SYNOROGENIC ALKALINE PYROXENITE DYKES ON SEILAND, NORTHERN NORWAY

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Alkaline titanaugite pyroxenite dykes occur in at least two areas on the island of Seiland in northern Norway. A detailed examination of the smallest of these complexes has revealed that the alkaline activity was syntectonic with respect to an early phase of the Caledonian orogeny and that the pyroxenites were emplaced during the progress of Barrovian amphibolite facies metamorphism. The dykes themselves are coarse-grained or pegmatitic, often composite, and commonly variable in both mineralogy and texture. Typical is the intimate association of apatite-magnetite-ilmenite pyroxenite and titanaugite syenite, both rock types being considered the result of the fractional crystallisation of a single mela-syenitic magma actively moving through a series of interconnected fissures. Fenitisation of the host gabbroic rocks involved either the addition of water and the formation of hornblendites or a series of changes resulting in a paragenesis resembling that of the intrusive pyroxenites.

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Dyke rocks found in two complexes on the island of Seiland contain the following principal minerals: titanaugite, ilmenite, magnetite, apatite, and amphibole together with accessory amounts of felspar and calcite. According to Washington (1901), such rocks, composed mainly of titaniferous augite and iron ore with little or no nepheline, can be classified as jacupirangites. This term was originally applied to magnetite clinopyroxenites transitional to nephelinites and ijolites (Derby 1891) and in modern usage jacupirangites are the ultramafic members of the melteigite-ijolite-urtite 'series' (Von Eckermann 1948, Strauss & Truter 1950, Butakova 1961, Wilkinson 1967). The Seiland magnetite-ilmenite-apatite clinopyroxenites are, however, transitional to a suite of coarse-grained and pegmatitic dyke rocks including melanocratic to mesotype sodic syenites (the 'shonkinites' of Sturt & Ramsay 1965), leucocratic to ultraleucocratic syenites, and carbonatites (the 'shonkinitic' suite of Robins 1972a). Although they are undersaturated, none of the members of this suite contain modal felspathoids. Sturt & Ramsay (1965) recorded mafic assemblages typical of peralkaline syenites in rocks described as shonkinites and leucocratic syenites in the Breivikbotn alkaline complex but, chemically, the suite is metaluminous according to the definition of Shand (1947). The pyroxenite dykes of Seiland are, therefore, unlike the true jacupirangites in their associations, but their chemistry is similar to them and such that there can be no doubt that they can be described as alkaline (Table 1).

Table 1. Analyses of two alkaline pyroxenites from Seiland and jacupirangites from Jacupiranga and Magnet Cove.

	1	2	3	4
SiO_2	35.4	44.2	38.4	35.4
Al_2O_3	7.2	7.6	7.0	9.2
TiO_2	4.0	1.7	4.6	4.0
Fe_2O_3	11.3	4.7	9.0	8.9
FeO	14.5	11.2	6.2	7.2
MgO	6.2	6.7	11.6	7.8
CaO	16.9	18.6	19.0	20.8
Na_2O	2.0	2.0	0.7	1.5
K_2O	0.3	0.5	0.7	0.6
MnO	0.5	0.5	0.3	0.3
P_2O_5	1.3	1.0	0.8	2.2
H_2O+	0.2	0.3	0.3	1.0
CO_2	n.d.	n.d.	0.3	0.1
	99.8	99.0	98.9	99.0
C.I.P.W. Norms				
or	—	2.8	—	–
ab	–	2.7	—	–
an	10.0	10.2	13.7	17.0
lc	1.3	—	3.5	2.6
ne	9.1	7.9	3.4	6.5
di	45.6	62.0	44.6	37.2
ol	3.1	0.5	5.7	1.5
cs	3.3	—	5.6	7.4
mt	16.5	6.8	7.8	11.1
hm	—	—	3.7	1.3
il	7.6	3.2	8.6	7.6
ap	2.7	2.3	1.9	5.0

1. Apatite-ilmenite-magnetite pyroxenite, Seiland (179).
2. Felspar-bearing apatite pyroxenite, Seiland (167).
3. Type jacupirangite, Jacupiranga, Brazil (Washington 1901).
4. Jacupirangite, Magnet Cove, Arkansas, U.S.A. (Erickson & Blade 1963).
1 & 2: Major elements were determined by XrF in the Department of Earth Sciences, University of Leeds, England; FeO, Na_2O, K_2O and H_2O+ by classical methods. Analysts amanuensis M. Tysseland and vit. ass. K. Iden, Universitetet i Bergen.

This account of the geology and petrography of the Kræmmervik complex (Fig. 1), the smallest, and most clearly exposed, of the two known dyke complexes of Seiland involving the 'shonkinitic' suite, represents, as far as the author is aware, the first description of alkaline pyroxenites emplaced into an orogenic environment. Such rocks are normally thought of as occurring exclusively within cratogenic areas, often directly associated with alkaline volcanic fields. Carbonatite, another rock type normally considered axiomatic of stable tectonic conditions, has already been described as a synorogenic intrusive phase from several localities in the Seiland province – from Stjernøy (Strand 1952, Heier 1961), Sørøy (Sturt & Ramsay 1965), and Seiland itself (Robins 1972a). The latter account first noted the presence of 'jacupirangite' on the island of Seiland, but Oosterom was possibly
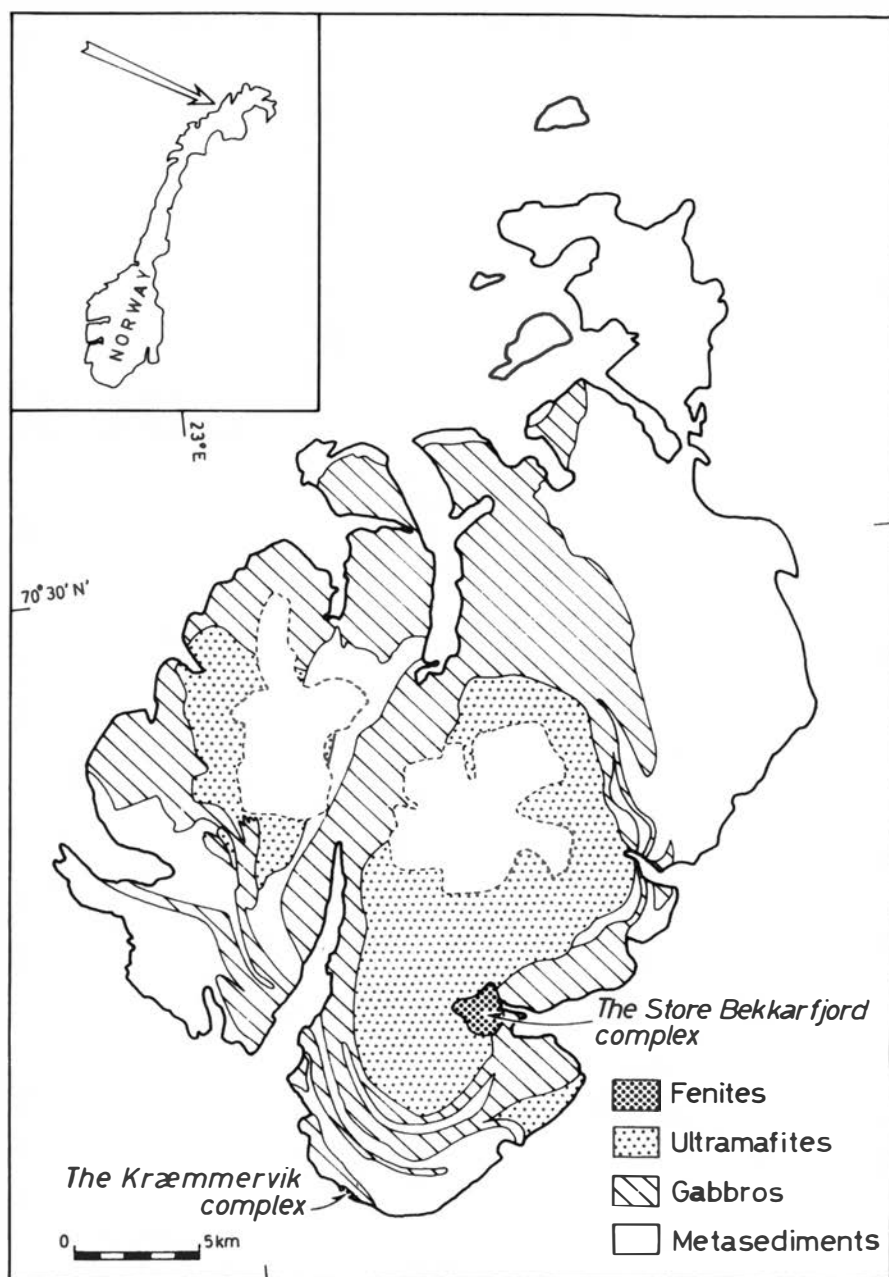
Fig. 1. General geology of Seiland showing the location of the Kræmmervik and the Store Bekkarfjord complexes. Map compiled from Worthing (1971), Robins (1971) and unpublished results of B. Jackson, B. A. Sturt and D. Speedyman.

the first to locate a dyke of this rock type, later (1963) described as an apatite-rich hornblendite, during a reconnaissance of the Store Bekkarfjord complex (Fig. 1). Oosterom (1954, 1963) also briefly described the effects of

metasomatism in this complex, but these were only subsequently related to the emplacement of alkaline pyroxenites (Robins 1972a).

The environment of the alkaline activity

The psammitic metasediments of the southern part of Seiland, which are presumed to be of Eocambrian-Cambrian age, were complexely deformed during two main periods of early Caledonian tectonic movement (D_1 and D_2), each punctuated by episodes during which gabbros and peridotites, the characteristic rocks of the province, were emplaced. The injection of large volumes of basaltic magma took place in three main episodes: syn-D_1, syn-D_2 and post-D_2 (Robins 1971). Lesser amounts were emplaced in the period between D_1 and D_2, during which the Barrovian regional metamorphism reached its almandine-amphibolite-facies peak, an event dated as having occurred about 530 m.y. ago (Pringle & Sturt 1969). The extensive peridotite occupying the central regions of Seiland was emplaced at a late stage in the second period of deformation and in some places shows layering analogous to that of the syn-D_2 gabbros. The latter show the effects of strong deformation as a gneissosity, which usually parallels the primary rhythmic layering. This planar structure and the D_2 schistosities of the metasedimentary host rocks are disposed about an extensive synform which controls much of the outcrop pattern of the island of Seiland. The formation of this structure was postdated by the emplacement of the post-D_2 gabbros, the alkaline rocks and carbonatites, in that order. The second period of deformation took place whilst the metamorphism waned in intensity, but amphibolite facies conditions nevertheless extended long enough to affect the post-D_2 gabbros. Evidence of the regional grade during the emplacement of the alkaline rocks will be reviewed later. The individual members of the suites of alkaline rocks were affected by a late phase of the Caledonian diastrophism which resulted in the local development of strong schistosities, essentially limited to the dykes in which these rocks occur and their immediate environs.

The detailed tectono-thermal and intrusive history of the Kræmmervik complex, taken in isolation, can only be directly related to more widespread events by the known timing of the penetrative deformation of the host syn-D_2 gabbro. On a regional scale it has, however, been established that the 'shonkinite' suite was emplaced during one of the latest phases of intrusion, individual dykes being found in the post-D_2 gabbro intrusions. Crosscutting relationships also indicate that this suite predated both the biotite-magnetite syenite and the felspathoidal syenite suites of Robins (1972a). The intrusive relationships within the Kræmmervik dyke complex demonstrate that the members of the 'shonkinite' suite were emplaced in two discrete episodes separated by the intrusion of basic magmas (Fig. 2). The alkaline pyroxenite, together with the intimately associated titanaugite syenite, were the first members to be intruded. They occur as often dilational and usually steeply-dipping dykes not more than about 30 cm in width (Fig. 3), invariably cut
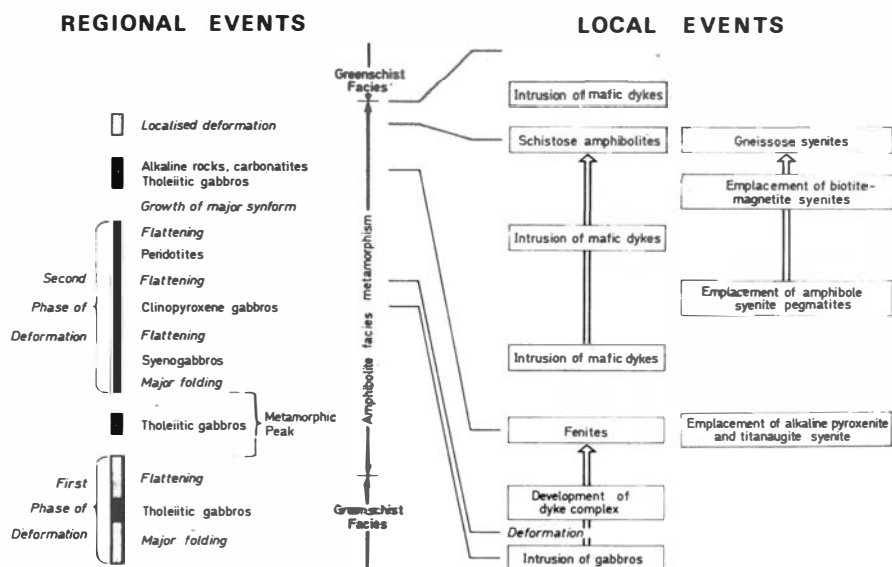
Fig. 2. Summary of the tectono-thermal and intrusive history of Seiland and the evolution of the Kræmmervik alkaline complex.

Fig. 3. Dilational apatite-rich alkaline pyroxenite dyke sharply cutting through variably fenitised gabbro and dyke rocks.
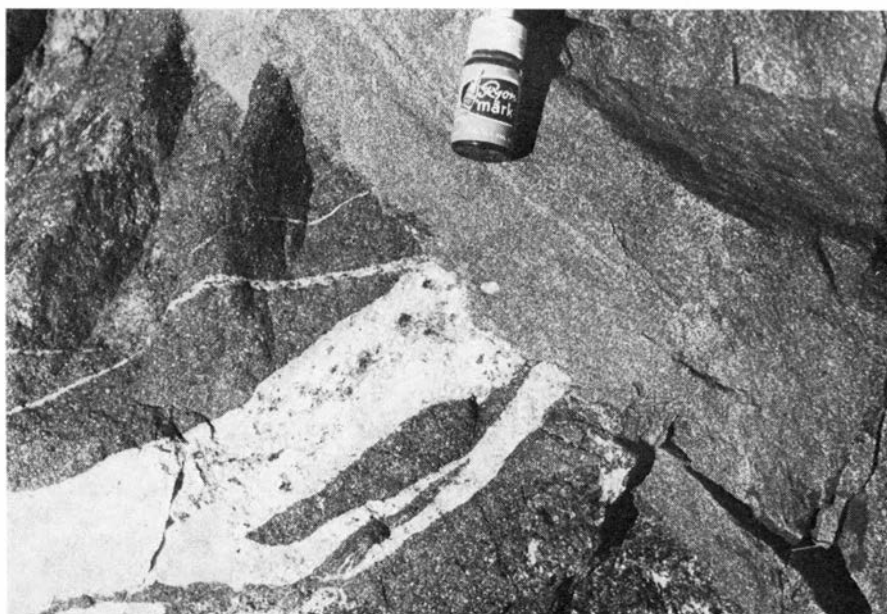
Fig. 4. Amphibole syenite dykelets and fenites crosscut by a deformed gabbroic dyke.

by the amphibole syenite dykes. It can be observed that different alkaline pyroxenite dykes have crosscutting mutual relationships, implying at least three phases of emplacement.

The members of the shonkinite suite emplaced subsequently to the alkaline pyroxenites and the associated syenites contain an amphibole, hastingsite or ferrohastingsite, as the dominant mafic mineral, in contrast to the titanaugites of the earlier phases. These mesotype to leucocratic amphibole syenite dykes frequently show the effects of strong, but localised, deformation and subsequent recrystallisation. The main effect was the breakdown of the primary coarse-grained or pegmatitic fabrics and the development of intense gneissic foliations which, as a rule, parallel the dykes' walls. In the most advanced stages of deformation, the intrusive contacts are destroyed and the host rocks may become tectonically interleaved with the syenite gneiss. Together with the foliation, strong sub-horizontal lineations defined by both felspar and amphibole are often developed, their orientation reflecting the translations achieved across the deformed zone.

It can be demonstrated in the field that the emplacement of the hastingsite syenite dykes was both immediately pre- and post-dated by the intrusion of basic (gabbroic) dykes which were later involved in the local phase of deformation. The earliest of these cut through both the alkaline pyroxenites and the titanaugite syenites, but are transected by the amphibole syenites. At least two phases of intrusion of basic magma seem to be represented in this episode. The later dykes dilate the amphibole syenites (Fig. 4), but were themselves cut by thin biotite-magnetite syenite pegmatites before the onset

of the deformation. The latter affected the whole complex, though the development of planar tectonic fabrics is mainly restricted to the dyke rocks. The alkaline pyroxenites and titanaugite syenites are, however, less deformed than the later syenites and basic dykes and, therefore, may appear at first glance to be late in the intrusive sequence. The latest phases of injection in the complex are, in fact, represented by a further series of gabbroic dykes. These are relatively numerous, possess no tectonic fabric, are dilational in form, and crosscut highly gneissose examples of amphibole syenite.

The various sets of mafic dykes within the Kræmmervik complex show metamorphic assemblages diagnostic of the regional grade during the emplacement of the 'shonkinitic' suite. Those dykes affected by the late-stage deformation, usually contain a penetrative schistosity and few relicts of the primary mineralogy or texture. The majority are fine grained schistose amphibolites containing the assemblage:

hornblende ± oligoclase–andesine + diopside + biotite + calcite

indicating syn-kinematic metamorphism in the almandine-amphibolite facies. The youngest mafic dykes have retained a large proportion of the primary gabbroic mineralogy and texture in an arrested stage of replacement by the assemblage hornblende + andesine + calcite, demonstrating that amphibolite-facies conditions had persisted for some time after the deformation of the alkaline rocks. Since the highest grade reached in the area was in the D_1-D_2 metamorphic episode when sillimanite, orthoclase, and garnet were developing in the metasedimentary rocks of appropriate composition, and the second period of deformation was accompanied and succeeded by amphibolite-facies conditions, it seems quite certain that the 'shonkinitic' suite in the Kræmmervik complex was emplaced, as well as deformed, under conditions equivalent to those of the Barrovian amphibolite facies.

The mineralogies developed within the alkaline rocks during their deformation and subsequent recrystallisation depended essentially on the different chemical environments represented. In the leucocratic sites of the amphibole syenites, the deformation resulted in the straining and kinking of the primary antiperthites, whilst the post-kinematic annealing produced a polygonal mosaic of albite crystals with potassium felspar located along grain boundaries and concentrated at triple point junctions. Annealed aggregates of calcite co-existed with the alkali felspars, the absence of a more anorthite-rich plagioclase being possibly due to a lack of aluminium. The recrystallisation of deformed amphibole-bearing assemblages in the syenites was, however, quite different. In this case, reactions took place which led to the formation of granular coronas between the amphibole and the alkali felspar which include the minerals oligoclase, biotite, clinopyroxene, and ores. These minerals, together with the excess amphibole, form a syntectonic assemblage in some amphibole-rich parts of the syenites. In the alkaline pyroxenites and titanaugite syenites, there is no sign of instability in the primary amphibole, instead, metamorphic amphibole developed during the subsequent thermal history. The primary plagioclase also underwent recrystallisation in some

places, and the paragenesis is, therefore, that expected for basic and ultra-basic rocks during amphibolite-facies metamorphism.

All the components of the Kræmmervik complex were cut at a late stage by joints occupied by the minerals epidote, albite, calcite, and quartz. Else-where in the neighbourhood of the complex, similar veins are associated with the development of the assemblage albite + epidote + biotite + chlorite + calcite in the gabbroic country rocks which normally retain evidence of the primary mineralogy partially overprinted by amphibolite-facies assem-blages. The veins resulted from hydrothermal activity associated with the establishment of greenschist facies metamorphism in the area at an extreme-ly late stage in the Caledonian tectono-thermal cycle.

Petrography of the alkaline pyroxenites and melanocratic syenites

Primary textures and relationships are, generally, well preserved within the alkaline pyroxenites; tectonic strain being concentrated in places containing high percentages of ductile iron-titanium oxides. Sharp intrusive contacts are normally developed between the dyke rocks and the strongly fenitised hosts, but chilled zones are never present. There often is, however, a sharp decrease in the grain size from the coarse-grained or pegmatitic fabrics of the core within a few millimetres of the dyke walls. On average, the dykes are around 14 cm thick, about 30 cm being the maximum width. On the other hand, within the small area represented by the Kræmmervik complex, they are numerous and can be traced laterally across wave-washed surfaces for distances of up to 10 metres. In this distance, the dykes may wedge out, send out thin apophyses, bifurcate, change their internal character, and pos-sibly change their general form from being distinctly dilational to rather ir-regular. Entirely characteristic of the dykes is, however, a composite struc-ture in the non-genetic sense of Thomas & Bailey (1924), involving either the intimate association of pyroxenite with melanocratic and, to a lesser de-gree, mesotype titanaugite syenite or with texturally and mineralogically dis-tinct types of pyroxenite. Also distinctive is a comb-structure, defined by the subparallel orientation of titanaugites and/or apatites, which is usually well developed in zones along the dyke walls.

Several combinations of rock types have been noted from individual com-posite dykes, the simplest combination being that of apatite-rich pyroxenite outer zones with a core consisting almost exclusively of ilmenite and apatite (Fig. 5). The apatite crystals in the outer zones of these dykes are highly elongated parallel to their c-axes which are, in general, orientated at right angles to the contacts. Virtually every apatite in these, as in the other types of dyke, lacks a core; a rod of titanaugite or one of the other minerals runs down the central part of each crystal. These skeletal crystals are partly en-closed within large clinopyroxenes, forming either subhedra or euhedra, which are themselves surrounded by granular ores and apatite. The marginal
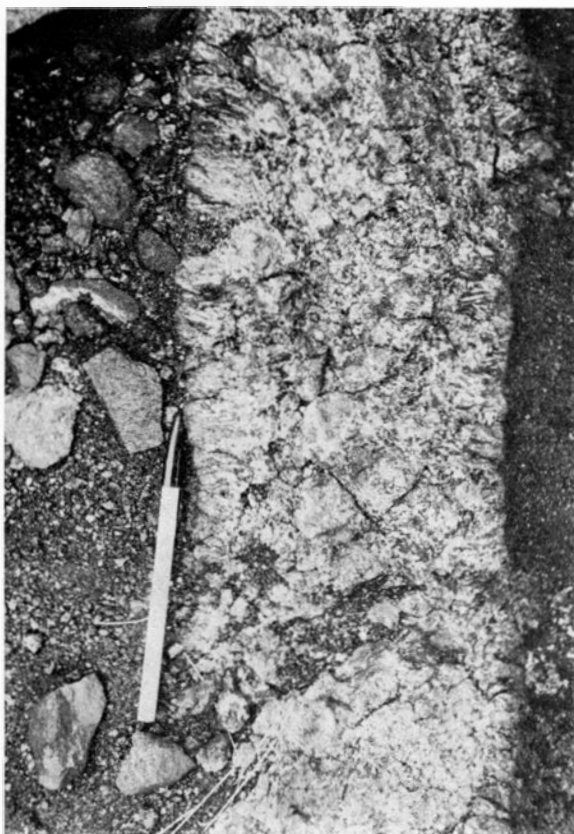
Fig. 5. Composite alkaline pyroxenite dyke with sub-parallel skeletal apatite crystals in the wall zones and a core zone consisting almost exclusively of ilmenite, magnetite, and apatite.

zones thus are more or less clearly porphyritic, though this feature may be obscured in those places containing large quantities of subparallel apatite crystals. The core is distinguished only by the lack of both pyroxene and a parallel orientation of apatite prisms, and its contact with the outer zones is irregular, being defined mainly by the crystal faces of the titanaugites. It is, in fact, not sharply defined, the core being continuous with the matrix of the outer zones.

In other dykes, the place of the ore-rich core is taken by a pyroxenite consisting of a fine-grained ultramafic matrix enclosing titanaugite euhedra (Fig. 6). The latter are striking in appearance, though often quite widely spaced. These porphyritic cores are usually poorer in apatite and often also in ilmenite than the surrounding rock; the apatite may also be much less e-longate and relatively unorientated, but still skeletal. Patches within this type of core may, however, be rich in ores and thus closely resemble in composition the rocks developed against the walls. The main contrast is a tex-tural one; the fine-grained matrix of the core with its granular or random fabric being very unlike the coarse-grained margins in which both apatite and clinopyroxene may have their long axes at right angles to the contacts.

Fig. 6. Alkaline pyroxenite dyke consisting of a fine-grained core enclosing large titanaugite crystals and coarse-grained wall zones rich in skeletal apatite. The central pyroxene measures about 5 cm across.

Many of the dykes in the complex show a porphyritic pyroxenite core, but differ from those described above in the character of the rocks forming the margins. In many cases, this material consists of pegmatitic titanaugite syenite containing variable amounts of both alkali felspar and apatite. The majority of the pyroxenes in this rock type are again subhedral or euhedral, and they may be concentrated at the dyke walls and define a comb-structure. They are, however, distinctive in apparently enclosing irregular patches of felspar or calcite which, because they become more numerous towards the edges of the crystals, may impart a curious ragged appearance. Despite their different texture, there seems no reason to doubt that these particular clinopyroxenes are anything but magmatic in origin. Apatite is usually not a voluminous mineral in the syenites, indeed its abundance seems to vary anti-pathetically with that of felspar, so that with an increase in the amount of apatite, syenite wall zones may pass laterally into apatite-rich pyroxenite zones like those described above; the interstitial role of the felspar in the one place is taken by granular apatite in the other. The ore minerals, which are also a minor component of the titanaugite syenite zones, figure as pro-minently in the pyroxenite wall zones as usual. This type of transition, when
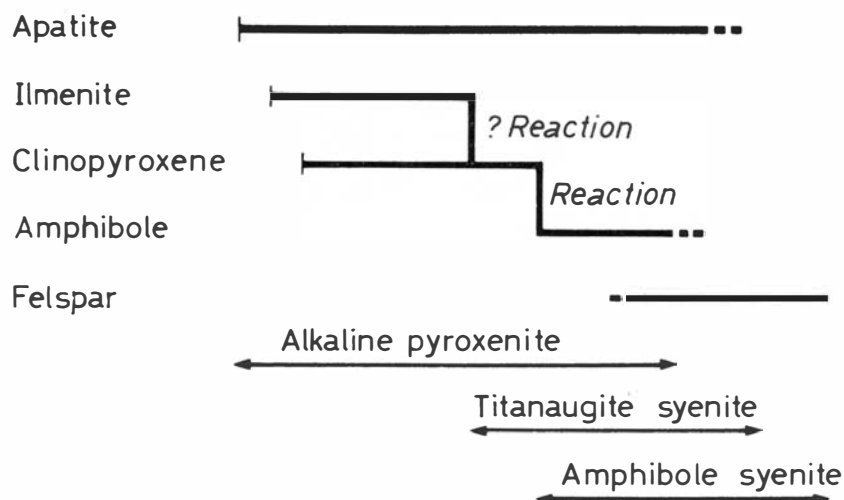
Fig. 7. Sequence of crystallisation and mineral variation in the alkaline rocks of the Kræmmervik complex.

occurring in the wall zones, it not necessarily accompanied by any change in the character of the porphyritic material occupying the core of the dyke, though this may itself be impersistent along the length of the body. If, however, such a transition occurs in one wall zone, it invariably also takes place in the opposite zone.

Exactly analogous lateral variation can be observed within dykes which lack a core of porphyritic pyroxenite. In their most mafic portions they are pyroxenitic, with long hollow apatites orientated normal to the walls and enclosed within large titanaugite anhedra or subhedra which are separated by patches rich in more granular apatite. In other places, a typical syenite mineralogy is developed with large pyroxene individuals enclosed within a felspathic matrix. Some sites show, however, characteristics intermediate between these two end points, with pyroxenes packed tightly together along the dyke walls becoming euhedral against the felspar occupying the centre. Close to the walls these pyroxenes may enclose subparallel apatite prisms.

The textural observations carried out on thin sections confirm the field investigations made on the dykes themselves and extend the intimate relationship between the pyroxenites and the dark syenites to the microscopic scale. The general order of crystallisation of the main minerals is fairly constant in all the various rock types involved in the dykes (Fig. 7). Apatite is clearly one of the earliest phases, though it probably also formed simultaneously with all the others, and is usually followed by clinopyroxene, the oxide minerals, then amphibole, and, finally, felspar. In detail, however, there are variations from this series, as well as ambiguities, particularly in the relationships of the ilmenite and magnetite. In some cases, an early generation of ilmenite preceded and accompanied the growth of the pyroxene but, in
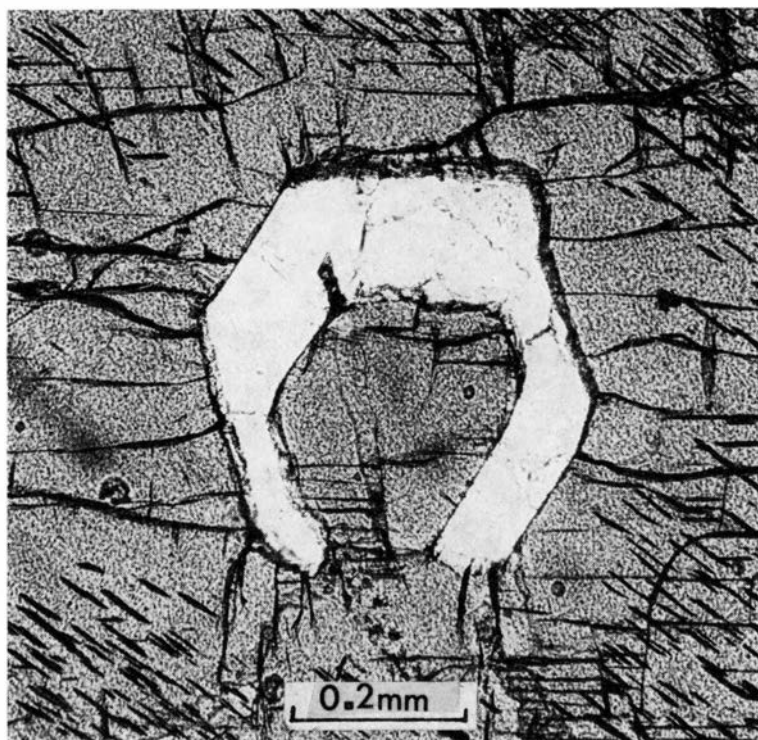
Fig. 8. Basal section of a skeletal apatite poikilitically enclosed within titanaugite (sample no. 179).

others, it seems that the oxides had a reaction relationship with the residual liquids crystallising plagioclase, which involved the formation of further clinopyroxene. The main generation of the ores, however, post-dated that of the pyroxene and preceded the nucleation of plagioclase crystals.

The relatively undeformed apatite, in almost every case, forms elongated prisms with or without pyramidal terminations, which are occupied internally by the minerals which occur, usually poikilitically, in the immediate vicinity, either pyroxene, amphibole, ilmenite, magnetite, or plagioclase. The shape of the interior of the apatites may be of negative crystal form, cylindrical, or rather irregular, whilst the surrounding shell may be complete, open ended, or lacking one or more prism faces (Fig. 8). One variety of open-ended apatite has an interior which flares towards one end of the prism in a trumpet-like fashion. Platey inclusions of a highly birefringent mineral (?monazite) are commonly enclosed within the apatite, and are orientated in symmetrically arranged planes paralleling the c-axis. In the silicate-rich locations, deformation has affected the apatite crystals only to the extent of the formation of sub-grain boundaries, though the rotation across these may be large. Within deformed ore-rich sites, on the other hand, the apatite prisms are highly strained, fractured, and even folded. During the flowage of the surrounding oxides, many apatite crystals underwent intensive
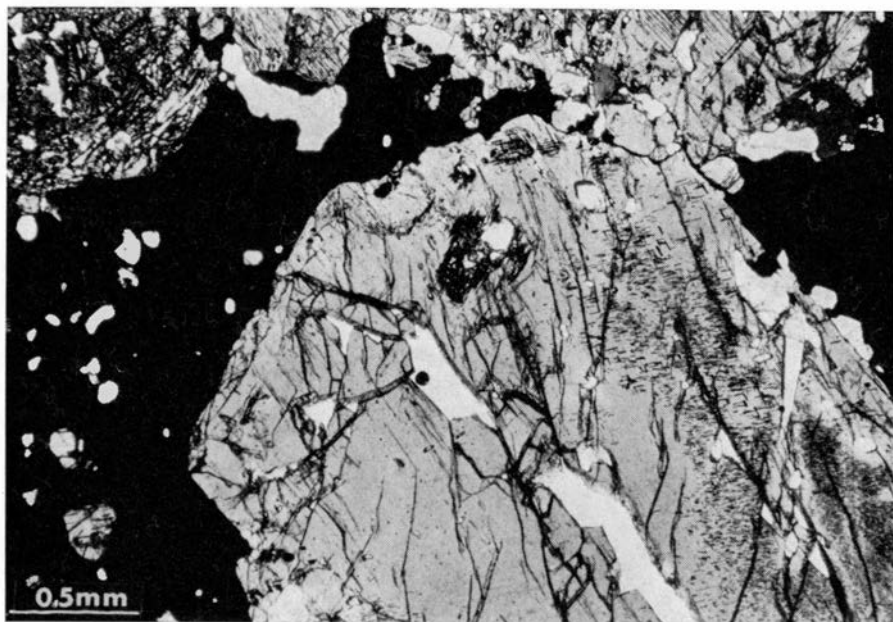
Fig. 9. Large titanaugite phenocryst enclosed within a finer grained and rather granular aggregate of ilmenite, apatite, and some pyroxene (sample no. 179).

fracturing and the developing fractures were occupied by ores as the individual fragments were stretched apart along the foliation.

The clinopyroxene occurs in several textural forms:

Large euhedral or subhedral crystals often showing zoning and twinning (Fig. 9);

Small anhedra, either derived from the recrystallisation of the first or of primary origin;

Coronas located along some ilmenite-plagioclase grain boundaries;

Symplectitic intergrowths with ilmenite.

In any one example, the earliest pyroxene crystals are usually much larger than those of the later species. They are usually simply twinned on (100), progressively zoned outwards, optically strongly or distinctly pleochroic in greens, violets, and pinkish violets, and show strong dispersion $(r > v)$. Crystal faces are frequently well developed, but against areas richer than normal in plagioclase, the clinopyroxenes may take on a sieve-like texture in which the embayments are occupied by optically continuous areas of plagioclase or calcite (Fig. 10). Some thin sections confirm the field interpretation that these pyroxenes represent primary growth forms since their zoning is parallel to the embayments, some of which are rational and have developed crystal faces. In many of the melanocratic syenites, embayed pyroxene is developed almost to the exclusion of any other textural type. In the pyroxenites, the earlier pyroxenes tend to be euhedral, while the later pyrox-
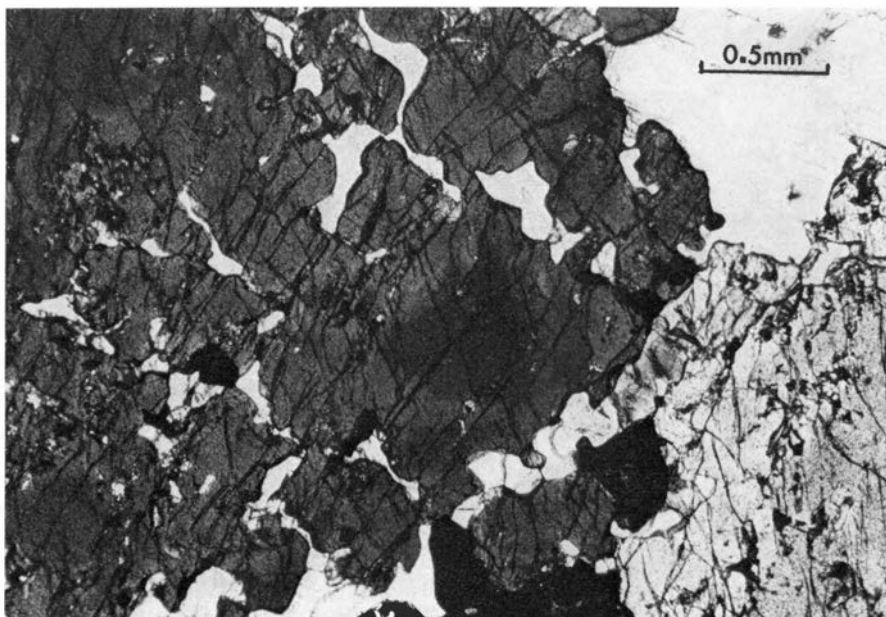
Fig. 10. Zoned and embayed clinopyroxene poikilitically enclosed within plagioclase. Felspathic pyroxenite (sample no. 168).

enes occurring in relatively felspathic areas are embayed. Developed in association with the embayed pyroxene is another textural type of pyroxene, either forming anhedra enclosing vermicular grains of Fe-Ti spinel (Fig. 11), or rims along the grain boundaries of ore vermicules. There is a complete gradation in some examples from vermicules of ore enclosed poikilitically in plagioclase, to those enclosed poikilitically in clinopyroxene, an intermediate stage occasionally being describable as a titanaugite-ore symplectite. In this particular case, the pyroxene-ore intergrowths do not appear to be of synantetic origin, even though they are often developed between large grains of Fe-Ti spinel and plagioclase. They were probably developed by magmatic corrosion of pre-existing grains of ore, in some places accompanied by the simultaneous crystallisation of titanaugite and in others followed by the later growth of felspar.

The 'iron oxides', including the species ilmenite and magnetite, have varying relationships depending on their timing. The earliest are euhedral and are now preserved within the clinopyroxenes, while the later often form granular aggregates, in some places enclosing the euhedral clinopyroxenes (Fig. 9). In both cases, the oxides may poikilitically envelop earlier apatite. Against plagioclase, the oxide species do not develop crystal faces, instead very irregular caries-type grain boundaries can be observed in association with the locally developed vermicular or even graphic intergrowths of ore within the felspar. These observations are interpreted as implying the instability of the oxides in contact with the late-stage alkali felspar-rich liquids.

Fig. 11. Vermicular grains of iron-titanium oxide irregularly enclosed within a single titanaugite which borders on a large and corroded ilmenite (sample no. 183).

The individual crystals of ilmenite are homogeneous, showing no exsolution phenomena, while thin lamellae of spinel along (111) directions are characteristic of the associated slightly anisotropic magnetite. The ratio of these species varies from dyke to dyke, some sites being composed exclusively of ilmenite and others dominantly of magnetite.

Amphibole crystallised at the expense of both the oxides and clinopyroxene, but its magmatic or metamorphic origin, as well as its relationships to plagioclase, are often ambiguous. Occasionally, however, amphibole crystals possess replacive grain boundaries against pyroxene and crystal faces against alkali felspar. A magmatic origin is also suggested for amphibole enclosing an abnormal concentration of apatite euhedra. Though much amphibole occurs in a non-diagnostic manner, some is clearly metamorphic, for instance, that which forms rims along clinopyroxene-oxide and clinopyroxene-felspar grain boundaries. This amphibole possesses irregular replacive contacts against both of the adjacent minerals.

Felspar, the latest of the primary minerals to crystallise in both the pyroxenites and the dark syenites, ranges in composition from an oligoclase to albite and often contains exsolved lamellae of a potassium-rich phase. This plagioclase or antiperthite may poikilitically enclose some of the earlier pyrogenic minerals or show other textural relationships indicating later growth, though it may also be replaced by a metamorphic generation of amphibole as well as by scapolite or calcite. The primary felspar crystals are often deformed, as indicated by undulatory extinction, bent albite twins, and the for-

mation of sub-grains, and such crystals may be replaced by smaller felspars with mutual grain boundary relationships of annealed type. This recrystallisation was most commonly initiated along the primary grain boundaries, particularly those against amphibole.

The fenites

The zone into which the pyroxenite dykes were emplaced was originally composed of a rather complex mixture of basic and ultrabasic rock types which were texturally and mineralogically reconstituted to various degrees during amphibolite-facies metamorphism. In several places, the alterations which preceded and accompanied the intrusion of the alkaline suite have been so intense that little remains as evidence of their original character, while in others, the hosts can be broadly separated into two major components: the Upper Border Group of the Rognsund layered gabbro (Robins 1972b) and a dyke complex emplaced into it. The former involves a variety of rock types originally composed of various combinations of basic plagioclase (labradorite or bytownite), aluminous clinopyroxene, magnetite, ilmenite, and olivine. Particularly common were gabbros describable as plagioclase-pyroxene cumulates and clinopyroxene crescumulates. The dyke complex is clearly the result of a number of phases of emplacement of different rock types, mostly gabbroic, but including bojites, wehrlites, olivine pyroxenites, and cortlandites. Locally, the density of the dykes is such that the gabbroic hosts are excluded from the assemblage or restricted to angular patches caught between the later intrusions. Psammitic metasedimentary rocks, occurring in a large raft within the Rognsund gabbro, form the eastern margin of much of the Kræmmervik complex, but never come into close contact with either pyroxenite or melanocratic syenite. As a result, the psammitic rocks are unaffected by the fenitisation. Though some amphibole syenites penetrate a short distance into this raft, the general rarity of other intrusives within it makes a strong contrast with the abundance of dykes in the adjacent complex. This contrast is possibly a result of the different mechanical properties of the two environments; the metasediments possessing a strong planar fabric lacking in the surrounding gabbros.

Characteristic of some of the products of intense fenitisation of the basic country rocks is the appearance in them of patches and streaks rich in apatite. The apatite in this environment forms equant crystals, and in some places is concentrated to the extent of a nearly pure apatite rock containing only minor amounts of pyribole and sphene. Normally, however, the fenites are composed of amphibole and titaniferous clinopyroxene, with only minor quantities of apatite, scapolite, biotite, ores, and sphene, as well as the relict minerals from earlier igneous and metamorphic assemblages (Table 2). In these places, it is clear that the basic dykes were most easily reconstituted during fenitisation; the host uralite gabbros were much less affected, and peridotitic rocks appear to have developed only small amounts of porphyro-

Table 2. Modal analyses of fenites from the Kræmmervik alkaline complex.

Sample	166	169	171	174	178	180	23738
Clinopyroxene	69	14	46	19*	48	4**	42
Amphibole	11	77	47	72	47	72	46
Ore	14	3	1	tr.	1	2	7
Sphene	3	–	–	–	tr.	–	–
Biotite	–	–	–	1	–	15	–
Apatite	1	–	tr.	tr.	tr.	1	tr.
Calcite	1	tr.	tr.	–	tr.	2	tr.
Scapolite	tr.	tr.	2	–	2	–	–
Plagioclase	–	1	3	tr.	1	–	4
Olivine	–	4	–	7	–	4	–

* Partly altered to amphibole.
** Includes some relict orthopyroxene.

blastic amphibole. The intensity of the fenitisation seemingly depended to a large extent on the primary composition of the rock, particularly on whether it approximated that of hornblende.

The timing of the development of the fenites is indicated by a number of observations. They tend to become more coarsely crystalline within a few centimetres of the pyroxenite or mela-syenite dykes, whilst against the amphibole syenites the normally coal-black colour changes to green. The latter corresponds in many cases to both the development of further amphibole at the expense of any clinopyroxene present, and to a change in the pleochroic scheme of the pre-existing amphibole. The relationship between the fenites and the amphibole syenites is made absolutely clear where these dyke rocks cut across and displace the apatite-rich schlieren. On the other hand, the direct connection between fenitisation and the emplacement of the pyroxenite is illustrated by isolated dykes of this type which crosscut the Rognsund gabbro outside the main alkaline complex. These dykes are surrounded by fenitic haloes up to 60 cm wide, mainly the result of the hydration of the pre-existing mineralogy. A problem is posed by certain strongly altered mafic dykes which crosscut the alkaline pyroxenites, but were themselves emplaced earlier than the amphibole syenites. Their alteration, involving the almost total destruction of the primary fabric and mineralogy and the formation of a granular mosaic of brown-green amphibole, with fresh diopsidic clinopyroxene and calcite occurring principally along the grain boundaries, is fairly typical of much of the fenites. It appears that, whilst the main fenitisation accompanied the emplacement and crystallisation of the pyroxenites and melasyenites, it also continued for some time afterwards. In fact, this later activity involved only the addition of water to rocks which, under the prevailing metamorphic conditions, were amenable to conversion into hornblendite.

The principal transformation within the intensely fenitised rocks was the replacement of the primary mineralogy by a titaniferous clinopyroxene, opti-

cally much like that within the alkaline pyroxenite and titanaugite syenite dykes. Texturally, this forms large anhedra surrounded or poikilitically enclosed by the very subordinate oligoclase, or by calcite, and partly replaced by a brown-green amphibole. In some instances, it is embayed in much the same fashion as the pyroxene of the titanaugite syenite. As noted earlier, in some places the extensive replacement of earlier assemblages by apatite took place during fenitisation. The main changes can probably be considered the result of the addition of calcium, together with variable amounts of chlorine, fluorine, phosphorus, and carbon dioxide and also the removal of aluminium. The formation of clinopyroxene probably involved relative enrichment in iron, and the formation of apatite-rich rocks the relative depletion of a series of elements, including large amounts of silica. The general trend can, however, be more usefully considered as the conversion of gabbroic and other similar assemblages to those closely resembling the paragenesis of the alkaline pyroxenites themselves. In those places undergoing less strong fenitisation, the main effect was the addition of water, resulting in the formation of hornblende-rich rocks from those whose pre-existing composition was appropriate. A similar type of metasomatism was associated with the emplacement of the carbonatite in the Lillebugt alkaline complex on the adjacent island of Stjernøy. In this case, the fenitisation which resulted in the formation of coarse-grained hornblendites from metagabbroic assemblages was also due to fluids bearing H_2O, CO_2, and P_2O_5 (Heier 1961, Oosterom 1963).

The origin of the pyroxenites

The evolution of alkaline pyroxenites in general is usually discussed in terms of several possible processes, including the fractional or even nonfractional crystallisation of appropriate magmas, the reaction of pre-existing rocks with magmas of various types, and the fenitisation of earlier rocks (Holmes & Harwood 1937, Upton 1967). In the Kræmmervik complex, limited amounts of pyroxenite formed due to the strong fenitisation of host rocks which were dominantly gabbroic in composition. Their development accompanied or possibly preceded the more widespread crystallisation of hornblende in the same host rocks which led, in some cases, to the formation of anchi-monomineralic hornblendites as the fenitic product. The metasomatic activity which resulted in these characteristic changes was, however, associated with the development in narrow fissures of alkaline pyroxenite of various types which texturally contrast strongly with the clearly fenitic pyroxenite. These dykes also include titanaugite syenite, whose origin was intimately connected with that of the pyroxenite.

   Although the forms assumed by the main pyroxenites of the Kræmmervik complex have, in this account, been consistently referred to as dykes, there is little direct or diagnostic evidence that magmatic activity played the dominant role in their origin. Some features may suggest that magmatic activity

was subordinate to such processes as pneumatolysis or metasomatism. The lack of chilled contacts, the coarse grain even in bodies a few centimetres thick, the general similarity of the mineralogy to that of some of the fenites, and the lateral variability of the mineralogy are all features which could be used as evidence against the introduction of a magma. On the other hand, the paragenesis of the pyroxenite dykes has a magmatic character and, in several places, the bodies themselves with their sharp contacts and dilational form have an intrusive appearance. Another important factor is the abundant evidence of the inward growth of individual crystals from the walls, implying the existence of openings maintained against the surrounding high pressure. In the author's opinion, the balance of evidence is in favour of magmatic injection, but the rocks show such modal variation that it is unlikely that they crystallised directly from a melt of their own composition.

Two of the internal features of the pyroxenites and syenites can be used as indications of the presence of a fluid phase during their crystallisation. Significantly, only one of these, the embayed titanaugite crystals, is shared by the most intensely fenitised of the country rocks. According to Spry (1969), such primary growth forms are unusual; they result from a crystallisation rate higher than that of slow layer growth and require a fluid medium. Important evidence of the magmatic as opposed to metasomatic (replacement) origin of the pyroxenite and various types of syenite dykes is provided by the characteristic skeletal habit of the apatite crystals they contain. These crystals, always highly elongated parallel to their c-axes, contrast strongly with the granular apatite found in the fenites, but match in many respects the apatite precipitated during the quenching of synthetic melts (Wyllie, Cox & Biggar 1962). Although there is, in this instance, no evidence of quenching, one can conclude that the skeletal apatite resulted from rapid dendrite-type growth (cf. Gardner 1972). This is most easily envisaged as occurring in an undercooled fluid medium relatively free of suspended material.

Accepting that the alkaline pyroxenites crystallised from a melt, there are a number of facts which can be used to circumscribe its nature. Its composition was such that it could crystallise apatite, titanaugite, ilmenite, magnetite, amphibole, and felspar in varying amounts at different places, but always apparently in much the same order. The composite structures and modal variations within the dykes thus probably reflect changes in magmatic composition with time, though these changes could not have been always in the same direction. The metasomatic effects of the introduction of the melt were such that the surrounding rocks either gained water alone or became replaced by assemblages similar to those crystallising from the fluid itself. The intensity of the metasomatism suggests that the magma was relatively rich in water and other volatiles, and this is also one explanation which could be advanced for the development of pegmatitic fabrics and the absence of chilled margins. Another allied possibility for the lack of chilling could simply be that there was little temperature difference between the in-

trusive material and the country rocks, since these were at that time under-
going amphibolite-facies metamorphism.

In view of the intimate association with melanocratic titanaugite syenite, it
is tempting to regard the alkaline pyroxenites as due to the fractional cry-
stallisation of magmas with mela-syenitic compositions, though, of course,
their presence in the complex would be only an assumption. On this basis,
the pyroxenites would have crystallised from magmas which were actively
moving through a series of interconnected fissures and depositing on the
walls those phases which crystallised at the highest temperatures. As pointed
out by Quirke & Kremers (1943), such a situation might be expected to re-
sult in large crystals of the individual species. The hypothesis can also be
used to explain many other features, such as the strong modal variation
within the dykes, the intense fenitisation, and the tendency for comb-struc-
tures to be present; it involves fractional crystallisation and the accumula-
tion of crystals, not due to gravitational sinking but because of their encrust-
ation on the cooling surfaces and the motion of the parental liquid. The se-
quence of crystallisation determined from textural observations indicates
that whatever magma was involved in the origin of the pyroxenites and tita-
naugite syenites, it could with further differentiation give rise to the spatially
associated, but later, amphibole syenites.

Summary

The Kræmmervik alkaline complex, which was formed during the later
stages of an early Caledonian cycle of deformation and metamorphism, con-
tains dykes of alkaline pyroxenite, a rock type normally considered to be
developed almost exclusively within continental cratonic environments, usu-
ally in association with alkaline vulcanicity. The pyroxenite resembles jacu-
pirangite chemically but is less undersaturated and associated in the same
complex with melanocratic to mesotype titanaugite syenites and mesotype to
leucocratic amphibole syenites, none of which contain modal felspathoids.
The amphibole syenite was emplaced as dykes at a later stage than the py-
roxenite and titanaugite syenite which, situated together in the same fissures,
were coeval. The amphibole syenite dykes were both preceded and post-
dated by the intrusion of basic dykes, the latest set of these being followed
by biotite-magnetite syenite pegmatites, before the onset of a localised phase
of deformation. The basic dykes are now mainly represented by schistose
amphibolites which provide evidence that the development of the complex
took place during the progress of Barrovian regional metamorphism.

The pyroxenite dykes are, in general, variable in character but they are
usually composite, coarse-grained or pegmatitic, and typically exhibit a
comb-structure. In the same body it is possible to find in genetic association
types of pyroxenite which differ in mineralogy and texture, as well as tita-
naugite syenite. Porphyritic pyroxenite often occurs along the dyke core
while the wall zones may be formed of either apatite-rich pyroxenite or tita-

naugite syenite or vary in composition between these two. Whatever the structure of the bodies, the sequence of crystallisation in each part of them is relatively constant, skeletal apatite being followed by clinopyroxene, iron-titanium oxides, amphibole, and felspar, either plagioclase or antiperthite, being last. The balance of evidence favours a magmatic origin of the pyroxenites located in the dykes, though the modal variations are such that it is highly unlikely that any part of them crystallised from a magma of the same composition. A petrogenesis involving the fractional crystallisation of a mela-syenite magma flowing through interconnected fissures is tentatively suggested, an accumulation of crystals taking place by encrustation. Small amounts of mineralogically similar pyroxenite was also formed by the intense fenitisation of the host gabbroic rocks, but it differs from that of the dykes in lacking skeletal apatite. The majority of the fenites, however, represent the addition of water to rocks undergoing amphibolite facies metamorphism. Those rocks with suitable compositions were thus converted into hornblendite.

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