide, ENE-trending silico-carbonatite dyke ~8 km ENE of Narsarsuaq. A homogeneous dyke rock with ~50% calcite is inferred to have undergone flow differentiation into contrasted silicate/oxide and carbonatitic layers during intrusion. Coin ca. 20 mm diameter.

the Eriksfjord Formation. However, subsequent reconnaissance studies indicate that dense, plagioclase-free ultramafic rock-types including amygdaloidal and apparently extrusive units compose a significant part of the sequence. Other extrusive expressions of aillikitic magmatism occur NE of the Ilímaussaq intrusion at Sitdlisit and Qassiarsuk (Fig. 1). At Sitdlisit, the basal volcanic unit (Mussartût Member) of the Eriksfjord Formation commences with a 2-m-thick layer of subrounded and highly carbonated UML clasts, overlain by basalt lava. The implication is that an initial explosive aillikite event directly predated the eruption of the basaltic/hawaiitic Mussartût lavas. Qassiarsuk, a few kilometres north of Sitdlisit, presents a shallowly dissected volcanic system involving a suite of carbonatites and ultramafic lamprophyres (Stewart, 1970) that has been correlated with the Mussartût Member of the Eriksfjord Formation (Andersen, 1997). Several diatremes at Qassiarsuk, attributed to volatile-rich ultramafic lamprophyre magmas, are associated with tuffs interstratified with Eriksfjord Formation sandstones. Stewart (1970) divided the Qassiarsuk igneous rocks into groups of (a) basaltic and (b) alkali ultramafic–carbonatitic affinity. Although the latter have been severely carbonated, probably at the time of volcanism, Stewart (1970) described the commonest lithologies among the intrusions and clasts as monchiquites and mica-pyroxenites grading, with increase in (pseudomorphed) olivine, to mica-peridotites. The pre-alteration mineralogy was deduced to have consisted mainly of olivine, clinopyroxene, biotite, magnetite, perovskite and apatite, of which relic pyroxene and perovskite are preserved in some lithologies. Biotite is commonly altered to chlorite and magnetite to haematite (Stewart, 1970). On the basis of Stewart's identification of carbonated pseudomorphs as being after melilite there is also gradation to alnöites and to rocks that may have been composed of >90% melilite. Some of these supposedly altered 'melilite rocks' occur as thin (2–3 m), highly amygdaloidal lavas with calcite and barites-filled amygdales. However, it remains contentious as to whether or not melilite was ever actually present; some of the calcite may be primary and the lavas may represent calcio-carbonatite lava flows.

Whereas the occurrences at Narsaq, Sidlisit and Qassiarsuk lie at, or shortly below, the base of the lowest volcanic member of the Eriksfjord Formation, aillikitic extrusive activity resumed at stratigraphically younger levels. Thus a blocky, breccioid aillikitic lava, at Nunarsarnaq, approximately 5 m thick and interstratified with the sandstones separating the Ulukasik and Ilímaussaq basaltic members, represents a distinctly later eruptive event and another, still younger, UML lava occurs towards the base of the highest volcanic unit (Ilímaussaq Member) in the Eriksfjord Formation (Larsen, 1977). Thus, aillikitic magmatism marked not only the inception of volcanism in the Eriksfjord Formation but also recurred on two later occasions before the eruption of the Ilímaussaq Member lavas.

Aillikite magmatism resumed yet again following the emplacement of the large Younger Giant Dyke gabbroic intrusion (1160 ± 5 Ma), which post-dated the Eriksfjord Formation. This magmatism, which preceded a major swarm of ENE-trending alkalic dykes as well as the

Dyrnaes-Narsaq and Ilímaussaq Complexes, gave rise to the Tugtutôq-Narsaq mela-aillikites and a number of closely associated diatremes. We conclude that aillikitic magmas recurred intermittently over several tens of millions of years, associated in time and space with more voluminous basaltic magmatism.

3. Tugtutôq and Nûgârmiut mela-aillikites

While clearly intimately related to the rest of the aillikitic–carbonatitic suite, the mela-aillikites described below present a special case. Preliminary descriptions were provided by Upton and Thomas (1973) and a detailed study of the petrography, mineralogy and geochemistry was given by Craven (1985). The mela-aillikites are typically very fine-grained (50–500 μm), greenish, brownish or black rocks, predominantly composed of olivine, clinopyroxene, phlogopite and Ti-magnetite. Some of the olivine is present as megacrysts. The high modal magnetite content confers high densities and a strongly magnetic character. The textures tend to be granoblastic, with well-equilibrated intergrain boundaries. Curviplanar, anastomosing patterns of pyroxenitic veins up to 10 cm thick are characteristic of the outcrops. In scarce pegmatitic patches, biotite and pyroxene crystals attain lengths of over 1 cm and possess euhedral terminations in druses. The outcrop inhomogeneity of these rocks, from millimetre to metre scale, together with their lack of typical igneous textures indicate that they cannot simply be treated as fast-quenched hypabyssal magmatic rocks. Consequently, the whole-rock analyses cannot be used as approximations to initial magma compositions. The olivines, pyroxenes and magnetites reflect a higher-temperature mineral assemblage which appears to have preceded phlogopite crystallisation and which generally was annealed to an equilibrated granoblastic fabric. The detailed petrography, however, indicates numerous reaction series. The typical lack of igneous textures in these rocks is ascribed to a partial re-equilibration in a volatile-rich residuum as temperatures declined.

3.1. Tugtutôq

A small body of mela-aillikite occurring at the intersection of two massive Gardar dykes (the Older and Younger Giant Dykes; Upton et al., 2003) will be referred to as Tugtutôq 1 (Fig. 3). It contains olivine megacrysts, pegmatitic segregations and sparse veins rich in ferrian-diopside and phlogopite. It is unusual in preserving relic igneous textures, with early pyroxene, olivine and FeTi oxides enclosed by interstitial biotite

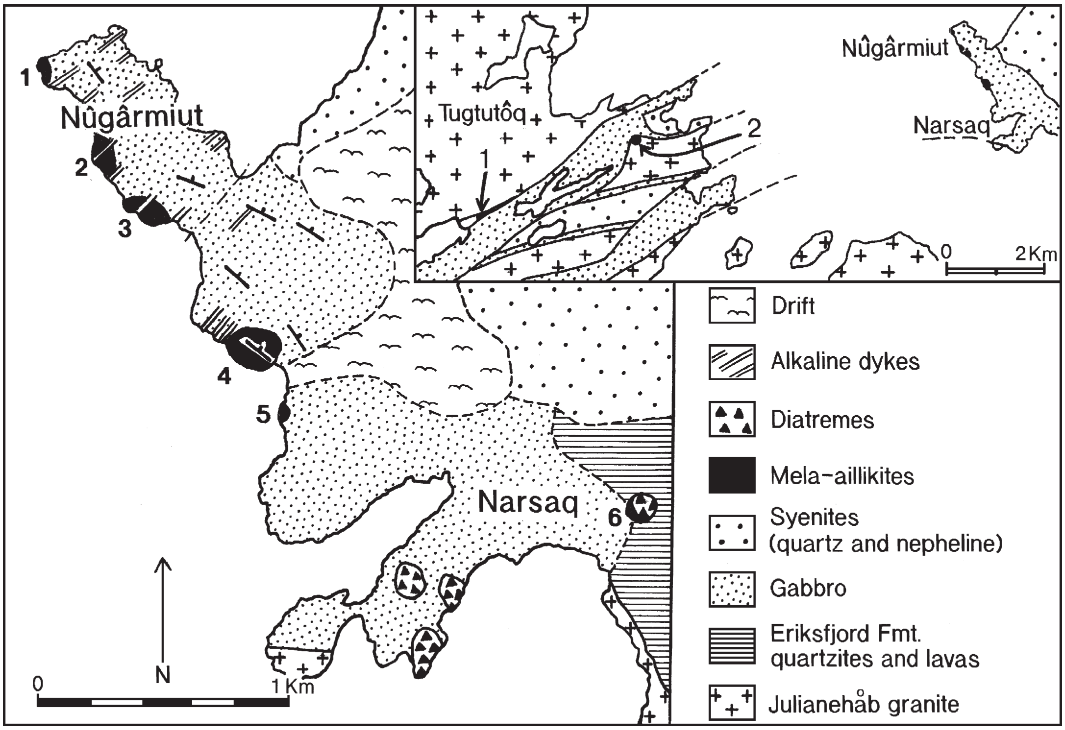

Fig. 3. Map showing localities of mela-aillikite outcrops and diatremes on Tugtutôq and the Nûgârmiut-Narsaq district.

and amphibole. A second mela-aillikite occurrence, Tugtutôq 2, is a vertical sided plug, approximately 80 m diameter, intruded along a contact between Gardar gabbro and pre-Gardar granites, that may represent a sub-volcanic feeder (Fig. 3). A (poorly exposed) breccia adjacent to it is interpreted as part of a diatreme that was largely obliterated by the plug. The latter contains up to 10% of corroded olivine megacrysts and small peridotitic xenoliths and is transected by ramifying pyroxenitic veins, up to 5 cm wide, showing bilaterally symmetrical zoning.

3.2. Nûgârmiut

Several outcrops of mela-aillikite occur intermittently along the west coast of the Nûgârmiut peninsula near Narsaq (Fig. 3). Since the upper contacts of these occur at approximately the same horizon within the layered Narsaq gabbro, it had been inferred that they represented protrusions of an irregular sill-like body (Upton and Thomas, 1973). However, an alternative interpretation is that they are independent stocks or bosses of ultramafic rock, intruded along a NW–SE lineament, that cystallised at a similar structural height as a result of devolatilisation.

The largest outcrop (Nûgârmiut 4, Fig. 3) has a minimum thickness of 90 m. The lower contacts of the mela-aillikite bodies are not seen but the upper contacts against gabbro are well exposed in some exposures where they are conformable with the ENE dip of the igneous lamination in the gabbro. The outcrops are large relative to the typical thin aillikite dykes and sills in the region, suggesting that abnormally large volumes of aillikitic magma were involved. The country-rock gabbro is correlative with the Tugtutôq Younger Giant Dyke Complex (Upton and Thomas, 1973; Craven, 1985).

Extreme textural and modal heterogeneity, reaction and replacement textures, veining and pegmatitic developments indicate that these intrusions had complex crystallisation histories. Consequently, the Tugtutôq and Nûgârmiut mela-aillikites are of special interest in that relatively high-temperature mineral assemblages are preserved. Complex diffuse contacts between the mela-aillikites and their gabbroic and granitic country rocks indicate that the magmas were highly reactive and probably emplaced at high temperature.

The five Nûgârmiut outcrops as well as those on the eastern side of Narsaq township (locality 6) are shown in Fig. 3. While Nûgârmiut 1 is wholly composed of black mela-aillikite (olivine mica-clinopyroxenite), bisected by a network of veins, Nûgârmiut 2 is complex and is divisible into (1) Outer, (2) Transition and (3) Central Zones. The Outer Zone, up to 50 m wide, completely encircles the transition and central zones and consists of olivine pyroxenite grading into an olivine-phlogopite pyroxenite, with micaceous veins and rare pegmatoid developments. Apatite, chlorite and serpentine are minor phases.

The Transition Zone separating the Outer and Central Zones largely consists of a mica-poor rock in which ferrian-diopside is the main component. The latter mineral, which confers a yellowish tint to the outcrops, is accompanied by perovskite, phlogopite, FeTi oxides, olivine, apatite, calcite, garnet, chlorite and cuspidine in highly variable modal proportions. The oxides include magnetite, ilmenite, partially oxidised to ferrian-ilmenite and titanohaematite, and minor amounts of rutile and pseudobrookite. Small amounts of covellite are also present. The Transition Zone contains discontinuous lenticular layers up to 2 m thick, of more leucocratic aspect within an otherwise melanocratic host. The pale layers are breccioid with dark ovoid fragments (1–2 mm) separated by a multitude of white veinlets. In these, the principal mineral phases appear to have reacted with residual melts to produce garnet (andradite–schorlomite) and it is the extensive development of garnet which, together with colourless diopside, phlogopite, clinochlore, serpentine, olivine, calcite, apatite and cuspidine, that gives rise to the light colouration. The Transition Zone is permeated by sinuous near-vertical veins up to 10 cm thick.

The Central Zone consists of an autobrecccia of subangular clasts, up to 40 cm across, of brown micaceous pyroxenite (or, more rarely, calcite + pyroxene-rich material) matrix-supported within yellowish ferrian-pyroxenite. The latter comprises ferrian-diopside, phlogopite, FeTi oxides and apatite and lacks both olivine and perovskite. Some individual clasts are themselves layered due to modal variations in magnetite and biotite. The Central Zone is thus an intrusion breccia in which an earlier layered pyroxenite was disrupted by later pulses that crystallised as ferrian-pyroxenite. Scarce, thin veins in the central unit post-date the brecciation. Nûgârmiut 2 indicates an extended sequence of events in which younger melts were able to brecciate earlier crystallised facies whose behaviour ranged from ductile to increasingly brittle.

The lowest exposures of Nûgârmiut 3, close to sea-level, consist of black mela-aillikite permeated by lemon-yellow ferrian-diopside-rich veins. Some 6 m higher, however, the rock grades into yellow ferrian-pyroxenite containing 2–3 mm segregations of both mica-rich and magnetite-rich facies. Where present, veins are planar and near-vertical, thus differing from the meandering veins in the lower rock. The uppermost 2–3 m of the outcrop, immediately beneath the roof of gabbro country-rock, exhibits layering conformable with the roof (Fig. 4). The layers, ranging up to ~20 cm thick, involve alternations of (a) leucocratic layers, (b) micaceous layers ± small (mm-scale) whitish ovoids, (c) ferrian-diopside-rich layers hosting segregations rich in mica and amphibole and (d) layers with phlogopite–magnetite segregations in mica-poor pyroxenite. The white ovoids and the palest of the leucocratic layers are oxide-free and are predominantly composed of diopside, monticellite, vesuvianite and andradite, together with some apatite, clinochlore and serpentine. This relatively low-temperature assemblage post-dated crystallisation of both the olivine pyroxenites and ferrian pyroxenites.

Nûgârmiut 4 is the largest outcrop (~300 m^2) and consists mostly of fine-grained black mela-aillikite cut by curviplanar veins. The mela-aillikites contain olivine macrocrysts up to 10 mm across, with some facies containing ~30% macrocrysts (Fig. 5). Towards the top of the outcrop, the black rock grades into yellow ferrian-pyroxenite with loss of both veining and macrocrysts. The uppermost 20 m of outcrop are well layered with cm-scale layering defined by variation in modal proportions of mica, magnetite and pyroxene.

Nûgârmiut 5 was a small mela-aillikite outcrop now obscured by urban expansion of Narsaq. Locality 6 (Fig. 3) presents a juxtaposition between a mela-aillikite body and a diatreme occupied by clasts of quartzite and basalt derived from the Eriksfjord Formation.

Fig. 4. Parallel layers of contrasted modal composition close to upper contact Nûgârmiut 4. Hammer shaft, 55 cm long.

Fig. 5. Olivine macrocrysts (±magnetite) in lower facies of Nûgârmiut 4. Coin ~20 mm diameter.

3.3. Veining

The meandering veins, which typically exhibit bilaterally symmetrical zonation defined by varying mineral modes parallel to the vein margins, are characteristic of the mela-aillikites (Fig. 6) The veins define flame-like patterns indicating that they were generated while their host-rocks were still ductile.

In Nûgârmiut 1, the smaller veins consist of biotite alone but the larger ones are polymineralic and bilaterally symmetrical with olivine-rich axial facies and biotite-rich outer facies. Complex veins in Nûgârmiut 2, mainly composed of ferrian-diopside, are cut by thinner (<2 mm) veins, composed largely of mica and calcite that are less tortuous than the earlier veins. Veining is intense in the Transition Zone, giving a vein/host ratio of 80:20 close to the Central Zone.

The veins are commonly divisible into a marginal, intermediate and axial facies. The thin marginal facies are typically pyroxene-rich, with relatively abundant titanite, calcite and chlorite, while lacking olivine and opaque oxides. The intermediate facies contain abundant oxides and are jacketed on their inner side by

Fig. 6. Nodular-weathering mela-aillikite transected by meandering vein system. Nûgârmiut 2. Coin ~20 mm diameter.

perovskite. The axial facies tend to be coarser-grained, with zoned pyroxenes and contain calcite, chlorite and olivine. Pegmatitic segregations, commonly present at vein intersections, comprise phlogopite and yellow ferri-diopside, sometimes zoned out to green aegirine-rich rims. Perovskite (rimmed by titanite), calcite, oxides, apatite, acmite, albite, garnet and epidote occur interstitially to the pyroxenes.

A second class of veins in the Nûgârmiut outcrops are thinner and less sinuous than the first class and inferentially represent lower temperature parageneses. They cut the ferrian-pyroxenites and consist largely of prismatic pyroxene grown normal to the vein walls while also hosting fine-grained assemblages of wollastonite, cuspidine, celestite, andradite, vesuvianite, hydro-andradite, chlorite and colourless mica. Cuspidine has grown as a reaction product around corroded wollastonite. The inference is that fluids transmitted through these late veins were rich in Ca, Ba, Sr, CO_3^{2-} and F^- ions.

3.4. Diatremes

Three diatremes, up to 100 m across, occur between 1 and 4 km SE of the Nûgârmiut mela-aillikite outcrop within the harbour area of Narsaq (Fig. 3). They cut the gabbro country rocks and are on strike with the Nûgârmiut mela-aillikites. They are largely filled with quartzite and basalt clasts derived from the Eriksfjord Formation (that overlay the Narsaq gabbro). Some quartzite clasts have cavities with calcite and gypsum. Veins and patches in one diatreme exhibit a crystallisation sequence of (a) epidote, (b) calcite and (c) (latest) purple fluorite. Some clasts are highly fluoritised. A similar diatreme ('Water Tower hill') lies adjacent to locality 6 (Fig. 3). As stated earlier, there is a diatreme adjacent to the Tugtutôq 2 mela-aillikite plug. This contains fragmented Julianehåb granite, quartzite and fine-grained ultramafic rock. The granite has been extensively melted, recrystallising to granophyre. Although the diatremes have not been studied in detail they provide evidence for energetic passage of high temperature and chemically aggressive gases. It is suggested that the diatremes originated from the violent degassing of the aillikitic magmas.

4. Mineralogy of the Tugtutôq and Nûgârmiut mela-aillikites

The mela-aillikites can broadly be subdivided into an olivine pyroxenite class, dominated by olivine megacrysts in a fine-grained matrix of olivine, fassaitic clinopyroxene, ilmenite, magnetite and mica; and a ferrian-pyroxenite class largely composed of ferrian-diopside together with olivine, magnetite, biotite and perovskite. From the relationships in Nûgârmiut 2, the ferrian-pyroxenites are seen to be younger (and inferentially of lower temperature) than the olivine pyroxenites. The mineral compositions are described below and representative mineral analyses presented in Tables 1a–d.

4.1. Olivine

Olivine is present in almost all facies, typically as equidimensional groundmass crystals although the embayed macrocrysts, particularly prominent in Tugtutôq 2 and Nûgârmiut 4 are generally recrystallised to neoblast mosaics. Olivine also occurs late (e.g. in the

Table 1a
Selected olivine and clinopyroxene analyses

%	Olivines					Clinopyroxenes						
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	41.82	41.16	40.11	39.74	37.57	53.73	50.17	44.21	46.61	45.81	43.59	45.34
TiO_2	–	–	–	–	–	0.48	2.08	3.71	2.35	2.31	3.84	1.21
Al_2O_3	–	0.04	0.03	–	–	–	2.19	5.90	6.21	6.86	6.09	6.34
Cr_2O_3	–	–	–	–	–	0.17	–	0.12	0.14	0.01	0.05	–
Fe_2O_3	–	–	–	–	–	2.11	2.76	6.86	4.59	5.72	8.46	11.30
FeO	1.42	5.32	9.84	13.42	26.68	–	1.43	0.43	1.27	2.14	0.16	–
MnO	0.31	0.40	0.53	0.31	0.51	–	0.05	–	0.22	0.17	0.04	0.27
NiO	0.11	0.05	0.13	0.29	0.18	–	–	–	–	–	–	–
MgO	55.64	52.04	48.61	45.74	35.31	17.83	15.39	14.10	13.52	13.29	12.76	11.30
CaO	0.29	0.87	0.18	0.08	–	26.79	24.38	23.92	25.18	22.60	23.81	22.94
Na_2O	–	–	–	–	–	–	–	–	–	0.41	0.46	1.22
Total	99.59	99.88	99.43	99.58	100.25	101.11	98.45	99.25	100.09	99.32	99.26	99.92
Fo (%)	99	95	90	86	70							

(1) 02R052 Central zone, micaceous ferrian pyroxenite, Nûgârmiut 2. (2) 02R101 Layered sequence, pegmatitic segregation, Nûgârmiut 3. (3) 03R164 Olivine pyroxenite with ferrian diopside segregation, Tugtutôq 1. (4) 02R148 Homogenous olivine pyroxenite, Nûgârmiut 4. (5) 01R965 Micaceous olivine pyroxenite, Tugtutôq 2. (6) 03R876 Ferrian pyroxenite, Nûgârmiut 4. (7) 02R081 Mica-rich horizon in layered sequence, Nûgârmiut 3. (8) 02R5920 Layered sequence, pegmatitic segregation Nûgârmiut 3. (9) 02R967V Olivine pyroxenite, Tugtutôq 2. (10) 03R164 Olivine pyroxenite with ferrian diopside segregation, Tugtutôq 1. (11) 03R119C Ferrian pyroxenite, Nûgârmiut 3. (12) 03R130 Leucocratic layer, Nûgârmiut 4.

–: signifies below detection.

Nûgârmiut 2 Transition Zone) as poikilitic crystals enclosing mica, pyroxene, perovskite and opaque oxides. Other clearly late crystallising olivines include anhedral crystals associated with, and sometimes rimmed by, monticellite in the leuco-layers of Nûgârmiut 3 and 4 and also those in the axial parts of the veins.

In most facies of the mela-aillikites, the olivine compositions lie between Fo_{87} and Fo_{82}, with zoning either absent or very slight (~3% Fo). Where discernible (e.g. in the lower facies of Nûgârmiut 4), the rims are slightly richer in Fe, Ca and Mn and poorer in Ni. In the more oxidised, late-stage facies, the forsterite content rises significantly. Thus, in the leucocratic layers in the

Table 1b
Selected biotite, amphibole and garnet analyses

%	Biotites						Amphiboles			Garnets			
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	37.63	36.72	36.70	35.39	34.06	33.98	49.31	39.68	40.15	21.21	28.58	30.39	35.26
TiO_2	3.07	5.20	6.71	6.92	11.02	9.36	0.94	5.44	5.00	19.99	11.04	8.47	0.93
Al_2O_3	13.39	13.38	14.34	13.91	14.78	14.09	7.72	11.40	11.34	1.50	1.27	0.62	1.82
Cr_2O_3	–	–	–	–	–	–	–	–	–	0.04	0.10	–	0.02
Fe_2O_3	–	–	–	–	–	–	–	–	–	22.79	23.78	25.67	27.16
FeO	4.64	5.08	5.04	7.66	7.35	13.88	3.61	10.12	10.39	0.63	–	0.57	–
MnO	0.08	0.12	0.05	0.13	0.07	0.14	0.09	0.16	0.11	0.32	0.09	0.05	0.02
MgO	24.18	22.06	20.70	18.9	16.30	13.39	20.65	13.66	13.11	1.53	1.50	1.01	0.53
CaO	–	0.02	–	–	–	–	12.92	11.81	11.69	30.95	33.35	32.42	33.87
Na_2O	0.26	0.25	0.75	0.43	0.44	0.58	1.64	2.66	2.35	–	–	–	–
K_2O	10.05	9.58	8.88	9.06	7.88	8.40	0.08	1.48	1.28	–	–	–	–
BaO	0.23	0.74	0.73	1.55	5.34	0.94	–	0.63	–	–	–	–	–
SrO	–	–	–	–	–	–	–	–	0.86	–	–	–	–
Total	93.53	93.15	93.90	93.94	97.24	94.76	96.96	97.04	96.28	98.96	99.71	99.2	99.61

(1) 02R053 Central zone, leucocratic ferrian pyroxenite, Nûgârmiut 2. (2) 01R041 Ferrian pyroxenite, Nûgârmiut 2. (3) 02R036 Ferrian pyroxenite, Nûgârmiut 2. (4) 03R080 Pegmatitic segregation in ferrian pyroxenite, Nûgârmiut 3. (5) 01R012 Homogenous olivine pyroxenite, Nûgârmiut 1. (6) 05R126 Olivine pyroxenite with pegmatitic segregation, Nûgârmiut 3. (7) 02R875 Olivine pyroxenite, Nûgârmiut 4. (8) 28R967 Olivine pyroxenite, Tugtutôq 2. (9) 01R228 Micaceous olivine pyroxenite, Tugtutôq 2. (10) 03R041 Ferrian pyroxenite, Nûgârmiut 2. (11) 01R072 Leucocratic ferrian pyroxenite, Nûgârmiut 2. (12) 03R073 Leucocratic ferrian pyroxenite, Nûgârmiut 2. (13) 01R084 Ferrian pyroxenite, Nûgârmiut 3.

Table 1c
Selected FeTi oxide (magnetite, ilmenite, pseudobrookite) analyses

%	Magnetites						Ilmenites		Pseudobrookites	
	1	2	3	4	5	6	7	8	9	10
SiO_2	0.02	0.04	0.09	nd	0.06	nd	0.04	0.19	0.04	0.04
TiO_2	23.31	21.73	0.73	2.38	50.92	53.03	50.12	55.87	50.26	49.77
Al_2O_3	6.16	7.61	8.85	5.06	0.15	0.51	0.29	0.26	1.46	1.42
Cr_2O_3	0.39	0.20	0.30	0.13	0.05	0.01	0.03	0.03	0.04	0.05
Fe_2O_3	13.53	17.83	61.63	66.40	7.39	4.98	18.46	14.15	39.22	40.48
FeO	50.92	47.94	16.61	6.45	35.50	31.55	9.77	2.57	2.45	1.56
MnO	1.38	0.70	1.15	1.15	0.54	1.38	2.07	2.75	0.08	0.23
MgO	0.15	2.25	10.02	16.93	5.51	8.27	18.66	25.12	6.03	6.17
Total	95.86	98.30	99.38	98.5	100.12	99.73	99.44	100.94	99.58	99.72

(1) 02R032 Nûgârmiut 2. (2) 01R005 Nûgârmiut 2. (3) 02R084 Nûgârmiut 3. (4) 02R119 Nûgârmiut 3. (5) 04R168 Tugtutôq 2. (6) 04R012 Nûgârmiut 1. (7) 04R144 Nûgârmiut 2. (8) 04R144 Nûgârmiut 4. (9) 02R036 Nûgârmiut 2. (10) 04R036 Nûgârmiut 2.
nd—not detected.

Nûgârmiut 2 Transition Zone, olivines of $Fo_{99–95}$ occur, whereas in the upper ferrian-pyroxenites of Nûgârmiut 3 and 4, olivines attain almost pure forsterite compositions ($Fo_{99–98}$). The calcium contents of the olivines increase from < 0.2% CaO at ~ Fo_{82} to ~ 0.96% CaO in olivines of Fo_{99} from Nûgârmiut 3. Thus, contrary to the normal course of magmatic crystallisation in which olivine becomes increasingly fayalitic, exceptional circumstances of rising oxidation state led to a reversal of this situation in the Nûgârmiut rocks. Whereas the nearly pure forsterites may have crystallised from residual magmas, the granoblastic textures suggest some sub-solidus recrystallisation.

4.2. Pyroxene

Clinopyroxene is ubiquitous and up to 90% modally. In the less oxidised rocks that constitute the bulk of the

Table 1d
Selected analyses of accessory phases

Mineral (%)	Chlorite	Vesuvianite	Epidote	Monticellite	Wollastonite	Cuspidine	Perovskite		Apatite	Celestite
	1	2	3	4	5	6	7	8	9	10
SiO_2	33.16	36.42	38.09	38.85	51.45	32.41	0.04	0.08	–	–
TiO_2	0.04	2.29	0.03	0.25	–	0.02	57.90	58.14	–	–
Al_2O_3	12.66	12.79	23.81	0.06	0.03	0.06	–	–	–	–
Cr_2O_3	–	0.03	–	–	–	0.02	–	–	–	–
FeO	1.99	4.21	11.19	0.45	0.06	0.08	0.55	0.73	0.05	–
MnO	0.02	0.03	–	0.03	0.12	0.02	–	–	0.03	–
MgO	36.03	4.03	0.04	24.33	0.03	0.03	–	–	0.03	–
CaO	0.07	35.46	23.02	36.06	48.24	60.66	39.18	40.13	53.82	–
Na_2O	0.04	0.03	–	0.03	0.03	0.04	–	–	–	–
K_2O	0.06	–	–	–	–	–	–	–	–	–
BaO	–	–	–	–	–	–	–	–	–	19.31
SrO	–	–	–	–	–	–	0.58	0.54	1.42	39.24
ZrO_2	–	–	–	–	–	–	0.11	0.09	–	–
P_2O_5	–	–	–	–	–	–	–	–	41.01	–
Nb_2O_5	–	–	–	–	–	–	0.38	0.31	–	–
La_2O_3	–	–	–	–	–	–	0.26	0.16	–	–
Ce_2O_3	–	–	–	–	–	–	0.67	0.46	–	–
Nd_2O_3	–	–	–	–	–	–	0.29	0.14	–	–
SO_3	–	–	–	–	–	–	–	–	–	42.45
F	–	–	–	–	–	12.79	–	–	3.67	–
Total	84.07	95.29	96.18	100.06	99.96	93.34	99.96	100.78	96.36	101.34

(1) 01R052 Central zone, micaceous ferrian pyroxenite, Nûgârmiut 2. (2) 02R097 Leucocratic horizon, Nûgârmiut 3. (3) 01R5920 Pegmatitic segregation in layered sequence, Nûgârmiut 3. (4, 5) 02R099 Leucocratic layer, Nûgârmiut 3. (6) 01R072 Leucocratic ferrian pyroxenite, Nûgârmiut 2. (7) 02R047 Ferrian pyroxenite, Nûgârmiut 2. (8) 02R089 Ferrian pyroxenite, Nûgârmiut 3. (9) 01R5920 Pegmatitic segregation in layered sequence, Nûgârmiut 3. (10) 04R099 Leucocratic layer, Nûgârmiut 3.

outcrops, the Ti content of the diopsidic pyroxenes is low, (<0.12 atoms per formula units (a.p.f.u.)) despite the high whole-rock TiO_2 content and is a consequence of Ti partitioning into the oxide phases. Mg contents are high (~0.88 Mg a.p.f.u.), Na contents are low (<0.04 a.p.f.u) and, with no octahedrally coordinated Al, the jadeite component is negligible. In Nûgârmiut 2, the oxidation ratio $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ increases from the Outer Zone through the Transition Zone to the Central Zone. The most oxidised pyroxenes are those associated with garnet and perovskite. Zoning, where detectable, is towards Fe^{3+}-, Al- and Ti-rich rims.

The remarkable late-magmatic ferrian-diopsides are bright yellow (and pleochroic) in thin section, the intensity of the colouration reflecting their Fe^{3+} content (Upton and Thomas, 1973; Craven, 1985). Their compositions can be represented in terms of $CaMgSi_2O_6$, $CaFe^{2+}Si_2O_6$, $CaTiAl_2O_6$, $CaFe^{3+}AlSiO_6$ and $CaFe^{3+}{}_2SiO_6$ components. It is the low contents of acmite and jadeite, rather than the high Fe^{3+} (up to 0.34 a.p.f.u) that make the pyroxenes exceptional. The pyroxenes are also unusual in comparison with other described ferrian-diopsides (e.g. Carmichael and Nicholls, 1967; Johnston and Stout, 1984) in their low Al and high Mg and Ca contents. There is a continuum from $CaFe^{3+}{}_2SiO_6$-poor to the $CaFe^{3+}{}_2SiO_6$-rich varieties that crystallised under highly oxidising conditions, close to the Hm-Mt buffer in a Na-, Al-poor environment.

4.3. Mica

Titanian phlogopite is also ubiquitous in the mela-aillikites, composing 5–60% modally. It was a late-crystallising phase, usually occurring as oikocrysts or around the oxide crystals; only in the pegmatitic facies are euhedral terminations developed. In the rare cases where zoning can be discerned, the margins are deeper brown than the cores. The micas have *mg* numbers of 0.65–0.95 and with >2 Al a.p.f.u. but <8(Si+Al) a.p.f.u. The Al_2O_3 contents are typically 13–15 wt.%. The micas differ from most other igneous biotites in their lack of eastonite ($K_2Mg_5AlSi_5Al_3O_{22}$) or siderophyllite ($K_2Fe_5AlSi_5Al_3O_{22}$) components. The TiO_2 contents vary between 3 and 12 wt.% and BaO ranges from 0 to 13 wt.%. These values are comparable to those of biotites from other ultramafic lamprophyres (Rock, 1986) although the higher TiO_2 distinguishes them from kimberlitic biotites. The Ti content is strongly influenced by the overall mineral assemblage, with Ti preferentially entering the oxide phases. The highest Ba values are found in the micas in the veins of Tugtutôq 2 and are among the most Mg–Ba-rich micas reported.

4.4. Fe–Ti oxides

These are all are typically Mg-rich but poor in Mn, Al, and Cr. Four oxide assemblages were noted:

1) Magnetite+ilmenite: Magnetite showing exsolution and oxidation exsolution commonly encloses subhedral to euhedral ilmenite.
2) Magnetite+perovskite: This is typical for the Transition Zone in Nûgârmiut 2 and the Nûgârmiut 3 and 4 ferrian-pyroxenites. Ilmenite is rare.
3) Haematite+garnet:
4) Magnetite+ilmenite+pseudobrookite: This occurs in Tugtutôq 1, the Transition Zone of Nûgârmiut 2 and the upper facies of Nûgârmiut 4. It is a complex association involving euhedral magnetite, Mg-ilmenite with exsolved haematite, Ti-haematite with exsolved ilmenite and pseudobrookite. The pseudobrookite commonly mantles the ilmenite but can occur as discrete crystals.

Magnetites in the mela-aillikites are typically Cr_2O_3-poor; magnetites with up to 1.72 wt.% Cr_2O_3 occur in Nûgârmiut 4 but otherwise magnetite values are generally <0.4 wt.%.

The compositional range of the ilmenites is very large and includes extremely geikielite-rich varieties with up to ~25% wt.% MgO. The very magnesian ilmenites are those from the most highly oxidised rocks and reflect the same phenomenon as shown by the olivines, namely that in these facies, Fe^{2+} concentrations fell to unusually low values resulting in abnormally high Mg values.

4.5. Garnets

Andradite–schorlomites and hydro-garnets are largely confined to pegmatitic patches, leucocratic layers and veins in the ferrian-pyroxenites. They range from nearly pure andradite to schorlomite with up to 20 wt.% TiO_2. Most grew around opaque oxides and are themselves commonly rimmed by haematite or perovskite granules. The crystals are generally anhedral and, occasionally, birefringent. The Nûgârmiut garnets tend to have high TiO_2 and MgO and low Al and Fe^{3+}. Their compositions imply that some of the Ti occupies tetrahedral sites. Crystallisation under high f_{O_2} is suggested by their faint colour and the requirement for all the Fe to be Fe^{3+} to attain stoichiometry.

4.6. Accessory minerals

Accessory silicates include chlorite, kaersutite, cuspidine ($Ca_4Si_2O_7F_2$), monticellite, vesuvianite, wollastonite, sphene, epidote, albite, various zeolites and serpentine. Accessory non-silicates include rutile, perovskite, apatite, calcite, celestite and sulphides (pyrrhotite, chalcopyrite, pentlandite and covellite). Perovskite occurs as isolated euhedra within silicate crystals or as reaction zones around the Fe-oxides. It is commonly surrounded by garnet although in some of the pegmatitic facies sphene surrounds the perovskite indicating a late-stage increase in a_{SiO_2}. Some of the perovskites have deeper-coloured cores and pale rims. Significant Ce enrichment in some may be explained by the presence of Ce^{4+} in the more oxidised rocks.

Plagioclase occurs close to the contact zones of Nûgârmiut 1 and 2, as an interstitial component in the lower parts of Nûgârmiut 3 and 4 and also in pegmatitic facies of Nûgârmiut 3. Its presence is taken to signify an increase in a_{SiO_2} in the contact zones and in Nûgârmiut the late stages of crystallisation. Compositions vary from An_{64-61} in the contact zones to almost pure albite in the Nûgârmiut 3 pegmatites.

Kaersutitic amphibole is a very minor component in comparison with pyroxene and phlogopite. The kaersutite in Tugtutôq 2 is remarkable for its high Sr content (up to 0.86 wt.% SrO; Tables 1a–d). Fluor-apatite (with up to 1 wt.% SrO) is ubiquitous, locally constituting up to 10% modally. Chlorite (almost pure clinochlore) occurs in association with the Ti-rich garnets. Each of the leucocratic layers of Nûgârmiut 3 has a unique mineral assemblage but all have oxide-rich segregations (±pyroxene, mica and olivine) surrounded by oxide-free areas. Around the margins of the segregations are reaction fringes involving perovskite and garnet grown at the expense of the oxides, pyroxenes and micas while the olivines react to yield monticellite rims. The intervening (microcrystalline) oxide-free areas comprise diopside, monticellite, vesuvianite, andradite, apatite, chlorites and serpentine. Epidote is mainly confined to the pegmatitic segregations where its presence is consistent with the other evidence for high f_{O_2} in the final stages of crystallisation. Wollastonite occurs in some of the Nûgârmiut 3 veins. Cuspidine, which may be considered as a proxy for 'fluorine-bearing larnite', is locally abundant, e.g. in some of the late-stage Nûgârmiut veins. Vesuvianite occurs with andradite and monticellite in the leucocratic facies of Nûgârmiut 3 and 4. Calcite, with up to 1.3 wt.% SrO, is locally abundant whereas relatively Ba-rich celestine occurs in thin veins in Nûgârmiut 3.

5. Mineralogy and petrography of the other aillikitic occurrences in the Tugtutôq-Ilímaussaq-Igaliko-nunatak Zone

The aillikitic dykes in the TIN Zone contained up to 50% of olivine phenocrysts or 'macrocrysts', although these were invariably pseudomorphed by calcite, chlorite or other phases (Martin, 1985). Olivine, clinopyroxene, magnetite and biotite that constituted the higher temperature assemblages have characteristically undergone deuteric recrystallisation resulting in assemblages dominated by calcite, chlorite, tremolite and opaque oxides. The mineralogy of the ultramafic lamprophyre dykes is generally in harmony with that seen in the Tugtutôq and Nûgârmiut mela-aillikites, e.g. involving notably Ti, Al and Fe^{3+}-fassaitic pyroxenes, Ti–Ba-rich phlogopites and magnesian ilmenites (cf. Pearce, 1988). As at Nûgârmiut, calcite in the dykes is moderately Sr-rich with up to 2 wt.% SrO.

Cr-rich cores to spinels in the aillikitic dykes and sills may be relic xenocrysts from disaggregated mantle xenoliths and the small clasts responsible for much of the nodular weathering of the dykes may be highly recrystallised peridotite xenoliths. Altered mantle xenoliths have been described from a minor UML intrusion south of Tugtutôq (Upton, 1991).

6. Geochemistry of the Tugtutôq-Nûgârmiut mela-aillikites and associated aillikitic–carbonatitic rocks

Forty-seven samples of the Tugtutôq-Nûgârmiut mela-aillikites were analysed by XRF at Edinburgh University. Fe^{2+} determinations were made by wet chemical analysis using the method of Wilson (1955). Representative analyses are presented in Table 2a with analyses of some other aillikitic intrusive and extrusive rocks, from further east in the TIN Zone, in Table 2b.

Despite the small-scale heterogeneity, the mela-aillikites present a broadly uniform group, poor in SiO_2 (37–32 wt.%) and Al_2O_3 (~5 wt.%), but rich in TiO_2 (~5 wt.%), MgO (~18 wt.%), CaO (~12 wt.%) and Fe_2O_3* (~20 wt.%). Although aillikites are defined as carbonate-bearing melilite-free UML, the very low carbonate content of the mela-aillikites is ascribed to late-stage decarbonation and loss of CO_2. The mean compositions of the Tugtutôq and Nûgârmiut suites, which are very similar (Tables 2a and 2b), are inferred to reflect the bulk compositions of the crystalline residue after loss of a high proportion of their original volatile constituents. The most primitive rocks are the olivine pyroxenites of Nûgârmiut 4 in which MgO values rise to

Table 2a
Representative analyses and mean analyses of mela-aillikites of Tugtutôq and Nûgârmiut

wt.%	1	2	3	4	5	6	7	8	9
SiO_2	36.61	35.74	27.13	35.61	34.93	33.78	35.16	34.08	36.16
TiO_2	3.40	2.68	5.86	5.90	6.34	6.99	5.54	5.58	5.10
Al_2O_3	5.48	5.07	5.53	5.46	5.30	5.22	4.92	5.37	6.29
Fe_2O_3	6.51	14.04	17.03	9.67	11.07	11.59	20.17	12.35	8.85
FeO	9.93	na	1.22	9.80	7.66	9.54	na	7.14	9.99
MnO	0.21	0.28	0.27	0.23	0.21	0.27	0.29	0.24	0.21
MgO	24.56	20.03	17.91	17.75	16.42	15.98	10.91	18.19	16.44
CaO	7.41	22.02	18.02	10.85	15.30	13.26	20.31	12.39	11.03
Na_2O	0.66	0.15	0.06	1.01	0.40	0.47	0.64	0.45	0.91
K_2O	1.33	0.00	1.63	0.83	0.22	0.51	0.07	1.07	0.89
P_2O_5	0.46	0.23	0.66	0.41	0.62	0.54	0.04	0.62	0.41
Total	96.56	100.24	95.32	97.52	98.47	98.15	98.05	97.48	97.27
ppm									
Ni	1050	799	315	726	429	436	324	579	642
Cr	1069	901	324	492	439	438	116	580	455
V	320	157	310	338	291	436	212	337	437
Sc	24	8	7	20	16	21	12	18	20
Cu	76	20	90	213	55	103	54	96	175
Zn	117	81	101	121	88	130	114	116	115
Sr	590	139	885	1259	638	940	795	654	1855
Ba	628	35	5403	846	1253	553	46	1376	993
Rb	57	2	108	57	11	37	7	75	58
Zr	225	216	298	257	296	361	415	301	237
Nb	53	52	87	61	49	92	62	75	63
Y	23	25	22	21	19	25	25	23	22
La	35.0	64.7	54.4	39.5	40.4	44.4	46.7		
Ce	76.5	131.3	100.4	81.6	83.4	101.1	116.6		
Pr	9.7	15.0	12.5	9.9	9.9	13.4	14.9		
Nd	49.0	68.6	58.0	47.5	48.7	64.7	65.1		
Sm	10.6	13.1	11.3	10.2	10.4	13.6	13.7		
Eu	3.1	3.6	4.0	3.1	3.0	4.1	3.9		
Gd	8.0	9.2	8.3	7.6	8.0	9.5	9.5		
Dy	5.3	4.7	5.0	4.8	5.1	5.8	5.7		
Ho	1.0	0.9	0.9	0.9	1.0	1.1	1.0		
Er	2.2	1.9	2.0	2.0	2.1	2.2	2.1		
Yb	1.4	1.0	1.1	1.2	1.3	1.2	1.1		
Lu	0.1	0.1	0.1	0.1	0.2	0.1	0.1		

Major and trace element analyses by XRF, except FeO which was determined by wet chemistry.
REE by ICP MS. na—not analysed, total iron presented as Fe_2O_3.
(1) Olivine pyroxenite, Nûgârmuit 4 (278154). (2) Whole vein, Nûgârmuit 4 (278136). (3) Leucocratic layer, Nûgârmuit 3 (278097). (4) Amphibole olivine pyroxenite, Tugtutôq 2 (278173). (5) Olivine pyroxenite. Nûgârmuit 1 (278006). (6) Ferrian pyroxenite, Nûgârmuit 2 (278072). (7) Ferrian pyroxenite, Nûgârmuit 2 (278041). (8) Mean composition Nûgârmuit (40 analyses). (9) Mean composition Tugtutôq (7 analyses).

27.90 wt.%, with Ni and Cr reaching concentrations of 1260 ppm and 1212 ppm, respectively. Aillikites, like kimberlites, combine high concentrations of both compatible and incompatible trace elements including Rb, Ba, Sr, Nb, Zn and LREE. These characteristics are shared by the mela-aillikites. Rb (up to 281 ppm) and Ba (up to 5400 ppm) are primarily housed in the phlogopites, while Sr (up to 2456 ppm) is partly retained in apatite, kaersutite, calcite and celestite. Mean values for Zr/Nb and La/Lu ratios are ~4.0 and 20.8, respectively. The rocks are also distinctly rich in V (300–500 ppm) and there is a close positive correlation between V and Ti. Zn (mean value 116 ppm) shows some positive correlation with Ti, suggesting it is housed mainly in the FeTi oxides. Cu contents are typically >100 ppm, rising to 275 ppm in Nûgârmiut 3.

Progression from the Outer to the Inner Zone in Nûgârmiut 2 is marked by an increase in K, P, Ca and Fe. There is also increase in Zn (150 to 450 ppm), Sr (350 to 950 ppm), Nb (28 to 85 ppm), La (10 to 65 ppm) and Y (16 to 27 ppm). The zonation and intrusion brecciation in this locality may denote

Table 2b
Comparative compositions of other aillikites and carbo-silicate rocks from the TIN Zone

wt.%	1	2	3	4	5	6	7	8	9	10
SiO_2	42.72	36.18	33.17	32.19	35.12	31.59	25.98	28.22	29.87	22.01
TiO_2	3.38	5.47	7.51	5.10	4.25	4.79	3.84	1.69	1.97	2.40
Al_2O_3	9.43	9.07	9.08	5.47	6.75	5.01	4.59	2.41	2.58	3.61
Fe_2O_3*	15.73	20.57	18.44	20.18	17.80	18.37	17.41	15.48	14.29	17.36
MnO	0.10	0.23	0.38	0.25	0.20	0.42	0.41	0.46	0.53	0.61
MgO	15.94	15.89	14.37	13.78	13.72	13.32	13.09	12.18	8.67	8.19
CaO	6.12	5.55	9.05	11.21	11.13	13.62	12.61	21.52	17.22	20.70
Na_2O	0.68	0.37	0.04	0.10	0.09	0.10	0.12	0.27	0.01	0.05
K_2O	2.91	3.14	1.86	2.33	0.18	2.22	1.97	1.97	0.34	1.22
P_2O_5	0.41	0.67	0.98	0.76	0.67	1.22	0.64	2.93	1.09	1.06
LOI	na	na	na	7.89	10.27	7.81	17.78	11.74	na	na
Total	97.42	97.14	94.89	99.26	100.2	98.47	98.44	98.85	76.57	77.21
ppm										
Ni	503	717	618	286	502	322	492	247	157	108
Cr	732	712	379	206	400	303	261	231	158	94
V	340	285	612	286	318	358	229	133	179	207
Sc	22	30	27	34	20	23	16	10	8	21
Cu	12	199	153	118	70	91	66	38	119	79
Zn	125	175	207	212	161	153	956	356	152	300
Sr	523	639	500	1825	670	1651	3401	4141	2121	2551
Ba	885	1626	429	1581	255	1990	3199	785	395	1084
Rb	105	160	161	110	16	110	53	142	14	37
Pb	2	n.d.	14	1	0	3	0	16	25	33
Th	6	n.d.	8	15	0	5	9	87	19	36
Zr	219	329	617	701	402	509	443	309	163	291
Nb	70	81	119	155	70	138	109	237	309	321
Y	20	29	27	50	24	30	30	72	65	82
La	51	56	55	234	50	92	150	432	326	384
Ce	65	118	125	476	114	186	335	861	648	791
Nd	33	na	na	n.d.	56	n.d.	n.d.	n.d.	261	346

All analyses by XRF. Fe_2O_3* = total Fe as Fe_2O_3. n.d.—not detected. na—not analysed.
(1) UML sill in Eriksfjord Formation, Nunasarnaussaq (101221). (2) ENE-trending UML ('monchiquite') dyke, coast north of Narsarsuaq (101258). (3) ENE-trending UML east coast Tugtutôq (86047). (4) ENE-trending UML ('monchiquite') dyke, coast north of Narsarsuaq (101246). (5) UML lava Nunasarnaq (101235). (6) ENE-trending UML ('monchiquite') dyke, coast north of Narsarsuaq (101252). (7) UML sheet in granite north of Narsarsuaq (101244). (8) ENE-trending UML ('monchiquite') dyke, coast north of Narsarsuaq (101256). (9) Inclined sheet of UML in granite-gneiss, Qassiarsuk (216639). (10) Irregular UML intrusion cutting diatreme, Qassiarsuk (216638).

recharge of a magma body by a more differentiated magma that had undergone more olivine, pyroxene and oxide fractionation.

The monticellite-bearing leuco-layers in Nûgârmiut 3 differ compositionally from the surrounding olivine pyroxenite in having higher $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ (increasing from 0.8 to 0.93), higher loss on ignition, CaO, MgO and Al_2O_3. Wide scatter in K, Rb, Ba and Sr values is attributed to their mobility and hence differential transport in migrating fluids. One analysed 'whole-vein' sample (278136; Table 2a) shows high CaO (~22 wt.%) and Fe almost entirely in the ferric state and notably low K, Rb. Ba and, Sr. It is regarded as the product of a mobile silico-carbonatitic melt or supercritical carbothermal fluid from which the more mobile elements were leached out.

Analogous geochemical features are seen in the other aillikitic rocks of the TIN zone (Upton and Fitton, 1985; Pearce and Leng, 1996). Ba concentrations > 1000 ppm are common, with values rising to tens of thousands ppm in some of the Qassiarsuk rocks. Sr contents commonly exceed 2000 ppm, rising towards 15,000 in Qassiarsuk lapilli tuffs. Steep LREE-enriched chondrite-normalised REE profiles are characteristic (Fig. 7). The highest LREE contents observed are those of aillikitic rocks from the nunatak region and from Qassiarsuk with La-Ce_N contents approaching 1000 × chondrite.

The normalised plots for the Tugtutôq-Nûgârmiut mela-aillikites fall within a very restricted range (shaded area, Fig. 7), essentially identical to those of other aillikitic rocks in the proximity of Ilímaussaq (namely a dyke-rock eastern Tugtutôq, ARM211, a lava from

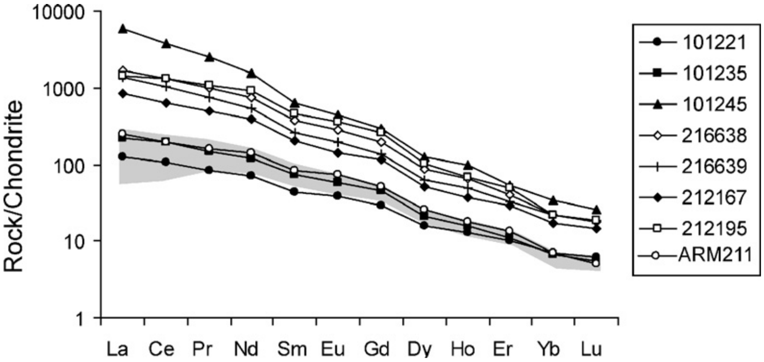

Fig. 7. Chondrite-normalised REE plots for Tugtutôq-Nûgârmiut mela-aillikites (shaded area). Also, for comparison, plots for eight other aillikitic samples from the TIN Zone. See text for detail. Normalising factors from Nakamura (1974).

Nunarsarnaq, close the NE margin of Ilímaussaq, 101235, and an intrusion at Nunasarnaussaq, adjacent to the SW margin of Ilímaussaq, 101221). For comparison, data for five other samples from localities 30 to 60 km further north-east are plotted. (A dyke near Narsarssuaq, 216638, two dykes from the G.F. Holm nunatak, 212195 and 212167, and two aillikitic intrusive sheets in the Qassiarsuk area, 216639 and 101245). These five samples show higher normalised REE contents than those of the Tugtutôq-Nûgârmiut area but, with the exception of the (more carbonate-rich) sample 101245, they have similar La/Lu ratios. It is, however, in the associated TIN Zone carbonatites that the highest contents of LREE, Ba and Sr are attained (Martin, 1985; Larsen and Rex, 1992; Pearce and Leng, 1996). The relatively high Zn content of the mela-aillikites has been noted and appears characteristic of the TIN Zone aillikites in general with the highest value (695 ppm), recorded for one dyke (Upton and Fitton, 1985).

7. Discussion

Rock (1986) subdivided ultramafic lamprophyres into aillikites and alnöites, the latter being melilite-bearing. Since no melilite has been described from the Gardar Province, doubt has been cast on the identification of carbonate pseudomorphs in some Qassiarsuk rocks as being after melilite (Stewart, 1970). Melilite crystallisation is favoured by (Si+Al)-poor alkaline melts and it may be that the Na/(Si+Al) ratio in the Gardar magmas was too low to permit its crystallisation (Velde and Yoder, 1976; Lloyd, 1985). Accordingly, it appears doubtful whether any of the Gardar rocks are true alnöites according to Rock's definition.

The Tugtutôq and Nûgârmiut mela-aillikites contain several minerals which, in species or composition, are rare or unique. Olivines grown from the highly oxidised late-stage melts approached pure forsterite in composition as a result of the diminishing availability of Fe^{2+} ions. The high magnesium content of ilmenites in the more oxidised facies was also a consequence of this process. The pyroxenes, micas and garnets combine low Si and Al with relatively high Ti contents and their tetrahedral sites are consequently inferred to host Fe^{3+}, and possibly Ti^{3+} as well as Al^{3+} and Si^{4+}. The high Ba content of the micas and high Sr content of the amphiboles have been noted. The occurrence of perovskite, wollastonite, vesuvianite, monticellite and cuspidine, an assemblage more characteristic of skarns, reflects the calcium-rich, silica-deficient environment in which they were precipitated. The occurrence of cuspidine in an igneous assemblage may be unique.

The Gardar aillikites are generally ultrapotassic ($K_2O/Na_2O>3$) but differ from kamafugites (Sahama, 1974) in not being perpotassic and in generally falling to the CaO-poor side of the kamafugite field. The transition from the typical olivine pyroxenite to ferrian-pyroxenite facies in the Nûgârmiut rocks implies evolution towards increasingly oxidised, Si-poor and Ca-rich compositions. Such a reduction in SiO_2 and enrichment in CaO is characteristic of both kamafugitic and kimberlite evolution (Larsen and Rex, 1992), and has also been also observed in the experimental system $KAlSiO_4–Mg_2SiO_4–SiO_2–F$ (Veksler et al., 1998).

In discussion of kamafugites, Stoppa et al. (2003) noted that melts that pass through the 'carbonate out' boundary (Olasson and Eggler, 1983) will experience massive CO_2 exsolution. Such loss of CO_2 will result in a more CaO-rich silicate fraction. We suggest that the complexly zoned calcic veins in the mela-aillikites testify to progressive carbonate breakdown of an escaping silico-carbonatitic residuum and concomitant high energy release of CO_2. Rapid expansion of the latter is held to have been responsible for the gas-drilled diatremes and the brecciation at some of the mela-aillikite contacts.

The Tugtutôq and Nûgârmiut suite crystallised under a range of oxidation conditions from those close to the QFM buffer to just below the HM buffer. The ferrian pyroxenite facies of the mela-aillikites are poor in hydrous minerals and it is suggested that the water component of the fugitive melts dissociated into H and O. On this hypothesis, the more mobile hydrogen ions may have been preferentially lost by diffusion, so that the enhanced oxidation was due to the presence of free oxygen. The principal assemblages appear stable at high-temperatures (>600 °C) whereas the occurrence of serpentine, vesuvianite, epidote, chlorite, hydro-garnet, etc., indicates crystallisation persisting to below 400 °C. The ferrian-pyroxenites are clearly younger and, we suggest, lower temperature, products than the olivine pyroxenites. The well-developed layering in the roof zones of Nûgârmiut 3 and 4 may denote lowering viscosities. While the mechanism by which the layering developed is unknown, crystal settling in a convecting magma appears extremely improbable in this context. Whether the ferrian pyroxenites crystallised directly from magma or are products of subsolidus recrystallisation remains problematic although their well-equilibrated textures are consistent with the latter process.

The veins that characterize the mela-aillikites may represent former conduits through which copious quantities of CO_2 escaped. The very fine-grained nature of the bulk of the mela-aillikites is attributed to rapid raising of relevant solidus–liquidus surfaces during volatile loss, initially resulting in fast crystallisation. The general absence of the expected igneous quench textures may denote recrystallisation in the presence of such volatiles as still remained.

The fugitive fluid phase is inferred to have been capable of leaching and transporting K, Rb, Ba and Sr from the crystallising melts. The mela-aillikites could therefore be regarded as cumulates whose crystallisation involved compaction and expulsion of low density, highly mobile residual fluids (cf. Hunter, 1996). In view of the close association of diatremes with mela-aillikite at Nûgârmiut 6 and Tugtutôq 2, it may be speculated that the area represents a sub-volcanic association. The carbonatitic lavas and tuffs at Qassiarsuk may provide an analogue for the hypothesized surface products that developed many tens of million years later in the Tugtutôq and Nûgârmiut areas.

Cuspidine (csp) crystallised at low pressure at, or just below, the solidus in the $KAlSiO_4$–Mg_2SiO_4–$CaSiO_4$–SiO_2–F system investigated by Veksler et al. (1998). According to these authors the melt in equilibrium with ol + phlog + di + csp at 1050 °C contained ~22 wt.% CaO and 7.4 wt.% F. While the experimental system was CO_2-free, it may give some indication of the composition of the residual melts from which the Nûgârmiut cuspidine crystallised. The presence of cuspidine, together with fluorapatite in the ferrian-pyroxenites, is taken as confirmation of crystallisation from a highly calcic and fluoride-rich melt. It is noteworthy that fluorite occurs in the associated diatremes and in the Qassiarsuk tuffs. Pearce and Leng (1996) recorded up to 13.7 modal % fluorite in carbonatitic dykes of the Igaliko region.

Sulphur is also inferred to have been a significant component, yielding sulphides in the more primitive olivine pyroxenite facies but sulphate (Ba-rich celestite) in some of the more oxidised ferrian pyroxenites. It is of interest that barite is a common constituent in the Qassiarsuk lapilli tuffs and in the groundmass of some small aillikitic dykes.

Sr and Nd isotopic data for the UML and carbonatite suite in the TIN Zone show broad overlap of values close to those for Bulk Earth (Coulson et al., 2003). Some initial data for the mela-aillikites (A.N. Halliday, personal communication) also fall within the same area. εNd values lie from −1 to +5 (mostly between 0 and +3) while $^{87}Sr/^{86}Sr_i$ values are 0.7025 to 0.705 (with the majority <0.704). All are distinctly less radiogenic than Group 2 kimberlites (orangeites) and Australian kimberlites but correspond to the field defined by Group 1 kimberlites and close to the field for OIB.

7.1. Kimberlitic affinities and distinctions

The Gardar aillikites, like both Group 1 and Group 2 kimberlites (orangeites) (Mitchell, 1995), are typically carbonated ultramafic rocks occurring in 'hypabyssal mode' (dykes, sills, inclined sheets and plugs) and in 'diatreme mode', as blocks in diatremes and as lapilli tuffs, tuff breccias and, very rarely, as lava flows. Although the average compositions of kimberlites and UML show many similarities (Rock, 1997), aillikites differ from kimberlites in being poorer in Si, Mg and Cr, richer in Al, Ca, Na, P and CO_2 and, most especially in Fe, with somewhat shallower REE profiles (Rock, 1986; Francis, 2003). Aillikites are always richer in Fe than kimberlites at any given Mg content and a limit of ~11 wt.% FeO* (total Fe) separates most aillikites from kimberlites (Francis, 2003). The Fe-rich character of the Gardar rocks under discussion is brought out on an Al_2O_3–FeO–MgO discrimination diagram (Fig. 8) which shows aillikites to be less magnesian than

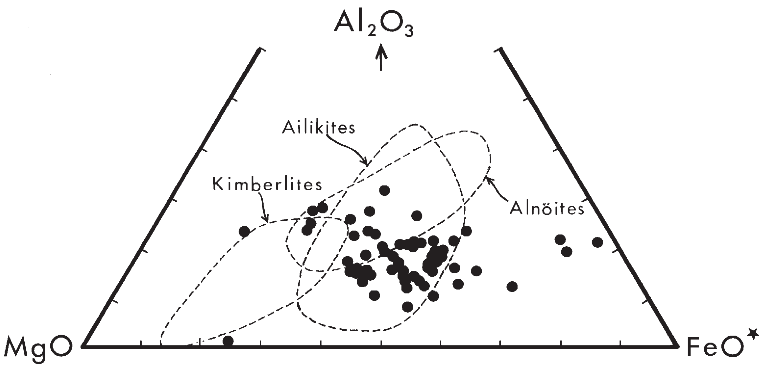

Fig. 8. Distribution of TIN-Zone aillikitic samples Al_2O_3–FeO_t–MgO diagram. Fields after Rock (1986).

kimberlites, with higher Fe, Ti, Al and Ca and lying to the Fe-rich side of the kimberlite field. While generally less aluminous than alnöites, the data points scatter across Rock's (1997) aillikite field, with many having still more Fe-rich values. That kimberlites have higher MgO/CaO ratios than most UML was attributed by Brey (1978) to the former having been derived from melting in the magnesite stability field (>30 kb), whereas UML arise from shallower levels within the dolomite stability field.

One difference in mineral chemistry separating the mela-aillikites under discussion from west Greenland kimberlites relates to their ilmenite compositions (personal communication, F.E. Hough). Those of the mela-aillikites are poor in Cr_2O_3 (<0.50 wt.%; mean value 0.03 wt.%) whereas the mean for the kimberlites is >2. wt.%. Conversely, the mean MnO content of the mela-aillikite ilmenites (~1.52 wt.%) is higher by a factor of ~10 than that for the kimberlites.

7.2. Petrogenesis

Judging from the occurrence of olivine megacrysts the parental magmas are inferred to have had olivine on the liquidus. Whole-rock compositions further suggest that the magmas possessed high contents of Mg, Ni and Cr. The occasional presence of mantle xenocrysts and xenoliths (cf. Upton, 1991) implies rapid ascent and the magmas were little affected by crustal contamination. They were thus relatively 'primitive' and the high Fe, Ti and V contents of the magmas point to derivation from source rocks enriched in these elements.

Although the genesis of both aillikites and Group 1 kimberlites must involve melting of carbonate-bearing systems, aillikites require sources significantly more Fe-rich than those for Group 1 kimberlites. Foley et al. (1999) envisaged inhomogeneous sources comprising peridotite impregnated by a system of ultramafic vein assemblages when considering aillikite genesis.

Metasomite facies rich in clinopyroxene and phlogopite would melt at lower temperatures than the surrounding (harzburgitic?) peridotites, a situation that would be enhanced in carbonate and F-enriched assemblages (Lloyd et al., 1985; Foley et al., 1999). McKenzie (1989) noted that metasomatic melts in the mantle solidify where the steady state geotherm is at their solidus and that the resulting metasomites could readily be remelted. The resultant melts would be rapidly modified by reaction with the peridotite wall rocks during ascent through the lithospheric mantle. The latter, at the depths assumed, would have been garnet-facies peridotites and the low HREE characteristic of the aillikite–carbonatite suite could be accounted for by their retention in garnet.

Aillikites and Group 1 kimberlites fall to the Si-poor side of the olivine-phlogopite join that separates them from the Group 2 kimberlites (orangeites) on the Si-rich side (Francis, 2003). According to Francis, this join may be a thermal divide and fractionation of olivine (±phlogopite) on the Si-poor side would lead to an increasingly Si-deficient carbonate-rich residuum with decreasing Mg. There is probably a gradation from the low Fe melts of typical Group 1 kimberlites (FeO<11 wt.%) through transitional kimberlites to Fe-rich aillikites (FeO>12 wt.%) with little change in Mg (Francis, 2003). While there can be little doubt that olivine was a liquidus phase in the Gardar magmas under discussion, this was not so for phlogopite, in contrast to the Aillik Bay suite (Malpas et al., 1986).

While the precise relationship between aillikites and the calciocarbonatites and ferruginous calciocarbonatites of the TIN Zone remains debatable, both are inferred to come from a common source (Pearce and Leng, 1996; Coulson et al., 2003). Some carbonatites may have been generated by immiscibility from carbonate-rich phonolite magmas (cf. Halama et al., 2005) while others may have originated by immiscibility from the UML magmas as proposed by Pearce and Leng (1996) or by fractional crystallisation from the latter if no silicate–carbonate immiscibility boundary (Kjarsgaard and Hamilton, 1989) was encountered. Aillikite compositions are sufficiently removed from any of the mafic alkaline rocks (including melilitites and melanephelinites) used in Kjarsgaard and Hamilton's experimental studies for this possibility to be entertained. Data presented by Upton and Fitton (1985) and Pearce and Leng (1996) indicate that any miscibility gap, if present, must be narrow. Consequently, while evolution of the mela-aillikites possibly involved exsolution of a conjugate carbonate melt we see no compelling argument that it did. Aillikites from the type locality (Aillik Bay, Labrador) were considered to have originated from the melting of carbonated peridotite at depths of 90–110 km. The associated carbonatites were thought to reflect the very smallest melt fractions (Malpas et al., 1986).

7.3. Recurrence of aillikite magmatism

Lamprophyre genesis occurred early in the Arsuk-Ivigtut zone, preceding the emplacement of dolerite dyke swarms. Comparable early development of UML in the TIN Zone is implied by the presence of UML xenolithic 'rafts' in the Motzfeldt nepheline syenites (personal communication, L.-M. Larsen). The Motzfeldt intrusion dates from ~1275 Ma (Upton et al., 2003). In the TIN Zone aillikite and carbonatite activity accompanied the onset of the Musartût basaltic eruptions in the Eriksfjord Formation while subsequently, the Ilímaussaq Member basaltic eruptions were heralded by aillikite eruption. In these instances, incipient heating or lithospheric extension may have promoted melting of readily fusible metasomites before melting of more refractory sources yielded the basaltic magmas. In this respect the Tugtutôq and the Nûgârmiut mela-aillikites are anomalous in that they followed, rather than preceded, the significant magma genesis event that yielded the Younger Giant Dyke gabbroic complex. Thus, in the Province as a whole, the UML-carbonatite association recurred intermittently throughout >100 Ma of Gardar magmatism, locally as a precursor to basalt magmatism.

8. Summary

Unusually large bodies of aillikitic magmas were emplaced at relatively shallow crustal depths in the Tugtutôq and Nûgârmiut areas. They underwent rapid crystallisation to predominantly fine-grained rocks consequent on the escape of low-density and highly mobile residues. However, crystallisation involved extensive mineral reactions, progressive textural modifications and formation of complexly zoned vein systems. The fugitive residuals are inferred to have been CO_3^{2+} and F^--rich silico-carbonatite melts characterised by high concentrations of Ca, Sr, Ba and LREE. It is the concentration of precisely these elements in the TIN Zone carbonatites that provides additional, if circumstantial, evidence for a cogenetic relationship between predominantly silicate aillikitic magmas and carbonatites. The extreme oxidation in the late-stage mela-aillikite facies may have been due to dissociation of water and loss of hydrogen.

We suggest that the parental aillikite magmas were derived from low-melting metasomite sources in the lithospheric mantle. It is speculated that such metasomites arose through the agency of fluor-carbonatite small-melt fractions from the asthenosphere as the lithosphere underwent transtensional stresses. We envisage repeated build-up of carbonated mica pyroxenite sources in which ilmenite was the likely chief repository of the abundant Fe and Ti. Such sources may have had the form of localised vein stockworks at depths less than 120 km but probably greater than 90 km, which readily underwent extensive melting either in response to heating by mantle plumes or to tectonically induced pressure reduction. Such sources may be regarded as shallow-level analogues of MARID-type assemblages (cf. van der Laan and Foley, 1994). The steep REE profiles are taken to indicate interaction of aillikite melts with garnet in the lithospheric mantle. The relatively non-radiogenic Sr-isotopic composition of the suite may indicate that the metasomites had a short residence history and that melting events took place relatively soon after their formation. Older UML-carbonatite associations in the province suggest that similar metasomite formation was repetitive over an interval >100 Ma.

Enrichment of the late Gardar basaltic magmas intruded as the giant dyke gabbros and younger dolerites in LILE, Nb, LREE and P relative to their predecessors (e.g. Eriksfjord Formation lavas) was attributed to a late Gardar metasomatic event (~1160 Ma), affecting the TIN Zone source regions (Upton and Emeleus, 1987). There may be a connection between this inferred source enrichment and the ascent of exceptionally large volumes of mela-aillikite parent magmas shortly after the intrusion of the giant dykes.

In discussion of the petrogenesis of ultramafic (Tertiary) lavas from NE Greenland, Bernstein et al. (2000) noted that they have much lower SiO_2 and Al_2O_3 and concomitantly higher TiO_2 and FeO than pene-contemporaneous basaltic lavas. These idiosyncrasies they attribute to low degree melting at very high pressures (>5 GPa) of hydrous, possibly CO_2-rich, and incompatible element-enriched mantle. Bernstein et al. note that, while the effect of addition of H_2O to dry peridotite at high pressure remains debatable, recent studies suggest that it causes reduction of SiO_2 and increase in MgO while lowering of the solidus. The resultant low degree hydrated melts may then have separated from their source and arisen through the lithosphere without mixing with mantle melts resulting from more advanced melting. Such a scenario may have application to the aillikitic magmas under discussion. However, some lithospheric control over the magma genesis is advocated on the grounds that several features of Gardar magmatism, including that of the aillikites, were repetitive over long periods of time. If all were due to asthenospheric processes it is necessary to postulate an improbable recurrence of circumstances (Upton et al., 2003).

The geographical coincidence of the aillikite–carbonatite association with the extraordinarily trace element-enriched peralkaline magmas of the TIN Zone, culminating in the Ilímaussaq agpaites, can scarcely be coincidental. Genesis of the latter is likely to have involved processes including infiltration of small-fraction asthenospheric melts into the deeper lithosphere and fractional crystallisation (particularly within the crust). Despite the extreme contrast between mela-aillikites on the one hand, and agpaitic syenites on the other, both may exemplify differing stages in the magmatic evolution. Whereas the Ilímaussaq agpaites represent the ultimate stage, the aillikites are interpreted as remobilised (large-fraction melts) that provide a ‘window’ on the deep lithospheric processes (cf. Coulson et al., 2003). Pre-concentration of incompatible trace elements in lower lithosphere metasomites was probably the fundamental factor responsible for the alkaline character of the entire Gardar Province.

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