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TERTIARY PERALKALINE RHYOLITE DIKES FROM THE SKÆRGAARD AREA, KANGERDLUGSSUAQ, EAST GREENLAND

BY

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WITH 2 FIGURES AND 7 TABLES

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Abstract

Tertiary peralkaline acid rocks (comendites) are described from East Greenland. These are dike rocks, which may be aphyric, carry sparse phenocrysts of alkali feldspar, or more abundant quartz, alkali feldspar and katophorite phenocrysts. Regarded as being closely related, are a group of peralkaline granitic rocks associated with the nordmarkitic syenites of the area, which contain quartz, alkali feldspars, arfvedsonite, pyroxenes ranging from hedenbergitic to acmitic, and assessories including zircon, Mn-rich ilmenite, astrophyllite and chevkinite. Analyses are presented for most of these phases and the chemistry of the rocks and that of the crystallization process in the dike centres is discussed.

These rocks have an origin clearly distinct from that of the nearby Skaergaard granophyres, which show no peralkaline tendencies, and it is postulated that the comendites have arisen from magmas of nordmarkitic composition which, in turn, arose at depth from a transitional basalt. This suite of rocks seems to reflect closely the tectonic setting, occurring in many areas of crustal attenuation, a situation in accordance with that believed to be present here.

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INTRODUCTION

Peralkaline oversaturated rocks (comendites and pantellerites) are known from many parts of the world and, in general, appear to be associated with rift tectonics. In Africa, they have been shown to occur at topographic culminations of the rift floor, as in the Naivasha area of Kenya (SAGGERSON, 1970), while GASS (1970) has postulated that transitional basaltic magmas, which are often regarded as being the parents of such rock types (COOMBS, 1963; BASS, 1972; BEST & BRIMHALL, 1974), are generated in regions of attenuation of continental crust. Such appears to be the case in the Red Sea area (GASS, 1970), at the type locality of pantellerites in the Sicily Channel (DI PAOLA, 1973) and in other regions.

The origin of these rocks has been extensively discussed and at least three schemes of petrogenesis have been proposed. Some workers (e.g. BRYAN, 1970) favour direct derivation of peralkaline rhyolites from basaltic parents, which, as noted above are probably transitional between olivine tholeiite and alkali basalt. Others, including CARMICHAEL & MACKENZIE (1963), THOMPSON & MACKENZIE (1967), EWART *et al.* (1968) and NOBLE (1968), regard their immediate precursors to be trachytic liquids. Finally, a third group have favoured partial melting of crustal rocks (ROMANO, 1968; VILLARI, 1969; BROWN, 1972; BROWN & FYFE, 1972), which have possibly been modified by the addition of alkaline volatiles from the mantle (BAILEY, 1970). The work of BAILEY & MACDONALD (1970) suggests that oceanic comendites may owe their origin to the first two processes whereas continental ones might arise by the last.

In this paper, we report the discovery of comendites which belong to the North Atlantic Tertiary Province in the Kangerdlugssuaq region of East Greenland and present evidence for their origin in this particular case. In view of the close association of such rocks with a specific tectonic setting, their presence affords some evidence as to the nature of the tectonic regime here in the Lower Tertiary and supports the model put forward by BROOKS (1973a). According to this model, Kangerdlugssuaq occupies a non-spreading rift which forms one arm of a triple junction developed at the crest of a domed uplift. The two other arms of the triple junction became involved in active spreading and are associated with voluminous tholeiitic volcanism. The discovery of comenditic rocks in this area considerably strengthens the analogy with the southern part of the Red Sea and the Kenyan rift which has already been drawn (Brooks, 1973a).

FIELD RELATIONS

The Kangerdlugssuaq region is one of intense Tertiary plutonic and volcanic activity (Wager, 1947; Brooks, 1973a & b). Early plateau basalts, which reach over 7 km in thickness and cover an estimated area of 60,000 km^2 at the present time, were subsequently intruded by mafic plutons, of which the Skaergaard intrusion (Wager & Deer, 1939; Wager & Brown, 1968) is the best known example. The coastal area were later bent by a major flexure with an associated dike swarm (Wager & Deer, 1938) and magmatic activity was terminated with the intrusion of a number of syenitic plutons, of which both undersaturated and oversaturated are represented. Localities discussed in this paper may be found on the maps published by Wager & Deer (1939), Kempe *et al.* (1970), Abbott & Deer (1972), and Brooks (1973b).

The peralkaline rhyolites or comendites, which are the subject of this paper, are quantitatively insignificant compared to the major plutons or flood basalts of the area. They have been divided into the following groups:

1. Blueish to black aphyric dikes, often spherulitic.
2. Dikes with black flinty margins which carry sparse phenocrysts of alkali feldspar.
3. Dikes with blueish margins and light-coloured centres which carry phenocrysts of alkali feldspar, alkali amphibole and quartz.
4. Sheets, dikes and segration veins associated with quartz syenites (nordmarkites).

Only one example of the first type has been found *in situ* but blocks of this material are abundant on the Skærgård halvø and at Skåret (Kraemer Ø) in a raised beach. The *in situ* example is a striking blue colour and cuts gneisses on Uttental Plateau, just north of the Skaergaard Intrusion. It is a little over 1 m wide and strikes approximately parallel to the coastal dike swarm. Three examples of the second type have been studied and these come from a wide area. They occur in areas of central plutonic activity and often occur as thin, black, flinty veins, although the thicker examples have light-coloured centres. Several examples of the third type have been located in place on Uttental Plateau and so far are restricted to this area. They cut the Skærgård gabbros, which they have bleached in zones up to 1 m from the contact, and the basement gneisses, in which the development of fluorite may be observed close to the contact. Studies of these contact effects, which are assumed to be similar to those described by MACDONALD *et al.* (1973) from the Gardar Province have so far been limited to the Cl, F and alkali determinations reported below. These dikes are up to 5 m wide and also strike approximately parallel to the coastal dike swarm.

All these dikes stand in sharp contrast to the granophyre veins of the Skaergaard Intrusion (WAGER & DEER, 1939, p. 206; WAGER & BROWN, 1968) which occur in the neighbourhood. These latter are not found outside the intrusion, do not have chilled contacts and show no peralkaline tendencies. In the Setberg area of Iceland, SIGURDSSON (1970) showed convincingly that granophyres similar in composition to those of Skaergaard were derived from tholeiitic parents, whereas peralkaline types were derived from transitional basaltic liquids. The known association with other rock types, as at Setberg, combined with the age relationships of the Kangerdlugssuaq comendites suggests that the most promising source of these rocks may be the syenites of the area, which is where the fourth type of peralkaline acid rock is found.

Of the numerous slightly oversaturated syenite intrusions in the area, we have studied three examples of material of granitic composition occurring in close association with them. These syenites have not been studied in detail, but many are, at least in part, slightly peralkaline with alkali pyroxenes and amphiboles and sometimes astrophyllite and aenigmatite. DEER (in press) notes that the Kap Boswell syenite, which contains aegirine, arfvedsonite and ca. 4 $^0/_0$ modal quartz, is cut by fine-grained veins with up to 15 $^0/_0$ modal quartz and high concentrations of aenigmatite. Two of the veins investigated by us (MM20390 and MM20391) come from the neighbourhood of Kap Boswell and both contain alkali pyroxene, the former in large amounts. The third sample (CKB70–36) is a segregation vein in the Snout Series syenites, a late intrusion carrying small amounts of modal quartz and intruding the large Kangerdlugssuaq intrusion. This vein has no sharp contacts with the enclosing syenite and is of coarse grain size, consisting of quartz (ca. 20 $^0/_0$), alkali amphibole (in part intergrown with acmitic pyroxene), astrophyllite and several percent of a striking cherry red zircon. The Snout syenites themselves have a peralkaline facies, whose distribution has not yet been determined. In the case of the nearby Bagnæsset syenite it appears likely that the peralkaline parts are found in the highest parts of the dome-shaped exposure and there are suggestions that the same is true in other cases. Similar peralkaline acid dikes, ranging from rhyolitic through microgranitic to granitic are abundant in the immediate neighbourhood of the Kraemer Ø syenite, which will form a separate

Table 1. *Approximate phenocryst modes of Kangerdlugssuaq comenditic rocks*

Sample no. and type	Volume % Feldspar	Quartz	Amphibole or pyroxene	Groundmass
MM20357(1)	–	–	–	aphyric
MM20723(1)	–	–	–	aphyric
CKB71–6(2)	sparse	–	–	ca. 100
MM20702(2)	ca. 1	–	–	ca. 100
CKB71–63(2)	8	–	–	92
CKB70–84(3)	24	10	1 (amph.)	65
CKB70–105(3) ...	23	18	1 (amph.)	58
MM20390(4)	17	9	1 (pyx.)	73
MM20391(4)	–	–	–	non-porphyritic microgranite

Modes based on > 1000 points.

For sample locations see Table 6.

study. All these veins are clearly derived from the syenitic magma and it is intructive to compare their mineralogy and chemistry with that of the comendite dikes (types 1–3), whose relationships are less clear in the field. Unfortunately, the origin of the very abundant quartz syenite (nordmarkite) material itself remains obscure.

PETROGRAPHY AND MINERALOGY

Approximate phenocryst modes are reported in Table 1, while the localities of the studied specimens are given in the footnote to Table 6. Mineral compositions have been determined by microprobe using the techniques described in our previous publications (Brooks & Rucklidge, 1973, 1974), except that a riebeckite standard was used for the determination of Si, Fe & Na in the pyroxenes and amphiboles. The astrophyllite was analysed using Zr and Nb metal as standards for these elements and an arfvedsonite standard for F. Amphibole nomenclature is after Ernst (1968).

The aphyric (type 1) dikes often contain abundant spherulites, up to about 1 cm in diameter, which are composed of radiating feathery alkali feldspar, quartz and acicular blue amphibole. The areas interstitial to the spherulites are occupied by more coarsely crystalline quartz, microperthite (in part in granophyric intergrowth) and stumpy, intensely blue amphibole, which analysis shows to be an arfvedsonite (Table 2, col. 3). Occasionally this interstitial material grades outwards to open vugs lined with euhedral crystals. These vugs may also be fllled with fluorite or hematite. Long, hair-like, blue amphiboles traverse the

Table 2. *Typical amphiboles from Kangerdlugssuaq commenditic rocks*

	1	2	3	4		1		2		3		4	
SiO	47.5	49.2	49.8	50.0	Si	7.625	7.95	7.883	8.05	7.858	8.12	7.902	7.96
Al_2O_3	1.74	0.87	1.40	0.31	Al	0.329		0.164		0.260		0.058	
TiO_2	1.05	0.93	1.16	0.90	Ti	0.127	5.05	0.112	4.95	0.138	4.88	0.107	5.04
FeO	32.8	34.3	34.8	32.6	Fe^{3+}	0.732		0.918		1.002		1.189	
MnO	1.89	1.55	0.70	2.91	Fe^{2+}	3.658		3.688		3.597		3.119	
MgO	1.14	0.11	0.22	1.00	Mn	0.257		0.211		0.094		0.389	
CaO	4.67	0.18	1.02	0.52	Mg	0.273		0.026		0.052		0.236	
Na_2O	5.13	8.36	7.31	7.42	Ca	0.803	2.63	0.031	2.90	0.172	2.57	0.088	2.65
K_2O	1.14	1.30	0.82	1.42	Na	1.597		2.599		2.236		2.274	
F	1.25	2.30	–	1.21	K	0.233		0.266		0.165		0.286	
$Fe_2O_3^1$	6.05	7.59	8.44	9.99									
FeO^1	27.3	27.5	27.2	23.6									
H_2O^2	1.27	0.78	1.83	1.32									
Sum^3	99.6	99.7	100.0	100.1									

[1]) Calculated on basis of 13 (X + Y) cations and 23 oxygens.

[2]) Calculated assuming (OH + F) ≡ 2.00.

[3]) After correction for oxidation state and O ≡ F.

1. Green amphibole phenocrysts in type 3 dike margins (CKB 70–84 and MM 20301) – katophorite.
2. Blue acicular groundmass amphiboles in centres of type 3 dikes (MM 20301) – arfvedsonite.
3. Stumpy blue amphiboles in aphyric (type 1) comendites (MM 20723) – arfvedsonite.
4. Blue-green amphibole intergrown with (replacing ?) aegirine in segregation vein in nordmarkitic syenites (CKB 70–36) – arfvedsonite.

spherulites and apparently formed at an early stage of devitrification. They are difficult to analyse because of their thinness, but apparently have a similar composition to the stumpy variety. Zircon is a common accessory mineral in the spherulitic dikes. Non-spherulitic varieties are completely aphanitic and are cryptocrystalline to glassy. In contrast to the blueish spherulitic facies, they are jet black.

The feldspar-phyric (type 2) dikes are also very dark in colour with a cryptocrystalline to felsitic groundmass. The sparse alkali feldspar phenocrysts are perthitic and are difficult to analyse by probe but apparently have bulk compositions of around Or_{40} to Or_{45} with Ca below the detection limits. This is within the compositions to be expected in such rocks and Nicholls & Carmichael (1969) have presented an important discussion of feldspar relationships in peralkaline acid rocks. The difficulties of distinguishing between phenocrysts and xenocrysts was stressed by them, and it may be that some of our samples contain xenocrysts, although in most cases the euhedral form argues against this. Sparse ilmenite phenocrysts and magnetite microphenocrysts may sometimes be present (CKB71–6), but these are not in equilibrium with each other and cannot be used to determine oxygen fugacity and temperature. However, in the analysed example (Table 3, col. 1 and 2), the high

Table 3. *Typical opaque minerals from Kangerdlugssuaq comenditic rocks*

		1	2	3	4	5	6	7
α series								
ilmenite	$FeTiO_3$	70.2		87		100		62.1
pyrophanite	$MnTiO_2$	24.2		–				29.5
hematite	Fe_2O_3	5.6		13				8.4
β series								
magnetite	$FeFe_2O_4$		97.9		96		97	
ulvøspinel	Fe_2TiO_4		0.4		4		3	
others			1.7		–			

1. Ilmenite phenocryst in aphyric margin of aphyric comendite dike (CKB 71–6). Avrage of 3 analyses.
2. Magnetite microphenocryst in groundmass of same sample as previous. Typical analysis, all very similar.
3. Ilmenite intergrown with magnetite in margin of feldspar-phyric comenditic dike (CKB 71–63).
4. Magnetite microphenocryst in same sample as 3.
5. Very fine ilmenite lamellae in magnetite in weakly peralkaline microgranite sheet (MM 20391).
6. Magnetite host of 5.
7. Ilmenite as large homogenous crystals in peralkaline granitic segregation vein CKB 70–36) in nordmarkitic syenites.

pyrophanite component in the ilmenite and low ulvøspinel in the magnetite seem to be indicative of low temperatures and rather strongly oxidizing conditions. In other cases the oxides are not homogeneous, but unmixed at low temperature (Table 3, col. 3). These dikes, when sufficiently broad develop a granophyric centre, which usually does not show a peralkaline mineralogy. In fact, the peralkaline tendencies of these dikes may only be revealed by chemical analysis of the chilled margins.

The type 3 dikes, (those with three phenocryst phases), show a contrast in mineralogy and chemistry between the margins and the centres, which matches the strong colour contrast noted in the field. The chilled margins have euhedral quartz and alkali feldspar phenocrysts up to 2 mm in size with the sparser amphibole phenocrysts somewhat smaller. These feldspars have a composition similar to those already described in the type 2 dikes, but in one case, sparse phenocrysts with a composition around An_5 (K below detection) were also observed. Feldspar phenocrysts are occasionally rimmed by granophyric material. The amphibole phenocrysts are pleochroic from brownish shades to a brilliant grass-green and are best described as katophorite (analysis Table 2, col. 1) being richer in Ca than the blue varieties. The groundmass in the margins of these dikes is cryptocrystalline in which only fine needles of blue amphibole and patches of fluorite can be resolved. In contrast, the centres are sometimes coarse enough to be point-counted and one sample (equivalent to the analysed sample CKB70–105) has 32 $^0/_0$ quartz, 53 $^0/_0$ alkali feldspar and 15 $^0/_0$ blue amphibole. This amphibole differs from that of the phenocrysts in being an arfvedsonite (Table 2, col. 2) which is high in F. Ti and Fe are very variable in these amphiboles, this being due to needles of ilmenite on a micron scale, which possibly arise by exsolution. In other cases (CKB70–84) the ferromagnesian groundmass phase is an acmitic pyroxene and is very pale in colour (Table 4, col. 1). As there is no obvious chemical difference between the two types of dike, the development of either amphibole or pyroxene is probably determined by the oxygen fugacity under crystallization and this may conceivably be connected to the nature of the enclosing rock. Amphibole apparently occurs where the dikes traverse gabbro, pyroxene where they cut acid gneiss but a more exhaustive survey would be necessary to confirm this. The centres of these dikes show considerable deuteric alteration when compared to the very fresh margins and the original green amphibole phenocrysts are now represented by aggregates of deep blue amphibole and opaque ore. Fluorite is apparently less abundant than in the margins and hematite is ubiquitous.

The segregation veins (type 4) vary widely in petrography, ranging from weakly peralkaline types to those with a pantelleritic

Table 4. *Typical pyroxenes from Kangerdlugssuaq comenditic rocks*

	1	2	3	4	Cations on basis of 4 cations	1		2		3		4	
SiO_2	42.3	49.2	51.9	51.4	Si	2.023	2.02	1.997	2.00	2.001	2.00	1.972	1.99
Al_2O_3	0.99	0.04	0.35	0.19	Al	0.045		0.002		0.016		0.009	
TiO_2	0.62	0.02	0.70	0.18	Ti	0.018	1.01	0.000	1.10	0.020	1.03	0.005	
Fe_2O_3	28.7	2.68	30.0	34.1	Fe^{3+}	0.837		0.082		0.872		0.987	1.02
FeO^1	3.50	27.1	3.38	0.84	Fe^{2+}	0.113		0.923		0.103		0.027	
MnO	0.03	0.00	0.30	0.36	Mn	0.000		0.000		0.010		0.012	
MgO	0.01	1.63	0.26	0.00	Mg	0.000		0.099		0.015		0.000	
CaO	0.02	18.8	0.81	0.90	Ca	0.001	0.96	0.818	0.90	0.033	0.96	0.037	0.99
Na_2O	12.8	1.02	12.40	12.8	Na	0.956		0.080		0.930		0.952	
K_2O	0.10	0.00	0.00	0.00	K	0.004		0.000		0.000		0.000	
Sum	99.1	100.6	99.9	100.8	mol. %								
					Di	0.1		9.0		1.4		0.0	
					Hd	10.9		83.7		11.2		3.7	
					Ac	89.1		7.3		87.4		96.3	

[1] Fe_2O_3 and FeO calculated on the basis of Σ cations = 4.

1. Pale pyroxene needles of groundmass in centres of type 3 dikes (CKB 70–84 and MM 20301) – aegirine.
2. Pyroxene in weakly peralkaline late-stage microgranite sheet (MM 20391) – sodic hedenbergite.
3. Green pyroxene of late stage peralkaline microgranite sheet (MM 20390) – aegirine.
4. Pale-coloured acmitic pyroxene intergrown with alkali amphibole in segregation vein in nordmarkitic syenite (CKB 70–36).

composition (see chemistry section below) with abundant alkali amphibole and acmitic pyroxene. The three analysed examples reflect this variation. In the two highly peralkaline samples (CKB70–36 and MM20390) the potash feldspar shows microcline twinning and there is a separate albitic phase. The pyroxenes in both these rocks are acmitic. In MM20390 it is the only major ferromagnesian mineral and is patchily green in colour. Microprobe analysis gave a rather variable TiO_2 content, but even when one of the lowest values found is taken (as in Table 4, col. 3) there is an excess of Ti which necessitates the calculation of a molecule such as $NaTiFe^{3+}SiO_6$. Similar, but more extreme, pyroxenes have been reported recently from pantelleritic ignimbrites of Gran Canaria (SCHMINCKE, 1969) and by PEDERSEN *et al.* (in press) in peralkaline tephra layers in northern Denmark, while FLOWER (1974) has studied their stability relationships experimentally. They seem to be characteristic of oversaturated peralkaline rocks which have crystallized under a high oxygen fugacity. The pyroxene in CKB70–36, which is even more acmitic, was also found to have a variable TiO_2 content and this was traced to the presence of minute ilmenite flakes, which may have arisen by exsolution of this same component. The pyroxene in this rock was apparently undergoing replacement by arfvedsonite (Table 2, col. 4), which has a high Mn content, thus resembling some of the arfvedsonites from the nearby Kangerdlugssuaq intrusion reported by KEMPE & DEER (1970). This type of replacement during cooling is precisely what would be expected from the stability relations of alkali pyroxenes and amphiboles given by ERNST (1968), and NICHOLLS & CARMICHAEL (1969). In this rock, large flakes of astrophyllite, abundant euhedral zircon, ilmenite and accessory chevkinite are also present. The astrophyllite, which is a fairly common constituent of peralkaline rocks in the area, has the composition reported in Table 5 and according to the compilation published by MACDONALD & SAUNDERS (1973) has an unremarkable composition. KEMPE & DEER reported the composition of an astrophyllite from the nearby Kangerdlugssuaq intrusion, which is similar*), Chevkinite, also reported by KEMPE & DEER in the nordmarkites of the Kangerdlugssuaq intrusion, is a fairly ubiquitous accessory mineral in the felsic rocks of the area. The analysis reported in Table 5 suffers from the fact that we did not have good standards for the rare earth elements, but it nevertheless compares fairly closely to the ideal formula for this mineral given by ITO (1967). Very few analyses of chevkinite are to be found in the literature and even fewer descriptions of its parageneses. However, it has been reported in fayalite-quartz syenties of New Hampshire

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* In Table XIX, p. 62, analyses 1, A and B of these authors OH has been incorrectly calculated. For example, that of analysis 1 should read 3.389 in place of 3.585. Their formula for astrophyllite also should be O_{25} instead of O_{29}.

Table 5. *Analyses of astrophyllite and chevkinite from peralkaline granite segregation vein (CKB 70–36) in nordmarkitic syenites*

	astrophyllite	chevkinite
SiO_2	35.9	20.5
TiO_2	9.10	14.8
ZrO_2	0.67	0.00
Al_2O_3	0.61	0.00
Fe_2O_3[1]	2.40	3.55
Nb_2O_5	2.01	0.00
FeO[1]	28.6	8.30
MnO	7.39	0.00
MgO	0.18	0.00
CaO	0.56	0.97
Na_2O	2.48	0.12
K_2O	6.05	–
R.E.[1]	–	49.06
H_2O[3]	2.54	–
F	1.05	–
Sum[4]	99.5	97.4
$-O \equiv F$	0.44	
	99.1	

Ions on basis of 31 (O, OH, F) for astrophyllite and 22 (0) for chevkinite

	astrophyllite		chevkinite		
Si	7.967	9.56	4.41		6.00 (Ti_2Si_4)
Ti	1.519		2.40 <	1.59 0.81	2.88 (BC_2)
Zr	0.072		–		
Al	0.160	7.66	–		
Fe^{3+}	0.402		0.58		
Nb	0.201		–		
Fe^{2+}	5.315		1.49		
Mn	1.390		–		
Mg	0.060		–		4.12 (A_4)
Ca	0.133		0.23		
Na	1.067	2.78	0.05		
K	1.714		–		
R.E.[2]	–		3.84		
OH[3]	3.763	4.50	–		
F	0.737		–		
cations	20.00		13.00		

[1]) Fe_2O_3 and FeO calculated from stoichiometry.

[2]) RE. = rare earths (La_2O_3 10.3 %, Ce_2O_3 20.9 %, Pr_2O_3 3.46 %, Nd_2O_5 11.4 %, Sm_2O_3 3.000, La^{3+} 0.82, Ce^{3+} 1.65, Pr^{3+} 0.27, Nd^{3+} 0.88, Sm^{3+} 0.22).

[3]) H_2O in astrophyllite calculated on the assumption that (OH, F) ≡ 4.50 as reported by Kempe & Deer, 1970.

[4]) Sn was sought in the astrophyllite and Y, Zr & Nb in the chevkinite, but not found.

Ideal formulae are (see references in text):–

astrophyllite: $(KNa)_3FeTi_2SiO_{25}(O, OH, F)_6$

chevkinite: $RE_4Fe^{2+}(Fe^{3+},Ti)_2Si_4O_{22}$ or $A_4BC_2Ti_2Si_4O_{22}$

(Jaffe *et al.*, 1956) and pegmatites associated with an aegirine granite in Madagascar (Lacroix, 1915). The ilmenite occurring in this rock is quite Mn-rich (Table 3), is homogeneous and is not accompanied by a spinel phase. The zircon has an unremarkable major element composition. The less peralkaline of these veins is represented by sample no. MM20391, which lacks the green colour shown by the more peralkaline varieties and is pale brown in hane specimen. It is composed of euhedral parthites with quartz, pyroxene and ore. The pyroxene is a less Na-rich type (Table 4, col. 2) than those just descrlbed and the ore is magnetite (Table 3), unmixed at low temperatures to ilmenomagnetite. All these samples differ from types 1–3 dikes in being coarser-grained; CKB70–36 has a granitic aspect while MM20390 and 20391 are best described as microgranites.

Summary of petrography and mineralogy

The pyroxenes of these rocks range from hedenbergitic types to highly acmitic types. Katophorite was the high temperature liquidus amphibole and was later replaced by aegirine, probably as a result of increasing oxygen fugacity and falling temperature, but also of decreasing Ca content in the later liquids. At even lower temperatures, the acmitic pyroxene was replaced by arfvedsonite, although this probably depends on several factors, principally the oxygen and fluorine fugacities. The absence of aenigmatite in the dikes and veins studied by us (although, as noted above, it occurs in other examples) is probably due to a high oxygen fugacity, rather than the degree of peralkalinity (agpaitic indices of over 1.4 are encountered, see below) as suggested by the diagrams of Ernst (1968, fig. 49, p. 87) and Nicholls & Carmichael (1969, fig. 4, p. 284). This conclusion is confirmed by the NaTi components of the pyroxenes and the compositions of the oxide phases. However diagrams of Ernst and Nicholls and Carmichael may be greatly modified by additional components. The presence of minerals such as astrophyllite and chevkinite are a testimony to the late stage build-up of Ti, Nb and rare earths while the abundance of zircon shows that Zr also became highly concentrated. Feldspars, although not studied in detail, conform in general to what might be expected for such rocks, the chilled samples containing feldspars with a similar composition to those reported from comendites in the past. The anorthite component is extremely low, indicating that the peralkaline trend cannot be due to the plagioclase effect, at least at this stage of differentiation, and they are more potassic than their rocks, which would lead to the generation of very sodic liquids (see discussion in Nicholls & Carmichael, 1969). In the more slowly cooled (type 4) veins, coarse perthite is present in the less peralkaline members, whereas two feldspars, a microcline coexisting with an albite, are found in the more peralkaline varieties.

Table 6. *Analyses and norms of Kangerdlugssuaq comenditic rocks*

	Syenite average	Aphyric Rhyolites		Rhyolites with feldspar as only phenocryst phase			Rhyolites with phenocrysts of quartz, feldspar and amphibole		Veins and sheets closely associated with syenites		
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
SiO_2	64.0	73.38	73.30	69.772	72.57	72.3	74.6	76.3	70.72	72.32	64.8
Al_2O_3	16.4	11.69	11.64	13.35	12.81	13.7	11.7	11.4	9.45	12.59	7.48
Fe_2O_3	1.72	1.95	1.70	1.86	1.94	1.38	2.36	1.94	5.22	2.01	4.10
FeO	2.07	1.48	1.65	1.47	1.15	0.34	1.00	1.13	1.81	1.34	5.37
MgO	0.41	0.00	0.03	0.05	0.06	0.10	0.00	0.00	0.00	0.00	0.71
CaO	1.13	0.51	0.56	0.56	0.70	0.06	0.17	0.08	0.72	0.72	0.55
Na_2O	6.69	4.52	4.41	6.22	5.85	6.31	5.25	4.76	5.49	5.23	4.34
K_2O	5.44	5.30	5.13	4.77	3.80	4.58	3.66	4.10	4.28	4.64	2.93
MaO	0.17	0.09	0.10	0.15	0.09	0.03	0.12	0.09	0.25	0.12	1.39
TiO_2	0.62	0.32	0.31	0.17	0.16	0.14	0.16	0.17	0.33	0.21	3.82
P_2O_5	0.08	0.02	0.03	0.07	0.04	0.01	0.00	0.00	0.04	0.03	0.30
H_2O+	0.23	0.60	0.42	0.36	0.10	0.09	0.26	0.15	0.14	0.22	0.39
Sum	99.0	99.86	99.28	98.75	99.27	99.3	99.3	100.0	98.45	99.43	99.3*
Analyst	A	B	B	B	B	C	A	A	B	B	A

* Total includes 2.1 % ZrO_2 (≡ 3.1 % normative Z) and 0.34 % Nb_2O_5.

C.I.P.W. weight norm.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Q	2.1	27.38	27.70	17.40	23.57	21.0	30.6	33.2	26.74	23.71	28.3
or	32.1	31.32	30.32	28.19	22.46	27.1	21.7	24.3	25.29	27.42	17.3
ab	54.1	30.62	31.31	42.11	44.74	45.2	39.7	35.7	24.78	38.93	22.1
ac	2.2	5.64	4.92	5.38	4.20	4.0	4.1	4.0	15.10	4.69	11.8
ns	–	0.28	0.10	1.03	–	–	–	–	1.05	–	0.3
di	4.3	2.14	2.29	2.06	2.82	0.2	0.7	0.3	2.95	3.01	0.7

Table 6. *Continued*

	Syenite average	Aphyric Rhyolites		Rhyolites with feldspar as only phenocryst phase			Rhyolites with phenocryst of quartz, feldspar and amphibole		Veins and sheets closely associated with syenites		
hy	1.1	1.22	1.56	1.74	0.28	0.2	0.4	1.1	1.67	0.42	5.0
mt	1.4	–	–	–	0.71	0.7	1.4	0.8	–	0.56	–
it	1.2	0.61	0.59	0.32	0.30	0.3	0.3	0.3	0.63	0.40	7.3
ap		0.05	0.01	0.16	0.09	0.0	0.0	0.0	0.09	0.07	0.71
Molecular pre cent											
SiO_2	76.5	83.37	83.59	80.48	82.28	80.9	83.9	84.6	83.87	82.42	86.1
Al_2O_3	11.5	7.81	7.81	9.07	8.54	9.0	7.7	7.4	6.59	8.44	5.8
Na_2O+K_2O	11.8	8.81	8.55	10.46	9.17	10.1	8.3	7.9	9.54	9.14	8.1
$\frac{100Na_2O}{Na_2O+K_2O}$	65.3	56.51	56.57	66.44	70.01	67.3	68.7	64.5	66.46	63.02	69.1
$\frac{Na_2O+K_2O}{Al_2O_3}$ (agpaitic index)	1.03	1.13	1.10	1.15	1.07	1.12	1.08	1.7	1.45	1.08	1.40
Rb	71	122	105	190	107	134	233	193	103	82	151
Ba	778	190	210	58	12	67	0	0	30	200	116
Sr	115	6	4	7	6	4	4	3	7	11	60
Y	40	61	68	104	120	54	116	78	76	46	307
Zr	855	574	593	1490	1030	466	1200	1510	778	292	14700
Nb	152	150	150	670	520	350	790	760	410	150	2350
	745	528	1017	2220	979	800	1150	980	1193	421	4780
		50		270		130	310	220			320

Cu, Co, Ni, V, Cr all below optical spectrographic detection limits.

Notes for Table 6: Next page.

PETROCHEMISTRY

Major elements. Many workers have noted that peralkaline magmas readily lose certain constituents on crystallization or devitrification (see e.g. Melchior Larsen & Steenfelt, 1974). Comparisons of volcanic rocks with their equivalent plutonics (Tutle & Bowen, 1958, p. 88; Bailey & Schairer, 1966, p. 150) and crystalline with glassy volcanic rocks (Noble *et al.*, 1967; Noble, 1970; Macdonald & Bailey, 1973) have shown that the greatest effect is loss of alkalis, mainly Na_2O, and halogens. Data relevant to this problem will be presented below but, as none of the samples studied by us is a true glass, this process will undoubtedly hamper any detailed discussion of the petrochemistry.

Table 6 reports chemical compositions for representatives of the four types of comendite described above, together with an average for six new analyses of the oversaturated syenite intrusions of the area. The C.I.P.W. norms of these rocks clearly reflect the peralkaline character of these rocks as deduced from the modal mineralogy and all samples have normative *ac*, while some also have small amounts of normative *ns*. All

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Notes for Table 6.

[1] Average of 6 syenites (CKB70–45, –46, 71–75 from Snout Series; CKB70–15, –40 from Bagnæsset and MM20386 from Jagtlejren). For locations see map *in* Kempe, Deer, & Wager, 1970.

[2] Blue spherulitic rhyolite, loose block, Skåret, Kraemer Ø (MM20357).

[3] Blue, drusy spherulitic rhyolite, loose block, Skærgårdshavlø (MM20723).

[4] Blue margin of sparsely feldspar-phyric dike cutting alkali granite, Nûk (66°59′N, 33°48′W), Kialeq district (CKB71–6).

[5] Thin, black, flinty dike with sparse feldspar phenocrysts, island of Pátûlâjivit, (67°36′N, 32°30′W) (MM20702).

[6] Black, flinty margin of feldspar-phyric dike with pale centre, cutting gneisses just north of Søndre Syenitgletscher (CKB71–63).

[7] Blue margin of strongly porphyritic dike cutting gneisses at north end of Uttental Sund (CKB70–84).

[8] Blue margin of porphyritic dike cutting Skaergaard intrusion gabbros of LZ, Uttental Plateau (CKB70–105).

[9] Green microgranite sheet cutting basalts, Keglen (MM20390).

[10] Buff-coloured microgranite sheet cutting basalts, Keglen (MM20391).

[11] Granitic segration vein, rich in astrophyllite, and zircon in Snout Series syenites, west side of bay in Amdrup Fjord (CKB70–36)

Analysts: A. G. Hornung, Dept. of Earth Sciences, Leeds. B, Ib Sørensen, Grønlands geologiske Undersøgelse, Copenhagen. C, J. Bailey, Institut for Petrologi, Copenhagen (H_2O^+ determined by loss on ignition corrected for Fe oxidation)

Trace elements. John Bailey, Institut for Petrologi, Copenhagen

Cl and F: Niels Hansen, Institut for Mineralogi, Copenhagen

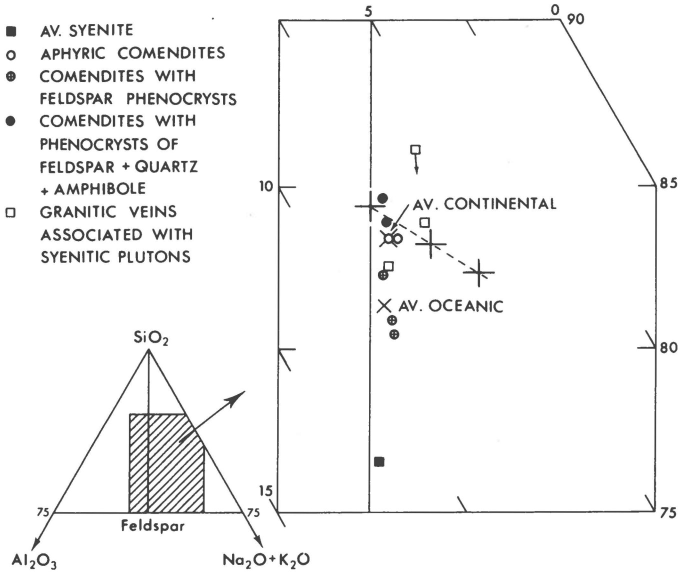

Fig. 1. Plot of Kangerdlugssuaq peralkaline rocks plotted in the system Na_2O-K_2O-Al_2O_3-SiO_2 using a projection diversed by Bailey & Macdonald (1969). Large crosses and broken line indicate the minimum melting compositions for increasingly peralkaline compositions as determined by Carmichael & MacKenzie (1963). The arrow on the most SiO_2-rich point indicates that its true position is believed to lie at lower SiO_2 compositions.

these rocks, with the exception of MM20390 and CKB70–36 (analyses 9 & 11), would be classified as comendites after the definitions of Lacroix (1927) and Macdonald & Bailey (1973). The two exceptions, which have more than 12.5 $^0/_0$ normative femic constituents, fall into the pantellerite field. The comenditic compositions can be closely matched by analyses in the literature; analysis 7, for instance, being very close to the average for 13 samples of continental comendites reported by Bailey & Macdonald (1970) and analyses 4–6 being close to their oceanic average based on 17 samples.

The chemical data are plotted in figs. 1 and 2 in terms of molecular percent SiO_2–Al_2O_3–K_2O–Na_2O in the projections introduced by Bailey & Macdonald (1969), who endeavoured to overcome the disadvantage, of the more normal plot of normative Q–*or*–*ab* (Tuttle & Bowen, 1958) which does not represent peralkaline compositions adequately. In the light of the above reservations regarding possible loss of Na_2O, these plots do not appear to be inconsistent with derivation of the comendites from a syenitic parent (represented by the average of six syenite analyses) by feldspar fractionation. The granitic vein from the Snout Series (CKB70–36) has an anomalous composition in that it is unusually quartz-rich. However, in view of the very coarse grain-size of this rock, this is re-

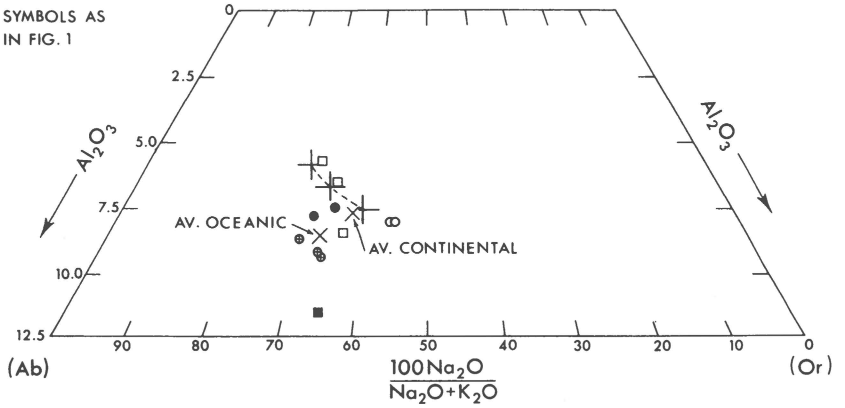

Fig. 2. The data in fig. 1 plotted into another projection in the same system to show variations in the Na_2O/Na_2O+K_2O ratio. The two aphyric samples, which have a spherulitic texture, plot anomalously far to the right suggesting that they have lost some Na_2O on devitrification.

garded as being due to sampling error and subtraction of ca. 2 mol. percent SiO_2 would bring its composition onto the cotectic close to sample no. MM20390, the other pantelleritic composition. Quartz in this rock appears to be particularly inhomogeneously distributed. The same sample is also abnormally high in MnO and TiO_2 for such a differentiated rock and this is probably related to the abundant astrophyllite in the sample. In general, the trends shown in figs. 1 and 2 with a band of compositions extending from trachytic compositions to the area of the quartz-feldspar cotectic is strongly reminiscent of the trend obtained by Bailey & Macdonald (1970) for oceanic comendite obsidians, which they interpreted in terms of fractional crystallization from the trachytic parents.

Trace elements. The trace element levels reported in Table 6 are similar to those normally reported for such rocks, and with the reservation noted above are roughly consistent with the above discussion.

Post-intrusion effects. Table 7 presents the results of analyses of both centres and margins for two dikes to allow some assessment of the problem of possible alkali loss noted above. The margins,being exceedingly fine-grained, are assumed to be a close approach to the composition of the original magma, while the centres are holocrystalline and, in the light of previous workers' experiences, would be expected to have undergone some chemical change. In both cases, Na_2O has fallen significantly and the degree of oxidation of the iron has increased in the dike centres. This has the effect of introducing minerals such as *he*, *ru* and *c* into the norms, while in the case of CKB70–6 the core is no longer peralkaline due to substantial (ca. 30 $^0/_0$) Na_2O loss so that both *ac* and *ns*, which

Table 7. *Comparasions of compositions of chilled margins and holocrystalline centres of East Greenland comendite dikes*

	CKB 70–84 margin	CKB 80–84 centre	CKB 71–6 margin	CKB71–6 centre
SiO_2	74.6	75.36	69.72	70.80
Al_2O_3	11.7	11.13	13.35	13.75
Fe_2O_3	2.36	3.51	1.86	3.17
FeO	1.00	0.00	1.47	0.94
MgO	0.00	0.3	0.05	0.40
CaO	0.17	0.00	0.56	0.00
Na_2O	5.25	4.45	6.22	4.27
K_2O	3.66	4.54	4.77	5.71
MnO	0.12	0.11	0.15	0.19
TiO_2	0.16	0.19	0.17	0.13
P_2O_5	0.00	0.04	0.07	0.13
H_2O	0.26	0.32	0.36	0.40
Sum	99.3	99.95	98.75	99.79
C.I.P.W. weight norms				
Q	30.6	32.95	17.40	23.51
or	21.7	26.83	28.19	33.75
ab	39.7	31.97	42.11	36.13
ac	4.1	5.00	5.38	–
ns	–	–	1.03	–
di	0.7	–	2.06	–
hy	0.4	0.75	1.74	1.00
he	–	1.78	–	1.17
mt	1.4	–	–	2.90
il	0.3	0.24	0.32	0.36
ap	0.0	0.00	0.16	0.32
c	–	–	–	0.55
ru	–	0.07	–	–
Rb	233	271	190	172
Sr	4	4	7	23
Y	116	125	104	115
Zr	1200	1530	1490	1460
Nb	790	800	670	680
F	1150	1030	2220	380
Cl	310	220	270	120

Cu, Co, Ni, V and Cr below optical spectrographic detection limits.

Analysts: major elements all B except CKB 70–85 which is A (see Table 2).

trace elements: C (see Table 2).

Cl + F: as in Table 2.

were present in the margin have disappeared. In the other case, Na_2O loss has not been so drastic (ca. 15 $^0/_0$) and the peralkaline nature is retained, and is reflected in the presence of acmitic pyroxene (Table 4, col. 1) or arfvedsonite needles (Table 2, col. 2) in certain of these dike centres. Among the trace and minor constituents, halogens show a fall from margins to centres, which is again much more marked in the case of CKB71–6. We may therefore conclude from the data in Table 7 that a sodium- and halogen-rich fluid has been lost from the more crystalline portions of these dikes as found by many other workers using a similar approach. The presence of such a fluid was also demonstrated by Roedder & Coombs (1967) in fluid inclusions in peralkaline granite blocks from Ascension Island.

On the other hand, Macdonald *et al.* (1973) used a different approach to this problem and, based on analyses of gabbros adjacent to an alkali granite, concluded that the fluid lost by the granite had been rich in K, in addition to F and H_2O (with no indication of Na addition). Accordingly, we have made partial analyses of Skærgård gabbro, both close to the contact of a comendite dike (analysed sample no. CKB70–105), where it is strongly bleached (sample no. MM27669), and about 10 m distant from the contact, where the rocks are apparently typical LZa gabbros (sample no. MM27670, c. f. EG5109 in Table 5 of Wager & Brown, 1968). These gave the following results:

	MM27669	MM27670
Na_2O ($^0/_0$)	3.87	3.92
K_2O ($^0/_0$)	1.45	0.36
F (p.p.m.)	418	180
Cl (p.p.m.)	0	5

As in the case reported by Macdonald *et al.* (1973), the introduction of F and K is indicated, but no Na. This apparent disagreement with the conclusion derived from a study of the dike rocks themselves must await further investigation.

DISCUSSION

The Tertiary comendite dikes of the Kangerdlugssuaq district are part of a wide spectrum of felsic rock-types in the area. Most abundant are the slightly oversaturated syenites (nordmarkites) from which it is here postulated that the comendites derive. Also present are metaluminous granitic rocks, e.g. the biotite granite of Amdrup Fjord (Kempe *et al.*, 1970) and the Skærgård granophyres (Wager & Brown, 1968). The origin of the latter is still in doubt, in spite of intensive studies and it is not clear to what extent they derive from melting of basement gneisses or by fractionation of the Skærgård magma. This is a classical problem in the North Atlantic province and has been discussed by many authors (see Beckinsale *et al.*, 1974, for a recent contribution). The biotite granites have not yet been studied and their affinities remain obscure. However, the association of peralkaline and metaluminous granitic rocks is a common one (e.g. Bowden & Turner, 1974) and it may reflect degrees of alkalinity in the parental nordmarkitic magmas, which straddle the "crossroads" of Bailey & Schairer (1964). Thus undersaturated felsic rocks are also represented in the area, and these may also be peralkaline (Brooks & Rucklidge, 1974) or metaluminous as in the case of the foyaites of the Kangerdlugssuaq intrusion (Kempe *et al.*, 1970). Unpublished isotopic results of R. J. Pankhurst, C. K. Brooks and R. D. Beckinsale indicate that many of these rocks have undergone considerable isotopic exchange with Precambrian basement gneisses and meteoric ground water and speculations on their mutual relations is thereby rendered complicated.

Although much more work will have to be done before reliable models for the inter-relationships of these various rock types can be erected it is clear from the evidence afforded by the segregation veins that the comendites discussed in this paper are related to the same magma as that which formed nordmarkitic plutons, by a process of feldspar fractionation as described by many authors and summarized by Macdonald (1974). In this particular case, our observations therefore confirm the views of the various authors mentioned in the introduction who regard trachytic liquids to be the immediate precursors of comendites. The similarity in the spread of points in fig. 1 to the oceanic comendites of Bailey & Macdonald (1970), seems to be an additional argument against a crustal origin for these rocks.

On a worldwide basis, pantellerites and comendites seem to have a fairly close association with transitional basalts and areas of attenuated crust as noted in the introduction. This is in close accordance with the occurrence of the nordmarkites and comendites in the outer parts of Kangerdlugssuaq, which in the model presented by Brooks (1973) must, in the lower Tertiary, have been a transitional zone between the actively-spreading coast-parallel rift system and the non-spreading fjord-parallel rift. It can readily be imagined that the crust underlying the outer parts of the fjord became attenuated without actually separating. Using other areas of the world as a parallel, we postulate that the nordmarkites were ultimately derived from transitional baslatic magmas, which have not yet been recognized at the surface, but which accumulated in a low density cushion under the rift. Here they underwent differentiation until the nordmarkitic magmas were produced, which could migrate upwards to the surface by reason of their low density, in the manner described by Gill (1973). The mechanism of this migration was at least in part by stoping, many beautiful examples of arrested stages of this process being present in the area. These nordmarkitic magmas then differentiated further to give the comendites described here. There is however no evidence for the earlier stages of this process, intermediate rocks being apparently completely lacking at the present surface.

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