GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 50

THE PETROLOGY OF A CAMPTONITE SILL IN SOUTH GREENLAND

BY

B. G. J. UPTON

WITH 3 FIGURES AND 3 TABLES IN THE TEXT
AND 1 PLATE

DANISH GEOLOGICAL CONTRIBUTION
TO THE INTERNATIONAL UPPER MANTLE PROJECT

Reprinted from
Meddelelser om Grønland, Bd. 169, Nr. 11

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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INTRODUCTION

During the Greenland Geological Survey's mapping of the islands lying between the Bredefjord and the Skovfjord close to the townships of Narssaq and Julianehåb in S. Greenland, a number of distinctive lamprophyre dykes and sills were encountered.

The islands themselves lie athwart one of the densest swarms of alkalic dykes associated with the Gardar volcanic cycle. In brief, the geology of the islands is as follows: Post-kinematic granodioritic rocks with minor amphibolitised basic intrusions lie within the migmatitic complex resulting from the folding and metamorphism of the Ketilidian and Sanerutian events (BERTHELSEN, 1961). Near Narssaq these are unconformably overlain by sandstones and alkalic plateau basalts of Gardar age. These have been totally eroded from the islands except where preserved as down-fallen blocks in volcanic centres. Into the granodioritic complex exposed on the islands an extensive but genetically related suite of mainly later Gardar basaltic, trachybasaltic, trachytic and comenditic magmas were intruded (UPTON, 1964a and 1964b). The majority of these intrusions take the form of WSW–ENE trending dykes. Crystallisation of the larger intrusions produced coarse grained syenites and gabbros. Towards the close of activity some sinistral movement occurred along several E–W or WNW–ESE trending wrench-faults, three of which are shown in Fig. 1.

The intrusion of a thinly scattered swarm of camptonitic dykes and sills, believed to have post-dated the sinistral faulting, marked a recrudescence of igneous activity at the close of the Gardar cycle in this district. The camptonite dykes share the WSW trend of the earlier dykes and appear to have been the feeders for the thin sills which, for the most part, dip towards the SW at low angles. Hornblende lamprophyre dykes of similar character are described by WATT (1963) from the Qaersuarssuk district separated from Tugtutôq by the Bredefjord. The age relationship of the lamprophyres to the other Gardar intrusions on Qaersuarssuk was indeterminable. AYRTON (1963) has also described Gardar lamprophyre dykes occurring more than 100 km to the NW in the Ivigtut region, trending NE–SW and intermediate in type between camptonites

Abstract

A number of small camptonite intrusions were emplaced as dykes and sills at a late stage in the magmatic history of the south Greenland alkaline province in the vicinity of Narssaq and Tugtutôq. Crystal fractionation in one 3 m thick sill lead to the production of a water- and carbon dioxide-rich residuum in the central part of the intrusion. In this central part the concentration and form of ocelli carrying analcite, calcite and zeolites suggests the separation of a vapour phase towards the completion of crystallisation. It is thought that the initial intrusion was of the regional alkali basalt magma modified by an addition of water, carbon dioxide, alkalies and calcium. Kimberlitic or carbonatitic magmas, or alternatively, syenite magma residuals are regarded as possible sources for this volatile-rich increment.

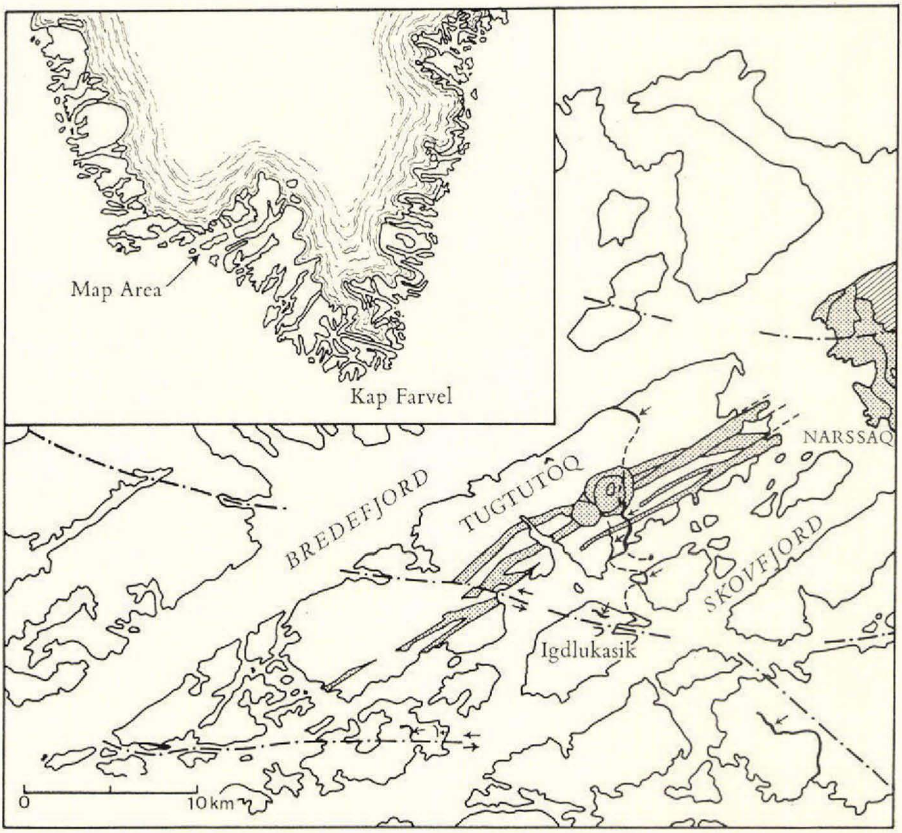

Fig. 1. Sketch-map of the Tugtutôq-Narssaq area.
(Dotted: major Gardar intrusives. Cross-hatched: Gardar 'continental' series.
The course of the camptonite sill is indicated across Tugtutôq).

and kersantites. Since these precede the Gardar dolerite dykes of the neighbourhood they are, in all probability, considerably older than the camptonite intrusions of Tugtutôq and Igdlukasik islands which form the subject of this paper. The late Gardar camptonite dykes extend NE from Tugtutôq across the intrusives and volcanic rocks around Narssaq. An analysis of one of these dykes is reproduced in Table 3, by permission of Dr. J. W. STEWART. The dykes, which seldom exceed 4 m in width, are characterised by fine black chilled zones and flow-banded central parts with trails of white ocelli. On the well-exposed granite hill-sides and coast sections of Tugtutôq, Qángue, Igdlukasik and Niaqornaq islands, the sills, though thin, form conspicuous features. Like the dykes, the sills tend to be layered parallel to the chilled surfaces. One sill, some 3 m thick, which outcrops on Qángue and Igdlukasik islands in the Skovfjord, is probably the same intrusion as that described from the nearby Julianehåb peninsula by NESBITT (1961). NESBITT reports

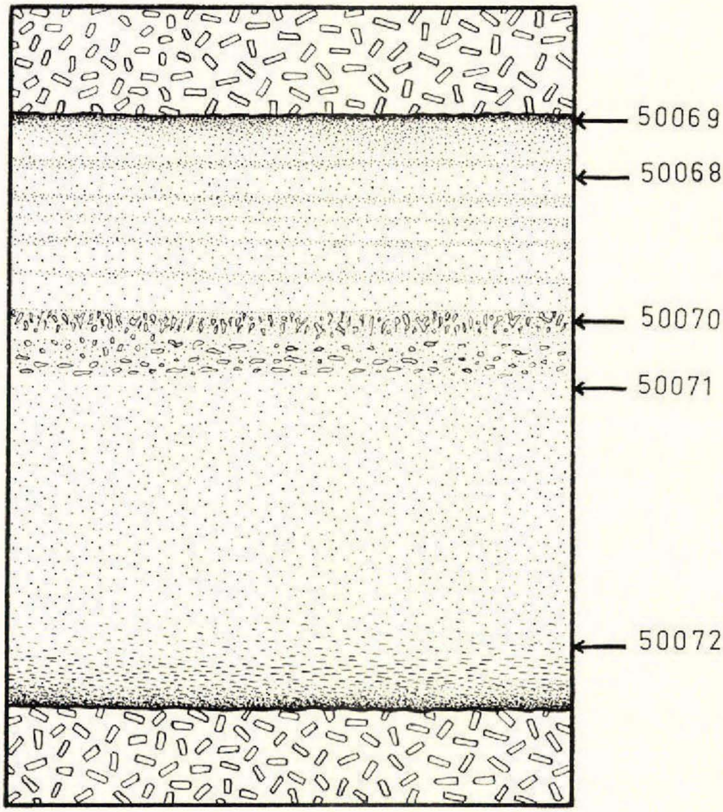

Fig. 2. Diagrammatic section across the camptonite sill in Mathæus Havn, Igdlukasik, showing relative positions of the specimens.

the sill to cut trachytic Gardar dykes but to be older than some of the dolerite dykes. However it is tempting to equate it with the lamprophyric sill on Tugtutôq which transects the quartz syenites of the late Gardar ring complex as well as numerous trachytic and doleritic dykes. Since the central complex is held to be younger than all Gardar basic dykes in the neighbourhood apart from the lamprophyres there is disagreement with the age relationships adduced from the Julianehåb peninsula.

The sill is excellently exposed on the coast of Mathæus Havn, Igdlukasik island, and this locality was chosen for more detailed study on account of the differentiation exhibited here, and because certain features suggesting late stage development of a vapour phase are of particular interest. The upper-most 2–3 cm in contact with the porphyritic granodiorite country-rock consist of dense black chilled material which grades downwards into a moderately coarse camptonitic dolerite containing small scattered sub-spherical ocelli. Within this otherwise homogeneous upper camptonitic dolerite were observed three differentiated layers, 1–2 cm thick, of a slightly finer grained modification, devoid of ocelli. About 1 m below the upper surface of the sill a more strikingly differentiated layer appears, sharply demarcated from the upper camptonitic dolerite. This layer is 10–12 cm thick and contains larger irregular ocelli with a distinct vertical elongation. These tend to branch as they approach the sharp contact with the upper camptonitic dolerite, (Fig. 2), giving the layer a coral-like aspect. Below this very distinctive horizon is a layer of similar thickness, again possessing unusually large ocelli but with a tendency to horizontal elongation.

Beneath this is camptonitic dolerite which persists unchanged down to the lower chilled contact except for an increasingly laminar arrangement of the constituent minerals parallel to the contact.

PETROGRAPHY

The upper chilled zone (analysed specimen 50069[1]) contains sericitised pseudomorphs after plagioclase suggesting that the magma was already below its liquidus temperature at the time of emplacement. The phenocrysts however are not well differentiated from the groundmass feldspar and the plagioclase of both generations has suffered some deuteric alteration. Small octahedra of ilmenomagnetite are accompanied by brown hornblende and a very little biotite. Radiating bundles of a golden-brown and very slightly pleochroic chloritic mineral enclose small interstitial wedges of calcitic carbonate.

The coarser camptonites below the upper chill (analysed specimen 50068) possess feldspars with strong normal zoning from labradorite cores through andesine to an alkali feldspar. Almost unzoned idiomorphic brown hornblendes attaining diameters up to 1 mm make up nearly one third of the rock. These have a high negative 2V, extinction $Z \wedge c\, 21°$, with X pale yellow brown, Y brown, and Z khaki-brown. (Hornblendes from the Julianehåb sill have nX 1.673, nY 1.683, nZ 1.687, $Z \wedge c\, 15°$ and $2V_\alpha\, 73°$ according to NESBITT, 1961).

The hornblendes commonly enclose slightly pleochroic titanaugites. These show repetitive zonation, marked dispersion and anomalous blue interference colours. Former olivines are represented by pseudomorphs consisting of ramifying veins of serpentine probably formed at an earlier stage in the alteration history than the intervening areas of talc and nearly colourless chlorite. Ilmenomagnetite octahedra are abundant and are found enclosed by both the hornblendes and the pyroxenes but not by the olivine pseudomorphs. Slender crystals of apatite occur throughout and biotite fringes are occasionally developed around the ore crystals. Yellow-green chlorites grow out from the earlier crystals into the interstitial cavities and enclose the latest minerals of which the ocelli consist, namely calcite and at least two zeolites, identified as phillipsite and thomsonite.

The layer with the up-growing 'coralline' ocelli (analysed specimen 50070) has more or less indeterminate feldspar, probably largely potassic

[1]) Numbers refer to specimens belonging to the Geological Survey of Greenland.

Table 1

Analyses of hornblende camptonites from the Skovfjord

	1.	2.	3.	4.	5.
SiO_2	40.72	43.39	41.85	42.63	43.08
Al_2O_3	16.40	16.39	16.09	15.93	15.77
Fe_2O_3	1.78	4.36	1.75	1.53	2.41
FeO	11.45	8.19	11.45	10.09	10.01
MgO	6.23	4.90	6.47	4.84	5.51
CaO	9.25	8.76	9.20	9.34	7.65
Na_2O	3.94	3.68	3.46	4.29	4.33
K_2O	.71	1.80	1.78	2.47	2.51
H_2O+	4.41	2.98	2.94	3.10	4.10
TiO_2	3.92	3.04	3.26	2.98	3.04
P_2O_5	.50	.46	.38	.60	.56
MnO	.20	.24	.22	.23	.23
CO_2	.20	1.64	.91	1.85	.68
S	.20	.25	.21	.29	.16
	99.91	100.08	99.97	100.17	100.04
Less O for S	99.81	99.95	99.88	100.02	99.96

Analyses carried out on material dried at 110° C, 2 hours. Analyses performed at the Geochemical Laboratory, Grant Institute of Geology, Edinburgh.

1. Chilled upper margin of sill on Tugtutôq (No. 30653).
2. Chilled upper margin of sill, Igdlukasik (No. 50069).
3. Upper camptonite, sill, Igdlukasik (No. 50068).
4. Camptonite with dactylitic ocelli, Igdlukasik (No. 50070).
5. Analcite camptonite, Igdlukasik (No. 50071).

oligoclase and alkali feldspar. Hornblende is again the most prominent ferromagnesian mineral, differing from the hornblende of the overlying camptonites in being more acicular in habit, more strongly zoned and having a slightly different colour. The crystal centres have a deep brown absorption colour parallel to Z and zone out to a deep blue-green marginal variety. The extinction angle for the whole crystals is close to 25°. Titanaugite is very scarce and pseudomorphs after olivine are absent. Ore and apatite occur as in the upper rocks. The ocellar cavities make up much of the rock with idiomorphic feldspar crystals projecting into them from the matrix rock as do some of the elongate hornblendes. The central parts of the ocelli are largely of clear analcite surrounding cores of carbonate. The grain size of the crystals in this rock varies widely, the crystals in the ocelli being distinctly larger than in the other rocks of the sill and the crystals in the matrix rock at this level are somewhat smaller than those in the overlying dolerite.

The zone immediately beneath the camptonite layer with the vertically elongate ocelli (analysed specimen 50071) contains a very little

(Table 1 continued)

C. I. P. W. Norms*

		1.	2.	3.	4.	5.
Or		4.65	10.92	10.88	14.92	15.64
Ab		14.79	26.58	12.42	14.60	14.74
An		25.85	23.88	23.77	17.51	16.81
Ne		10.98	2.94	9.65	12.31	12.72
Di		14.08	6.31	12.04	12.35	12.36
Ol		17.29	12.04	18.99	14.43	15.17
Mt		2.66	6.48	2.63	2.39	3.63
Il		7.78	5.98	6.42	5.78	6.02
Ap		1.40	1.04	1.04	1.38	1.35
Cc		.52	3.83	2.16	4.33	1.56
F'spar	Or	10	18	23	32	33
	Ab	33	43	26.5	31	31
	An	57	39	50.5	37	36
Cpx	Wo	51	51.5	51	50.5	51
	En	26.5	31	26	24	27
	Fs	22.5	17.5	23	25.5	22
Ol	Fo	51	61.5	50	46	51
	Fa	49	38.5	50	54	49

* water and sulphur omitted from norm calculations.

titanaugite. The mineralogy is otherwise the same as for the 50071 layer with the ocelli containing analcite and later calcite. From here down the sill grades into rocks almost indistinguishable from the upper camptonitic dolerites from above the 50071 horizon. Specimen 50072 from a few centimetres above the lower contact differs only from 50068 in lacking interstitial carbonate. Specimen 30653, from the upper chill

Table 2

Modal analyses of three camptonite specimens

	50068	50072	50071
Feldspar	41.5 %	42 %	31.3 %
Augite	5.5	8.0	—
Hornblende	30.5	30.5	30.0
Biotite	tr.	tr.	—
Ilmenomagnetite	6.5	8.5	8.5
Apatite	tr.	tr.	tr.
Analcite	tr.	tr.	22.0
Chlorite	14.5	11.0	8.2
Calcite	1.5	—	tr.

Table 3

	A	B	C	D	E	F	G
SiO_2	41.47	45.28	41.15	42.96	44.63	44.67	44.73
TiO_2	3.52	2.79	4.71	3.12	3.20	2.46	2.58
Al_2O_3	16.57	18.72	13.52	14.10	15.15	14.37	14.42
Fe_2O_3	3.10	2.39	5.03	3.37	3.71	4.50	2.93
FeO	9.92	11.21	13.13	6.87	5.00	7.19	9.51
MnO	.22	.24	.25	.18	.18	—	.15
MgO	5.62	6.04	4.12	7.91	6.08	7.02	8.08
CaO	9.09	7.90	7.34	9.78	7.42	9.45	8.31
Na_2O	3.85	3.54	3.53	1.80	4.13	2.99	3.60
K_2O	1.27	.89	1.68	3.55	4.40	1.91	1.96
H_2O+	3.73	.59*	1.26*	2.80	3.59	3.12*	3.12*
P_2O_5	.49	.44	3.13	.53	.72	—	.64
CO_2	.93	—	—	2.3	1.28	1.58	—
BaO	n.d.	—	—	—	.20	—	—
S	.22	.03	—	—	.06	—	—
	100.00	100.06	98.85	99.27	99.75	99.26	100.03

A. Mean of two chilled upper margins (30653 and 50069), Tugtutôq and Igdlukasik.
B. Mean of four gabbro analyses (Tugtutôq, Narssaq, Alángorssuaq and Kûngnât), provisionally taken as approximating the composition of undifferentiated Gardar basalt magma.
C. Hviddal syeno-gabbro, Tugtutôq (30684) (UPTON, 1964b).
D. Camptonite dyke, Qaersuarssuk, S. Greenland. Unpublished analysis, communicated by W. S. WATT. Analyst: B. I. BORGEN.
E. Lamprophyre dyke, Narssaq, S. Greenland. Unpublished analysis, communicated by J. W. STEWART. Analyst: B. I. BORGEN.
F. Average of 78 camptonites (MÉTAIS and CHAYES, 1963).
G. "Initial magma", Black Jack sill (WILKINSON, 1958).

* figures for total water content.

of a similar sill to the north, on Tugtutôq (plate 1 A) was analysed for comparison with 50069.

Petrographic and chemical evidence from the chilled facies of earlier intrusions, whether of trachytic or basaltic magmas, in the Tugtutôq region, has suggested that analyses of these do not give particularly reliable compositions for the initial magma in each case. There is reason to suspect that frequently passage of water from the biotite-hornblende bearing country rocks into the marginal facies of the intrusions has caused oxidation and hydration leading to higher Fe_2O_3/FeO ratios than would be suggested by the uncontaminated intrusive rocks away from the contact zones (UPTON, 1964a, pp. 52 and 57; UPTON, 1964b, p. 14). It, therefore, might have been anticipated that the 50069 chill would have a notably higher ratio than shown by the three analyses from the interior of the sill. This is in fact so, but it is not true in the case of the 30653 chill whose oxidation state as indicated by the Fe'''/Fe'' ratio accords well with those of the three specimens from the more central parts of the Igdlukasik sill, and indeed with those of Gardar gabbros and dolerites in general. (There is ample evidence, from the early precipitation of olivine and the relatively late appearance of ilmenomagnetite in the basic rocks as well as from the remarkable abundance and persistence of ferrous olivines in highly differentiated phonolitic and trachytic magmas genetically related to them, that the 'parental' alkali basalts of the south Greenland province were intruded in a notably reduced condition (Upton, 1964b)). Whatever the reason for this disparity between the two analyses, the ratio of iron oxides for the 30653 specimen is believed to more closely reflect the oxidation state of the initial 'camptonite magma'.

CONSOLIDATION OF THE SILL

The petrography and chemistry of the sill strongly suggest that crystallisation took place primarily against the roof and floor zones and that the ocelli-rich layers of specimens 50070 and 50071 represent the latest magma fraction. Inasmuch as this layer lies a little over half way up the sill it is evident that the growth rate from the floor proceeded at a somewhat higher rate than the corresponding downgrowth from the upper surface. HESS (1960, appendix 2) commenting on the fact that residual fractions in many differentiated sills occur roughly two-thirds of the way up suggested that faster growth up from the floors might be accounted for (a) by the higher hydrostatic pressures at lower levels tending to promote crystallisation, and (b) by the tendency for the cooler magma to be lying close to the floor of the intrusion. HESS considered crystal sinking to be negligible in most small sills. In the present instance, dealing with a very thin differentiated sill, it seems most unlikely that differences of hydrostatic pressure or temperature between the upper and lower parts of the sill could afford the answer. The sill was injected into granitic rocks blanketed by upwards of three thousand metres of Gardar sandstones and volcanics and one may assume the rate of heat loss to have been approximately equal across both upper and lower contacts of the sill. Higher hydrostatic pressure in the case of what was undoubtedly a water-rich magma would have caused lowering rather than raising of crystallisation temperatures. The discrepancies between upwards and downwards growth rates could be easily accounted for by assuming that a small percentage of crystals were nucleating within the magma body and settling to the floor, thereby slightly boosting the rate of growth of essentially solid material upwards from the floor zone.

Data are insufficient to try to account for all the minor layering features exhibited in the sill. The abrupt nature of the layering in the upper part of the sill may imply periodic replenishments or textural control by varying vapour pressure or possibly banding due to 'nucleation' control (WAGER, 1959). The abrupt incoming of large ocelli below the upper camptonitic dolerite with the forked dendritic vertical arrangement suggests the division of bubbles rising through a crystal mush and stopping against fully consolidated upper layers. If so, these bubbles originated at the level of the final residuals at the moment when vapour pressure of water and CO_2 achieved parity with the confining pressure. The sill may have behaved essentially as a closed system with the vapour cavities condensing and ultimately crystallising to yield the analcite-calcite ocelli. Continued late stage lateral movements in the latest phase mush may have caused the horizontal smearing of the ocelli at this level.

The small amount of differentiation exhibited in the sill shows a trend from a camptonitic dolerite towards an analcite hornblende microsyenite. Though limited, it is remarkable that differentiation occurred at all in so small an intrusion and one may presume that a high volatile content in the magma was responsible for prolonging crystallisation over a greater temperature range than was so for the more typical Gardar olivine dolerite intrusions of comparable size as well as reducing the viscosity. Similar differentiation has been recorded within camptonite intrusions from other regions. The striking instance is reported from Arizona by CAMPBELL and SCHENK (1950) of a 4 ft. dyke in which analcite-calcite filled ocelli increase in number and size from margin to centre. At the same time brown hornblende becomes increasingly abundant towards the centre, reaching a size of 4 inches in the median zone. Olivines are increasingly pseudomorphed from margins to centre. The authors interpret the occurrence as indicating concentration of primary magmatic CO_2 and water as crystallisation proceeded from the contacts inwards, with the central zone crystallising through a range of perhaps 800–200°C within an estimated 25 days of cooling. RAMSAY later (1955) described in detail the case of a 3 ft. Scottish dyke in which, from the black chilled margins to the coarsely crystalline centre, ocelli of analcite-phillipsite increase from zero to ca. 60 %. Hornblendes become increasingly important and the plagioclases become more sodic along the slightly more alkalic dyke centre. A larger scale case of a differentiated camptonite is known from the Okonjeje complex of Damaraland (SIMPSON, 1954) in which crystal settling may have played a part. The lower part of a stock-like intrusion has zoned olivine (Fa_{12-20}), augite, hornblendes and some 10 % of feldspathoids. This is overlain by more leucocratic rocks having higher Si, Na, K, H_2O and CO_2 in which interstitial calcite and analcite are prominent.

PETROGENESIS

Many authors have stressed the close field and chemical association of the camptonitic lamprophyres with olivine basalts. VINCENT (1952) considered normal fractionation processes adequate in explaining genesis of East Greenland Tertiary camptonites from basalt, by way of oligoclase basalt. Similarly WOODLAND (1962) favoured a basalt crystal-fractionation hypothesis, leading to an alkali undersaturated late magma. RAMSAY (1955) and GALLAGHER (1963) likewise noted the close relationship of the Carboniferous Scottish camptonites to the alkali olivine basalt magma of the Scottish Carboniferous province. In the intrusions under discussion, close kinship of the camptonite magma to the basalt magma intruded as dykes, ring-dykes, sills and extruded as the Gardar plateau series is scarcely to be doubted. Both the normal dolerites and the camptonites tend to be distinctive from those of other areas in having relatively high alumina but low magnesia and in possessing rather high FeO/Fe_2O_3 ratios although admittedly the distinctions from the East Greenland lamprophyres described by VINCENT are very slight. However, the normal differentiation trend for the Gardar basalts, attendant on fractionation of olivine and plagioclase, is towards magma fractions with fast rising Fe/Mg ratios and with the crystallisation of brown hornblende postponed until after the appearance of monoclinic alkali feldspar. In other words the gabbro and syeno-gabbro crystalline products are normally amphibole-free and hornblende first makes its appearance in the (larvikite) syenite and subsequent lower temperature assemblages. The camptonites by contrast are hornblende-bearing basic rocks with iron/magnesium ratios little different from those of the undifferentiated doleritic and gabbroic rocks. They have calcium contents higher than the supposedly parental basalts and were sufficiently rich in water and CO_2 as to ensure the early precipitation of amphibole and the abundant late crystallisation of zeolites and carbonate. The crystallisation sequence in what is understood to be the 'normal' cooling history of the Gardar basalt type (UPTON, 1964b. p. 44) is believed to have commenced at depth with the precipitation of first(?) plagioclase closely followed by(?) olivine in equilibrium with magma (L). Thus, with declining temperatures:—

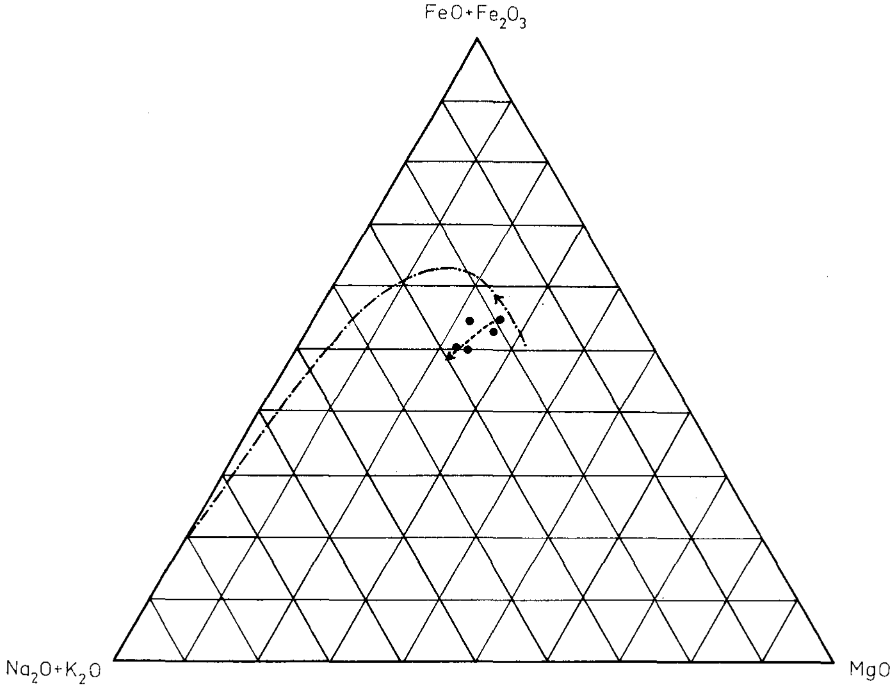

Fig. 3. Iron-alkali-magnesium diagram for the five analysed camptonites indicating the apparent divergence of their fractionation trend from the generalised fractionation trend for gabbroic, syenogabbroic and syenitic rocks in the district.

F'spar + Ol + L
F'spar + Ol + Mt + L
F'spar + Ol + Mt + Cpx + L
F'spar + Ol + Bi + Cpx + L

The feldspar in this sequence was initially a sodic bytownite zoning through oligoclase to anorthoclase and sanidine. Analcite appears restricted to the crystallisation of low temperature phonolitic residues and small amounts of supposedly primary carbonate have been recorded from both quartz syenites and foyaites thought to have been derived ultimately from the alkali basalt by strong fractionation. The crystallisation scheme for the camptonites, as deduced petrographically, contrasts strongly with this. Plagioclase, olivine, magnetite and(?) clinopyroxene were relatively early phases all of which may possibly have been crystallising at the time of intrusion, although their relative order of appearance is indeterminate. Amphibole followed the pyroxene at a comparatively early stage when plagioclase was still precipitating. Biotite is later than, and has a reaction relationship to, the magnetite and it is apparently earlier than the chlorite. Chlorite, analcite, calcite and phillipsite crystallised after the virtual completion of magnetite, amphibole and feldspar separation in approximately the order listed.

The chief differences from the crystallisation of the more typical 'dry' olivine basalt magma lies in the precocious appearance of hornblende and the conspicuous late stage assemblage of the ocelli. The contrast between the two situations resembles the contrasts noted experimentally by YODER and TILLEY (1962) for the crystallisation of basalts under anhydrous and hydrous conditions. Of the basalts used by YODER and TILLEY in their experiments, those having the most in common with the Gardar basalt type are the Hualalai alkali basalt (65992) and the Warner basalt from the Medicine Lake Highlands (127 ML 295). However it should be noted that neither of these conforms closely to the south Greenland basalt type. The Warner basalt is a hypersthene-normative basalt with relatively high Ca and Mg. The Hualalai basalt is a nepheline-normative basalt with 14.31 % Al_2O_3. The undifferentiated 'primitive' Gardar basalt is a high-alumina nepheline-normative basalt with Mg and Ca notably lower than the other two types.

Anhydrous runs at atmospheric pressure on these two basalts showed the appearance of olivine, plagioclase, chrome-spinel, magnetite and clinopyroxene in the following order:—

(a) *Warner basalt*	(b) *Hualalai basalt*
Ol + Pl + Ch.sp + L (1,225°C)	Mt + L (1.250°C)
Ol + Pl + Mt + L	Ol + Mt + L
Ol + Pl + Mt + Cpx + L	Ol + Pl + Mt + Cpx + L

whereas hydrous runs, at 2000 bars H_2O gave the following order of appearance for magnetite, olivine, clinopyroxene, amphibole and pseudobrookite:—

(a) *Warner basalt*	(b) *Hualalai basalt*
Mt + L (1,150°C)	Ol + Mt + L (1,100°C)
Ol + Mt + L	Ol + Mt + Cpx + L
Ol + Pl + Cpx + Mt + Psb + L	Mt + Cpx + Am + L
Pl + Mt + Am + L	Pl + Mt + Am + Bi

In view of the mineralogical similarity of the camptonites to the synthetic amphibolites produced by YODER and TILLEY further support is found for the contention that camptonites result from crystallisation of water-rich basalt fractions.

It has been estimated that the area under consideration was mantled by some 3 km of basalts and sandstones at the time of the late Gardar intrusions, corresponding to a confining pressure of at leat 12,000 psi. Utilising the data presented by YODER and FAWCETT (1963) on the stability limits of analcite and those of YODER and TILLEY (1962) on the naturala lkali basalt—water and natural high-alumina basalt—water systems for the pressure range 12,000—15,000 psi it would be expected that the amphibole would have commenced crystallisation around 970–1000° C and the analcite at around 540–550° C *if* the magma had been water saturated at the time of intrusion. Water saturation, however, was only achieved when the ocelli began to develop, in other words at the stage at which it is thought that a water-rich vapour phase separated. Hence the analcite may well have crystallised from water-saturated magma at the temperatures experimentally indicated but the amphibole, separating from a non-saturated magma, may not have appeared until a temperature substantially below 970° C.

Teschenite magmas contrast with camptonitic magmas in that though they too represent a type of hydrous alkali basalt they show no evidence of significant CO_2 enrichment. In the numerous examples of differentiated teschenite sills and laccoliths to be found in the literature crystallisation of brown hornblende is either suppressed until late in the cooling history or is inhibited entirely, whereas analcite may make an appearance at a relatively early stage. The 'initial magma' composition for the 500 ft. thick Black Jack teschenite sill of New South Wales (WILKINSON, 1958) is very similar to the average camptonite composition quoted by MÉTAIS and CHAYES (1963) (see table 3). As in the Tugtutôq-Igdlukasik sill differentiation took place by crystal growth inwards from the contacts displacing the residual magma which tended towards an analcite syenite. In the Black Jack sill there is an increasing coarseness of grain size with advancing crystallisation and the latest phases to appear include iron-rich chlorite, analcite and other zeolites with some iron-rich carbonate. Apart from its much greater size the chief dissimilarity between this fairly typical teschenite sill and the camptonite sill described above lies in the crystallisation of amphibole at a relatively early stage in the latter and the long range through which olivine was unstable.

The camptonites appear to be restricted to very small intrusions whose crystallisation behaviour approaches that of water-saturated basalt systems and the problem of their genesis largely resolves itself to a search for possible sources of the volatile additives. BARTH (1952) expressed the view that amphibole production in lamprophyres may result directly from the influx of water from the wall rocks of the intrusion. Marginal entry of volatiles may well have been commonplace with the more anhydrous Gardar intrusions, but this can scarcely be the explanation for the production of the camptonites. The latter are scarce and are limited to few intrusive episodes in the Gardar. Their chemistry suggests that if they *are* simply normal Gardar basalt magma augmented by volatile material, this cannot have consisted solely of water. Any such diluent to the basalt magma must have been a water-carbon dioxide rich liquid carrying alkalis and possibly calcium and only relatively small magma batches may have been modified in this manner. The possibility of CO_2 derivation from limestone has been considered by some authors but, as for the hypothesis of nepheline syenite genesis by syntexis of limestone, this is exceedingly unlikely in the present case where the camptonites are intruding granites of batholithic aspect. However rocks of kimberlitic and carbonatitic affinity occur within the region and there is the possibility that fugitive volatile fluids from intrusions of this type at depth may have become dissolved in basalt magma. Some of the nepheline syenites and quartz syenites of the region can be shown to have yielded late stage crystallisation residuals rich in water, carbon dioxide and alkalis which likewise might have caused small scale modification of the alkali basalt magma towards the camptonite type. Tholeiitic basalts probably rarely, if ever, yield camptonite derivatives. Yoder and Tilley's hydrous experiments on olivine tholeiite (Kilauea) showed the amphibole crystallisation at 1200–1500 psi to be 60–80° lower than for the high aluminous and alkali basalts under similar conditions. Furthermore Saha's data on analcite stability (Saha, 1961) show that in the water-saturated 'alkaline' system $Na_2Al_2Si_3O_{10}$-H_2O analcite is stable to about 510° in this pressure range while this upper limit is lowered to ca. 350°C in the silica-saturated $NaAlSi_3O_8$-H_2O system. These results suggest that the temperature of crystallisation of amphibole and analcite would be appreciably lower in a wet tholeiite than in a wet alkali basalt and that there is correspondingly less chance that they would develop before complete solidification.

The apparent absence of teschenitic intrusions from the Gardar province is in itself a matter of some interest. Teschenitic crystallisation may perhaps result from alkali basalt magmas rather drier than those of the camptonites cooling under low pressure conditions. In such circumstances the stability curves for analcite and hornblende may cross with hornblende appearing (if at all before complete solidification) after a relatively high water concentration had been attained by the crystallisation of anhydrous phases and after the first appearance of analcite. Possibly the critical conditions necessary for teschenite development failed to occur in the south Greenland Gardar as a result of the confining pressures being too high at the present erosion level.

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Plate 1

A. Camptonite sill on Tugtutôq cutting porphyritic granodiorite.

B. Horizon in the sill at Mathæus Havn containing vertically elongate calcite and analcite-rich ocelli.

A.

B.