GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN NO. 70

PLUTONIC DEVELOPMENT OF THE ILORDLEQ AREA, SOUTH GREENLAND

PART II:
LATE-KINEMATIC BASIC DYKES

BY

JUAN WATTERSON

WITH 39 FIGURES AND 4 TABLES IN THE TEXT,
AND 4 PLATES

Reprinted from
Meddelelser om Grønland Bd. 185, Nr. 3

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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Abstract

Basic dykes with primary amphibolite facies mineral assemblages were emplaced along active transcurrent fissures in the closing stages of a period of plutonic activity. The order of crystallisation, determined from petrographic evidence and from the composition of filter-pressed fractions, is consistent with consolidation of the magma at ca. 4000 bars water pressure at 800–850°C. The marked calc-alkaline trend of differentiation and the high-alumina characteristics of some dykes, illustrated by ten chemical analyses, is shown to be the likely result of a fractionation dominated by the separation of mafic from felsic phases. This type of fractionation is shown to be a consequence of the conditions under which the dykes crystallised, and is contrasted with fractionation taking place under conditions of low water pressure. The type of differentiation demonstrated by the dyke suite is shown to be capable of producing many of the characteristic features of the orogenic volcanic suite, including relatively large amounts of intermediate differentiates.

Oblique foliation in the dykes is shown to be related to transcurrent movements and is interpreted by reference to a model of rotational homogenous strain.

CONTENTS

SUMMARY

A suite of narrow lamprophyric dykes occurs throughout an area of several hundred square km of South Greenland. About 120 well exposed members of the suite outcropping on the coasts of the Ilordleq area are described. The dykes were emplaced during the closing stages of an episode of plutonic activity; plastic deformation of the mainly granitic country rocks was succeeded by brittle deformation involving transverse displacements along a conjugate set of almost vertical shear fractures, the period of intrusion of the dykes overlapping with the fault movements. Most of the dykes are of basaltic composition but the stable mineral assemblage at the time of consolidation (hornblende + andesine + epidote + sphene + [biotite]) was that characteristic of the almandine amphibolite facies of regional metamorphism. This is interpreted as the result of crystallisation of the dyke magma at high water pressures (ca. 4000 bars), the order of crystallisation of component minerals being similar to that reported by YODER and TILLEY (1962) for melts of basaltic composition under these conditions. It is suggested that the occurrence of amygdales in rocks crystallising at such high P_{H_2O} indicates a depth of consolidation of the dykes of about 10–12 km.

Wall-rock displacement during consolidation resulted in filter-pressing of some dykes, the separation of andesitic residual liquid giving rise to the extreme inhomogeneity of these dykes. Post-consolidation wall-rock displacements resulted in paracrystalline deformation of dykes and promoted autometamorphic recrystallisation. Mineral assemblages produced by this synkinematic recrystallisation reflect progressively lower temperatures attained during the post-consolidation cooling history of the dykes; these assemblages are those typical of the quartz-albite-epidote-almandine and quartz-epidote-biotite subfacies of the greenschist facies of regional metamorphism. The relationship between solid and fluid pressures during regional metamorphism is discussed.

The deformation caused by post-consolidation wall-rock displacements resulted in a characteristic oblique foliation in the dykes which is interpreted on the basis of a model of rotational homogeneous strain in which a distinction is drawn between rotation, or re-alignment, of

passive lines and planes, and rotation of included bodies. The folding of elongate xenoliths in the dykes is inconsistent with the mechanism of folding proposed by RAMBERG (1959) and FLINN (1962).

Potash metasomatism of country rocks bordering several of the dykes, reminiscent of adinoles and fenites, is interpreted as a result of the passage of alkaline fluids which preceded intrusion of the basic magma, rather than a result of contact alteration by the dykes.

Chemical analyses of eleven rocks of the suite show a distinctive trend of differentiation which is consistent with fractional crystallisation of a basic magma of commonplace composition, crystallising under conditions of high water pressure. The differences between differentiation trends in magmas in which the crystallisation of major phases is essentially contemporaneous, a situation approached in many normal high level basic rocks, and in magmas in which there is relatively little overlap of the crystallisation periods of major phases, such as basic magmas at high P_{H_2O}, is discussed. The latter type of differentiation, characterised by the Ilordleq dykes, is shown to favour the production of high-alumina basalt magma and relatively large proportions of differentiates of andesitic composition. Conditions under which the Ilordleq dykes crystallised are shown to favour the production of a typical calc-alkaline differentiation trend. The composition of residual liquid in Ilordleq dykes after 50–60 % crystallisation is contrasted with that of residual liquids at a similar stage of evolution in the Skaergaard and Stillwater intrusions. The development of nepheline-normative rocks from hypersthene-normative rocks is ascribed to fractionation of amphibole; subsequent development of quartz-normative rocks may be due to crystallisation and fractionation of biotite.

It is suggested that suites of the Ilordleq types are intrusives complementary to the typical orogenic basalt-andesite-rhyolite effusive suites; many characteristics of the latter suites are shown to be consistent with differentiation of basaltic magma at depth, under conditions of high P_{H_2O}. Brief consideration is given to the possibility of the transfer of water, and perhaps also alkalies, from rocks undergoing high grade regional metamorphism to contemporaneous basic magmas.

The Ilordleq rocks are considered in the context of the lamprophyre problem. It is suggested that an important consequence of the classification of many magmatic rocks on the basic of disequilibrium mineral assemblages, has been the failure to recognise physico-chemical conditions of crystallisation as being of importance equal with rock composition in determining the mineral assemblages of igneous rocks. It is concluded that by application of the mineral facies principle to igneous rocks, important genetic relationships would be more readily revealed, and many problems of nomenclature avoided.

PREFACE

This account is the second of a series of four dealing with various aspects of the plutonic rocks of the Ilordleq area. The chronology of the area and occurrence of basic dykes of various ages were described in Part I (WATTERSON, 1965). Parts III and IV dealing with deformation and metamorphism respectively are in the course of preparation. The location and the main geological features of the area are shown in Plate 4.

The suggestion that external conditions at the time of emplacement were responsible for important modifications of the dyke suite described was first made by the writer in 1960; subsequent investigations by the writer's collagues elsewhere in South Greenland have produced further information tending to confirm that emplacement of the dykes was associated with brittle deformation of the country rocks following an episode of more typically plutonic deformation. In the course of this work the term late-kinematic has proved a useful term of reference for the dyke suite and for convenience is retained in this account.

An interpretation similar in many important respects to that suggested for these dykes was suggested by KAITARO (1953) for a radial suite of lamprophyric dykes centred on the granite-monzonite stock of Åva in the Åland archipelago of SW Finland, and previously described by SEDERHOLM (1934). A visit to the Åland Islands in 1961, which was facilitated by the helpful advice of the late Prof. A. METZGER of Pargas University, confirmed that the Åva and Ilordleq dykes have important features in common, notwithstanding some differences in geological environment.

Acknowledgements: The field work on which this account is based was carried out under the auspices of the Geological Survey of Greenland during the summer months of 1959 and 1960. The writer is indebted to the Director of the Survey for facilities provided for carrying out the field work and other kindnesses, and to the Mineralogical Institute of Copenhagen for laboratory facilities provided between 1959 and 1962. Discussion with my colleagues in Copenhagen and elsewhere has been

most useful and is greatly appreciated. Dr. JANET WATSON and Dr. J. H. ALLAART kindly commented on the manuscript, to which many corrections and improvements have been made following suggestions by Mr C. PULVERTAFT to whom I am most grateful for editing and criticism.

Line drawings for text figures have been improved and redrawn by Mr J. LYNCH of Liverpool University.

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May, 1966.

I. INTRODUCTION

The local geological setting and age relations of the dykes have been described in Part I, and are summarised below.

The oldest rocks in the area comprise a supracrustal series of metasedimentary and metavolcanic rocks which are of Ketilidian age. Cutting these rocks are narrow basic dykes, the first period dykes, which probably are genetically connected with the supracrustal volcanics. Both supracrustal rocks and dykes are cut by granite which was emplaced during an episode of regional metamorphism and deformation. A further set of narrow basic dykes, the second period dykes, post-date the plutonic activity and are thought to have been emplaced as normal dolerites in cold country rocks. A further episode of plutonic activity, the Sanerutian episode, followed the emplacement of the second period dykes. Regional metamorphism and deformation, and reactivation of the earlier granites characterised this episode during which second period dykes were folded, disrupted and migmatised.

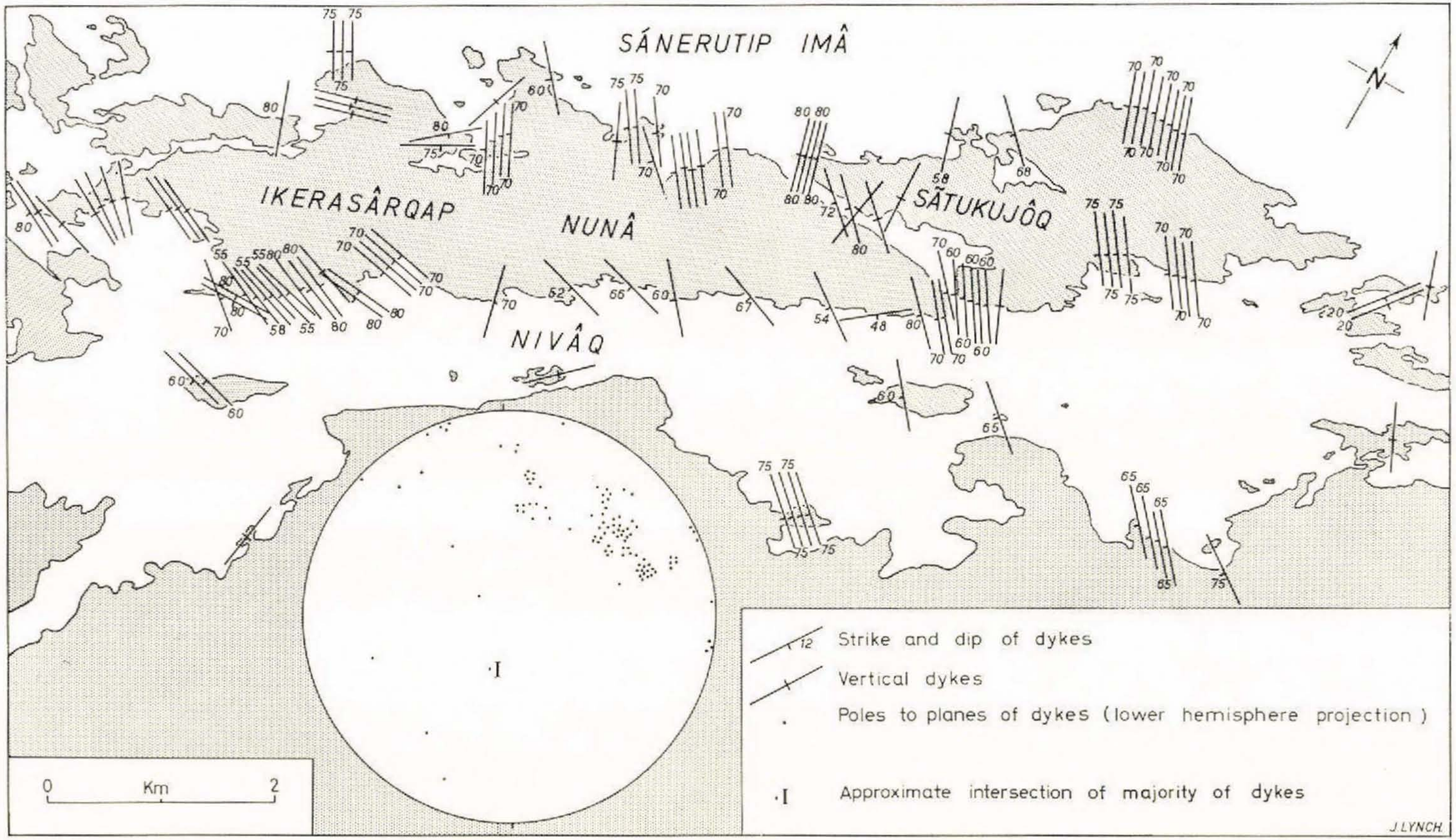
The dykes which are the subject of this account clearly post-date the Sanerutian migmatisation and plastic deformation. On the basic of the evidence presented in the following pages these dykes, the third period dykes, are thought to have been emplaced into country rocks at elevated temperatures and during the operation, at least intermittently, of compressive forces. There is no direct evidence to show that the non-cratogenic conditions were connected with Sanerutian plutonic activity, but they are interpreted on the basis that this is so. The similarity of stress patterns during the Sanerutian plutonism and at the time of emplacement of the third period dykes suggest that a late-Sanerutian age is at least not unlikely. Late-Sanerutian refers only to the Sanerutian as seen in Ilordleq; in terms of the regional development mid-Sanerutian may eventually be found more appropriate. Although in Ilordleq the Sanerutian reactivation clearly precedes intrusion of the late plutonic igneous rocks, the relationship elsewhere between igneous and plutonic activity is not yet certain. An isotopic age of 1500 ± 70 m.y. of biotite (Rb/Sr) from a granite at Julianehåb, which was probably reactivated during the Sanerutian plutonic episode (Bridgwater, 1965), compares with ages of 1600–1650 m.y. from rocks of the Rapakivi suite (*op. cit.*) to which the Ilordleq dykes are thought to belong. It would be unwise at this stage to assume that this igneous activity anywhere predates Sanerutian reactivation of regional type, as this reactivation has not itself been accurately dated, 1500 ± 70 m.y. representing only a minimum age.

The late-kinematic dykes in Ilordleq are cut by numerous dykes, mostly dolerites, emplaced during the Gardar volcanic episode. The duration of this episode has not yet been established but ages of late Gardar rocks range from 1255–1020 m.y. (*op. cit.*). Post-dating the Gardar dykes are a few dolerites which may be of Tertiary age.

The regional context of the late-kinematic dykes is discussed in Section VII.

Nomenclature: Although many features of the dykes are those more usually associated with metamorphic rocks, all were developed either during or immediately after consolidation of a magma and are to that extent primary features. The mixture of elements typical of both volcanic and plutonic rocks has made for difficulties of nomenclature. As the dykes consist largely of plagioclase and amphibole, and a large proportion are foliated, they are referred to as amphibolites. Other terms which could have been used, the writer believes to no advantage, for some or all of the dykes include lamprophyre, microdiorite, leucomicrodiorite, andesite, hornblende dolerite, kersantite, spessartite, camptonite and possibly appinite.

The mineral facies classification and terminology used is that of FYFE, TURNER and VERHOOGEN (1958).



Distribution and orientation of late-kinematic dykes in the northern part of Ilordleq

Fig. 1. Northern part of Ilordleq showing distribution and attitudes of dykes outcropping on coastal exposures.

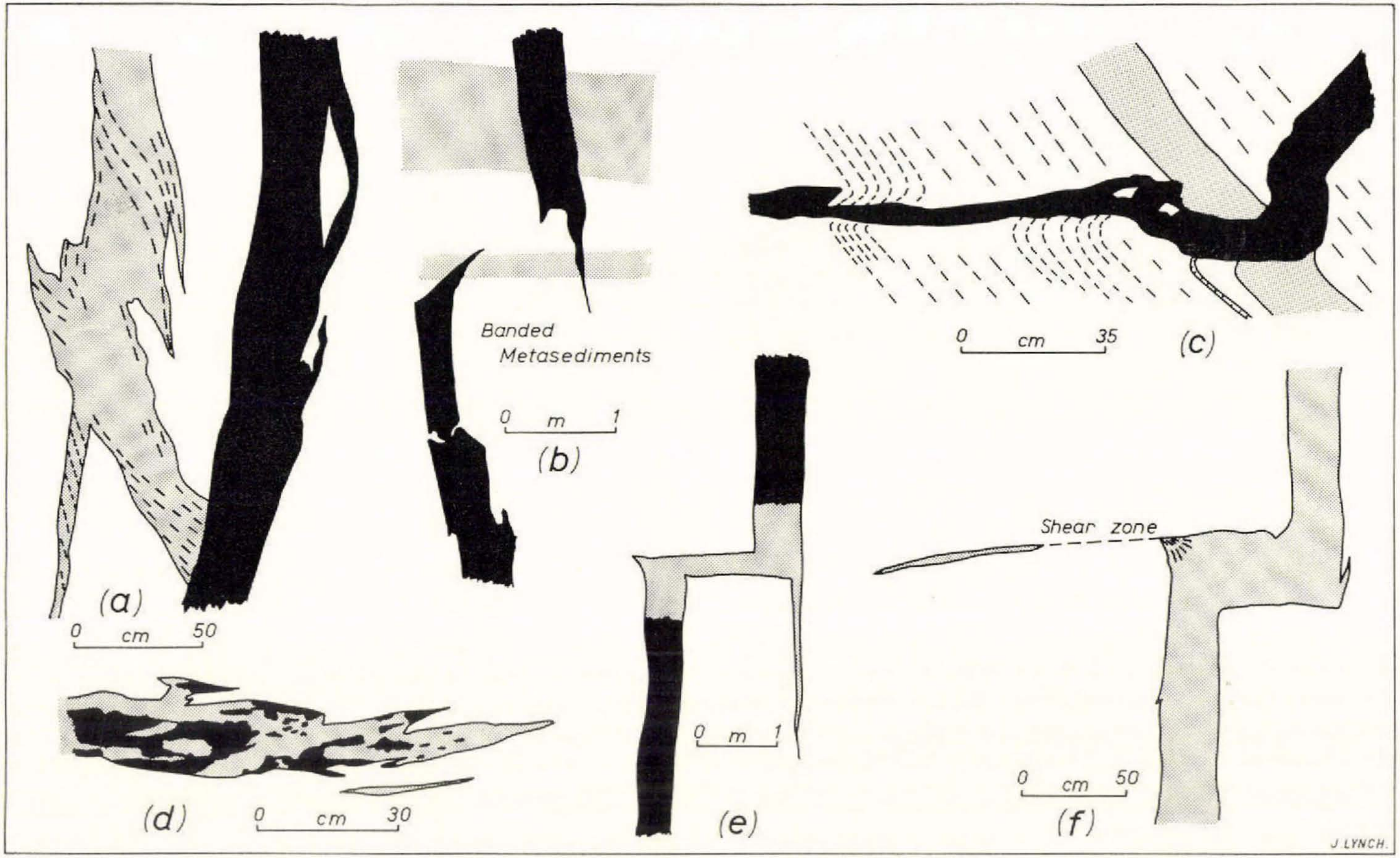


Fig. 2. (a) Foliated type-B dyke cut by unfoliated type-C dyke (black) which post-dates foliation in earlier dyke. (b) Discontinuous en echelon dyke cutting banded metasediments. Undisturbed banding of metasediments shows primary origin of dyke discontinuity. (c) Flat-lying type-B dyke (black) showing deflection of country rock structures adjacent to dyke margins (see also fig. 20). (d) Inhomogeneous type-A dyke showing irregular distribution of mafic (black) and felspathic (stippled) components. (e) Dyke with textural inhomogeneity due to filter pressing (stippled area) only adjacent to off-set structure. (f) Type-B dyke with apophysis and foliation related to shear zone in country rock.

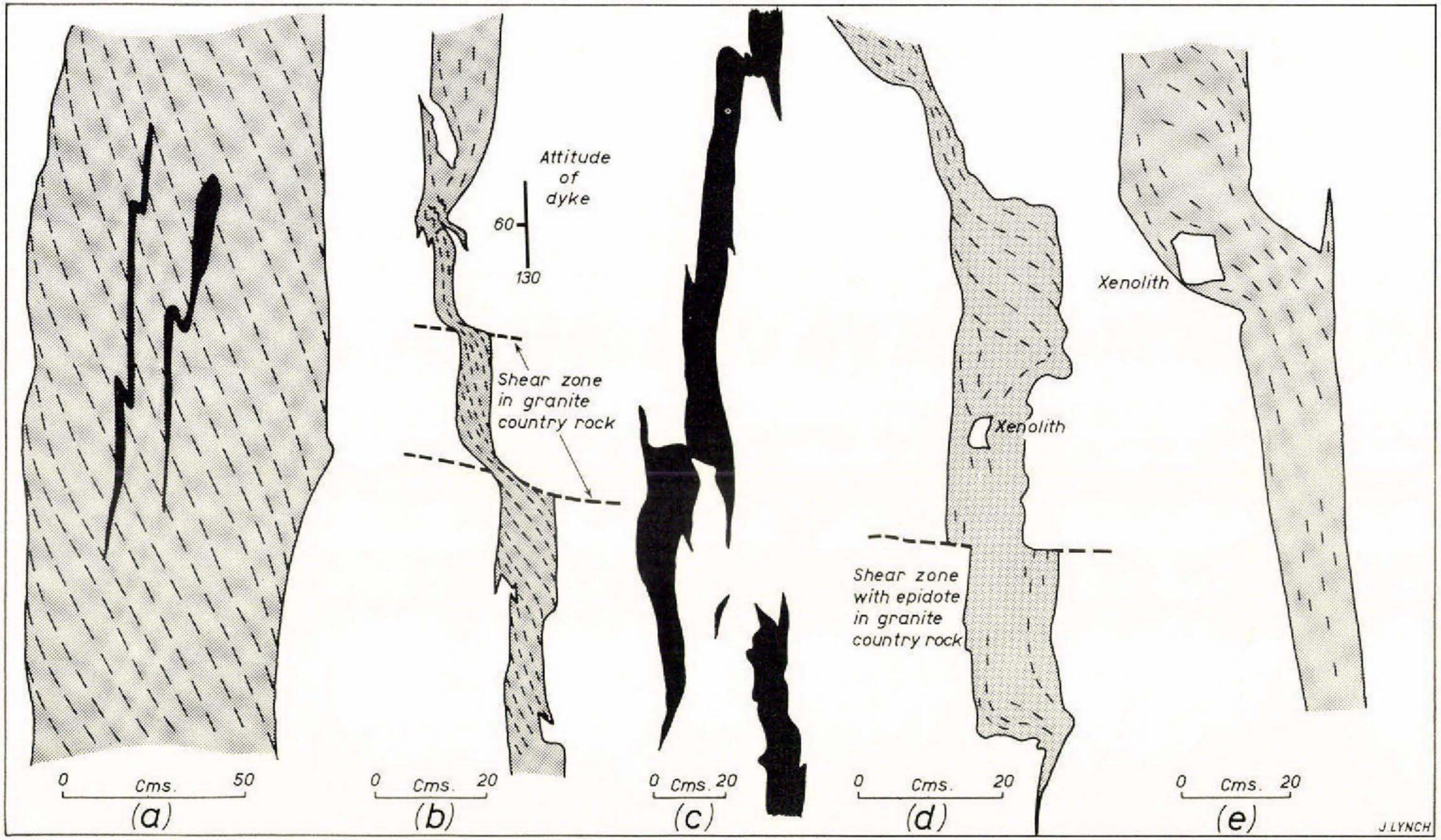


Fig. 3. (a) Type-B dyke with folded elongate xenoliths (black) of country rock granite. Axial planes of folds are parallel to oblique dyke foliation (broken line). (b) Irregular type-A dyke with oblique foliation. Dyke off-sets related to shears in country rock and deflection of dyke foliation. (c) Type-A dyke with primary nature of irregularities and off-sets shown by apophyses. (d) Xenolithic type-B dyke with off-set related to shear in country rock and truncating dyke foliation. (e) Poorly foliated type-B dyke with xenolith.

II. FIELD RELATIONS

(a) General features

The dykes described occur throughout the Ilordleq area but as important features of their field relationships are best seen on clean coastal exposures, the following account deals mainly with dykes occurring in the northern part of Ilordleq, shown in fig. 1, where about 120 dykes were found. Few of the dykes have been traced for more than 50 m inland but this was due to lack of time and exposure rather than impersistence of the dykes. However, several dykes wedged out even in the short distance for which they were followed and this together with the irregularities described below suggests that individual dykes are not likely to persist over great distances. The strike of the dykes is variable, the two dominant directions being NW and NE; only few of the dykes are vertical, most having hades of 15–30° (see fig. 1).

The most important conclusions regarding the origin of the dykes are based on field evidence; much of this evidence is best demonstrated by illustrations of the dykes shown in figs. 2–17.

In the early stages of the field work in Ilordleq and other parts of South Greenland, some late-kinematic dykes were confused with metabasaltic dykes such as the second period dykes of Ilordleq. The importance of the distinction for chronological purposes has been referred to in Pt. I which contains a description of the metabasalts and a summary of the criteria by which the dyke suites have been distinguished.

(b) Features of individual dykes

(i) Outcrop patterns

A characteristic feature of the suite is the irregular shape of many individual dykes, resulting from an abundance of apophyses and by apparent faulting, or off-setting, of dykes along planes oblique or transverse to the strike directions of the dykes (figs. 2, 3, 4).

An off-set pattern or 'en bayonet' arrangement of parts of individual dykes does not of itself require unusual conditions of emplacement. Apparent off-sets are common in basaltic dykes of typical cratogenic suites,

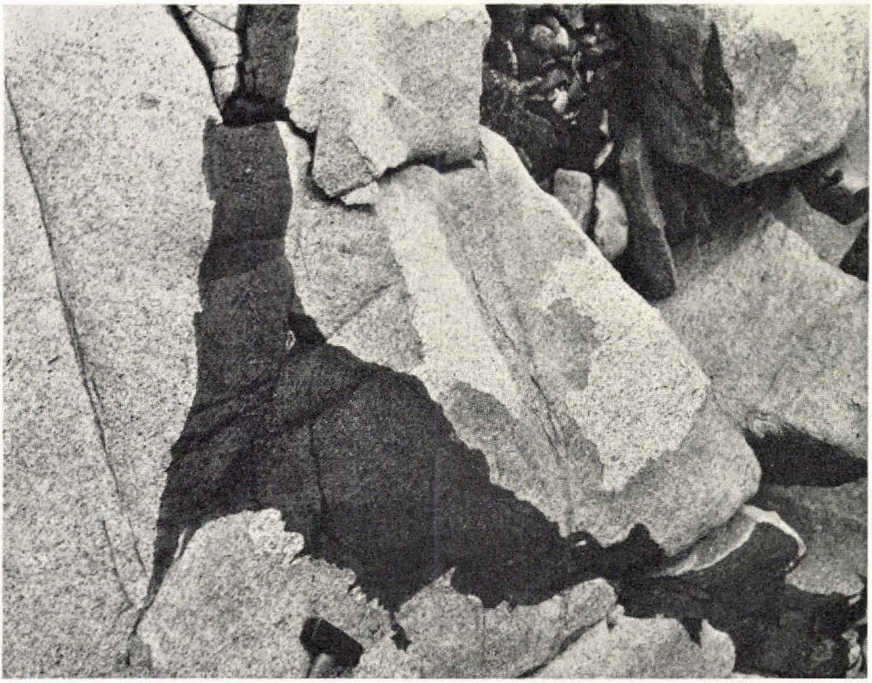


Fig. 4. Type-B dyke showing extreme irregularity with only slight deflections of country rock foliation.

such as that of the British Tertiary volcanic province (Harker, 1904), and the writer has seen examples in the Gardar dolerites of South Greenland. In the late-plutonic dykes of Ilordleq it is the association of several other features with the apophyses and off-sets which make these latter deserving of particular attention.

In the basaltic dykes described by Harker (*op. cit.*) and the Gardar dykes of Greenland, the off-set outcrop pattern can be accounted for without supposing lateral displacement of the country rock along the line of off-set, either before, during or after dyke emplacement. This is not so in several examples seen in Ilordleq, where relations between off-sets, foliation and textural inhomogeneities in the dykes, and shear zones in the country rock, show that transverse faulting of the dykes took place at approximately the same time as dyke emplacement.

Figure 5 shows a shear zone in the country rock granite along the line of off-set of a dyke. Welding of the fracture and drag of the earlier granite foliation both suggest that at the time the movement took place, conditions were such as to allow some recrystallisation of the granite, and to enable the granite to deform plastically to some degree. Figure 2(f) shows an off-set dyke in which displacement in the country rock is shown by a shear zone along which an apophysis of the dyke has

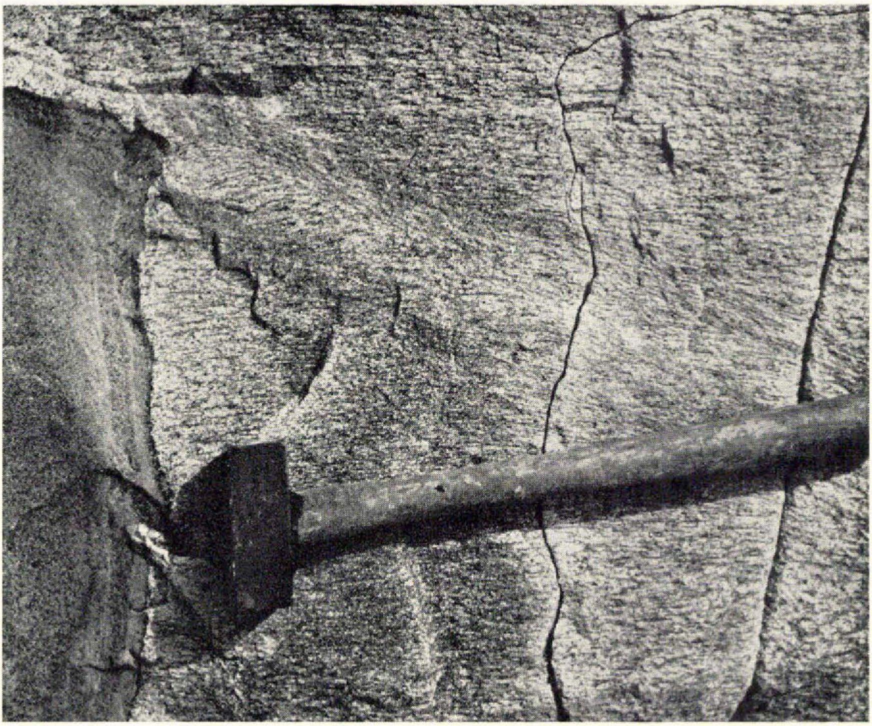


Fig. 5. Shear zone with deflected foliation in granite country rock, in line with off-set structure in dyke (top left). Slight displacement of dyke margin immediately to left of hammer head is aligned with small quartz filled shear in country rock granite.

penetrated. In many cases apophyses of off-set dykes continue across the line of off-set, without being displaced as would have been the case had the off-set post-dated consolidation of the dyke.

The above examples show that in some cases at least, offsetting of dykes is due to transverse fault movements, that these movements did not take place after consolidation of the dykes, and that the granite was not cold and brittle at the time of faulting. Many dykes showing off-sets do not have shears in the country rock granite corresponding to the off-set of the dyke. This may be due to complete healing by recrystallisation of the fracture in the granite, and the lack of drag of granite foliation could be due to the fact that the line of off-set in most dykes is parallel to the foliation in the surrounding granite (see figs. 6, 7, 8). It is likely, however, that in some cases no fault movement has occurred and that the off-set is due to the original irregularity of the dyke fissure (fig. 2(b)); this is most likely in cases where irregularities can be matched across a dyke (fig. 10) or where both ends of the dyke do not abutt against the line of off-set, but are joined by a transverse septum of

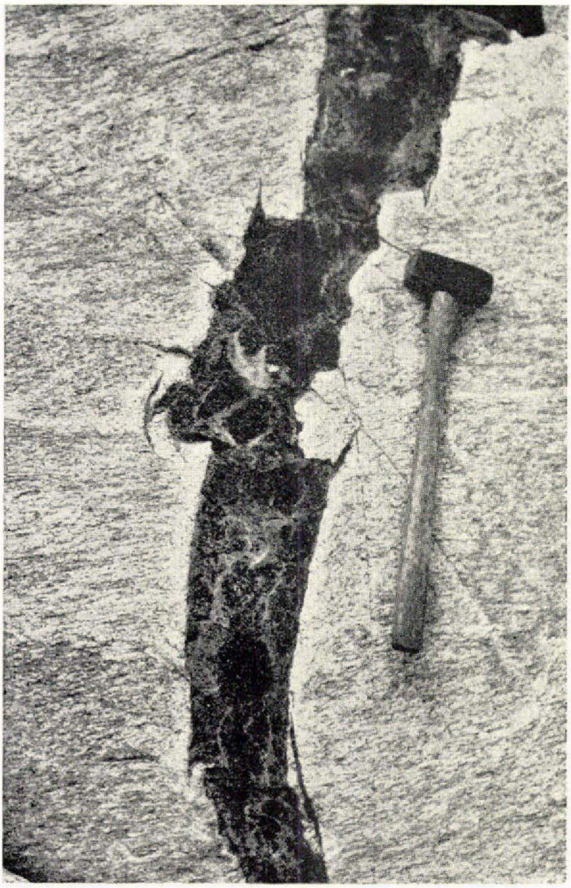


Fig. 6. Type-A dyke showing primary nature of irregularities, marked textural inhomogeneity, and blended zone in country rock immediately adjacent to dyke margins.

Fig. 7. Late-kinematic dykes cutting migmatitic Sanerutian hornblende granite.

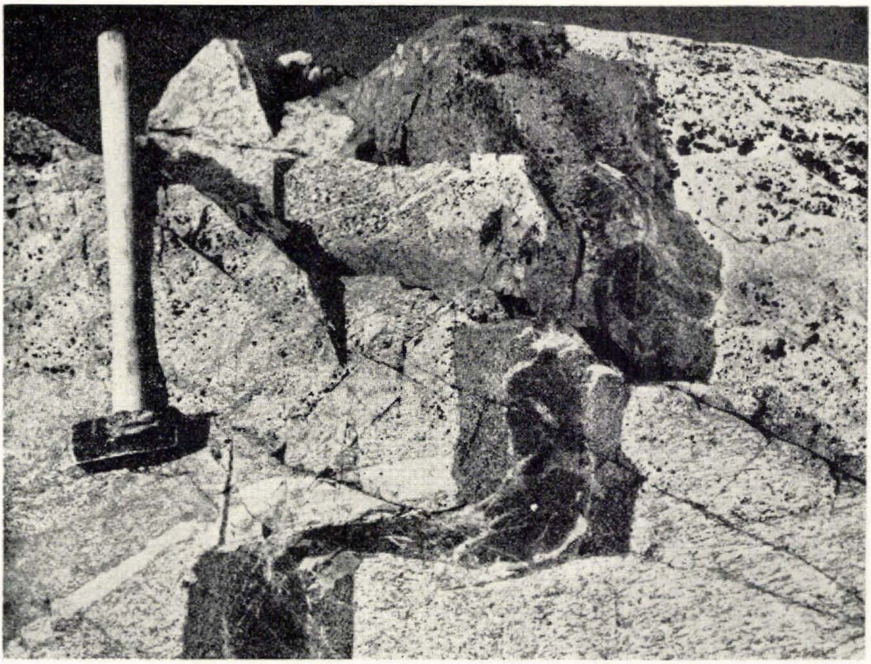


Fig. 8. Multiple type-A dyke, showing textural inhomogeneity due to filter-pressing. Sequence of events in this dyke appears to be (i) intrusion and crystallisation without filter pressing, followed by off-set (ii) intrusion of continuous central portion forming septum between parts separated by off-set, with deformation and filter-pressing during crystallisation.

dyke material (fig. 2(e)). Even in these cases the transverse septa may post-date the faulting with the main part of the dyke pre-dating the movement (see fig. 8) as in the case of apophyses which are not displaced along faulted off-sets.

Having shown that the irregularity of the dykes is not a late superposed feature it is necessary to determine whether the irregular fracture pattern could pre-date the dykes and therefore possibly be largely the result of forces unrelated to those operating when the dykes were emplaced. That this is not so can be shown by reference to the foliation and textural features described below.

Apart from apophyses and off-sets, the margins of many dykes are also irregular on a smaller scale and rapid changes in thickness, and splitting and thinning out are frequent. Such features are of course found in many normal dolerite dykes, but the frequency with which they occur in the late-plutonic dykes contrasts strongly with the common regularity of small dolerite dykes, a typical example of which is shown in fig. 9. The Gardar dyke illustrated is similar in size to the late-plutonic

Fig. 9. Gardar dolerite dyke showing regularity and jointing typical of the cratogenic Gardar dyke suite in Ilordleq.

dykes and is emplaced in the same country rock granite in a NW part of Ilordleq.

Not all the dykes under discussion show the features described above and some are found with the regular margins and outcrop patterns of typical minor hypabyssal intrusions (figs. 10, 11). No sharp distinction can be drawn between the irregular and regular dykes as all gradations between the two extremes are found. The degree of irregularity is closely correlated with other distinctive features:—

(1) the foliation within the dykes is most strongly developed in the most irregular dykes, while in the most regular dykes no foliation is evident in the field.

(2) Textural inhomogeneities are characteristic of the irregular dykes. Dykes of regular form are even-textured. Within one dyke, greater textural inhomogeneity is found in the more irregular parts of the dyke.

(3) Where intersections are found, the earlier dyke is always the more irregular, and has more marked foliation and textural inhomogeneity.

It is convenient to refer to dykes showing extreme irregularity and other associated features as type-A dykes, those showing the greatest regularity as type-C dykes, and the many dykes transitional between

Fig. 10. Homogeneous type-C dykes. Matching margins of right hand dyke show little or no displacement along dyke fissure.

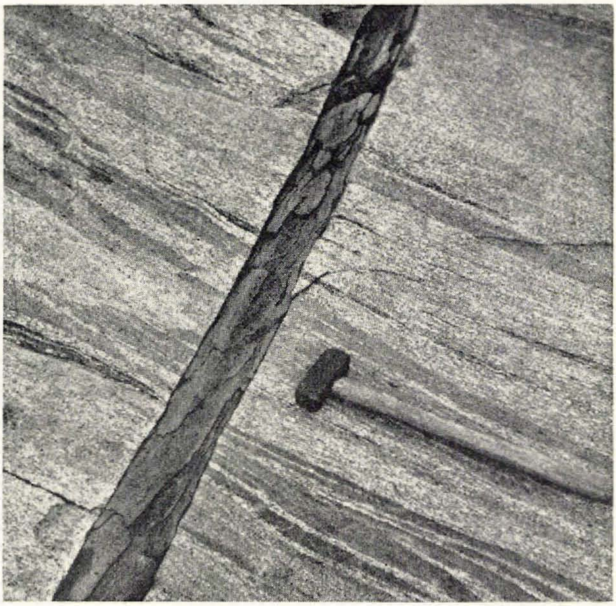


Fig. 11. Narrow type-B dyke with displacement of country rock structures.

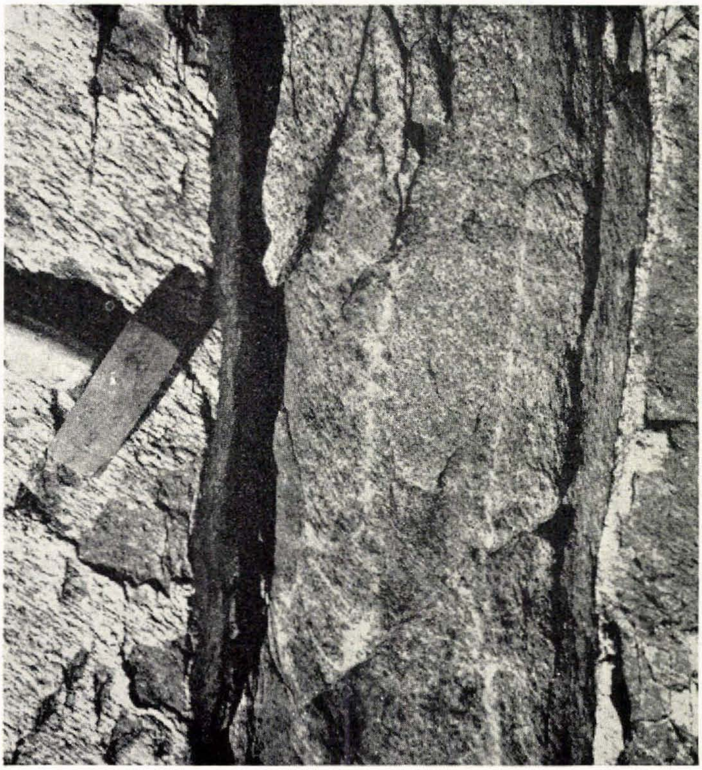


Fig. 12. Dyke with well developed S-foliation indicating dextral displacement, and mafic aggregates in felspathic groundmass. Some veining of groundmass by leucocratic material.

the two extremes as type-B dykes. There is continuous gradation between type-A and type-C dykes in respect of nearly all the features mentioned but type-A dykes are sharply distinguished from other dykes on the basis of important textural features.

(ii) Foliation and textural features in the dykes

A strong foliation is a feature of many of the dykes and is of importance in determining the conditions of emplacement. The dykes consist mainly of hornblende and plagioclase. The foliation is expressed in two ways: (i) as orientation of individual amphiboles, which owing to the fine grain size of most dykes often cannot be seen in handspecimen; (ii) as an alignment of textural inhomogeneities and therefore found only in A- and B-type dykes.

Textural inhomogeneity in the dykes is an expression of the concentration in varying degree of mafic material, which is shown in the following two ways.

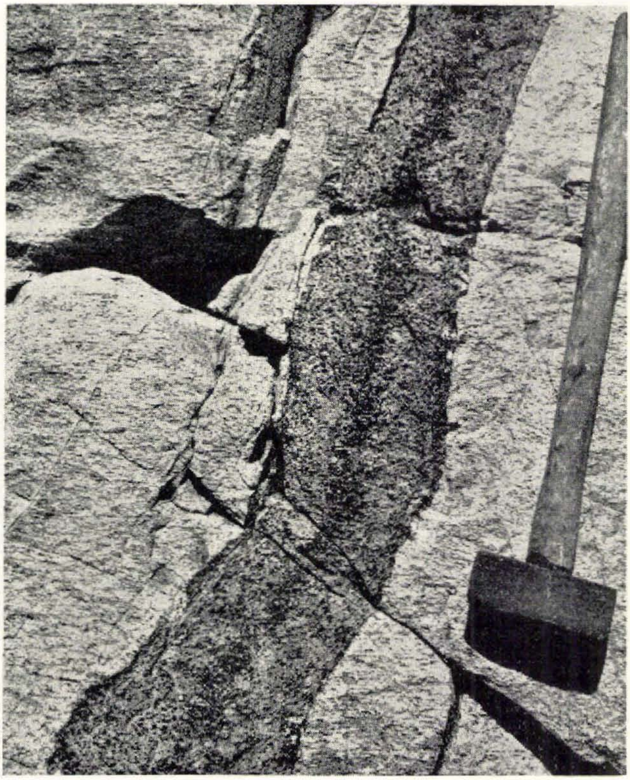


Fig. 13. Type-B dyke with crude directional structure defined by shapes and orientations of mafic aggregates. Distribution of mafic aggregates with concentration in one central zone is a more simple arrangement than that found in many dykes.

(i) Aggregates of amphibole, up to 1.5 cm in size in a homogeneous groundmass, the aggregates being distributed inhomogeneously throughout the dyke but with an ordered arrangement (see figs. 12, 13, 14). Dykes showing only this type of inhomogeneity are type-B dykes.
(ii) Larger mafic aggregates up to 20 cm in size which are veined by the more leucocratic groundmass material, the distribution of dark and light components within the dyke showing no ordered arrangement (figs. 2d, 6, 8, 15). Only dykes showing some of this type of inhomogeneity are classified as type-A dykes, many of which are similar in some respects to net-veined bodies (WAGER and BAILEY, 1953; WINDLEY, 1965).

Foliation is expressed mainly in the directional features of the first type of inhomogeneity although crude directional patterns can be seen with the second type. The amphibole aggregates are usually 2–10 mm in length, ellipsoidal in shape with long and intermediate axes parallel to the groundmass foliation and the intermediate axis parallel

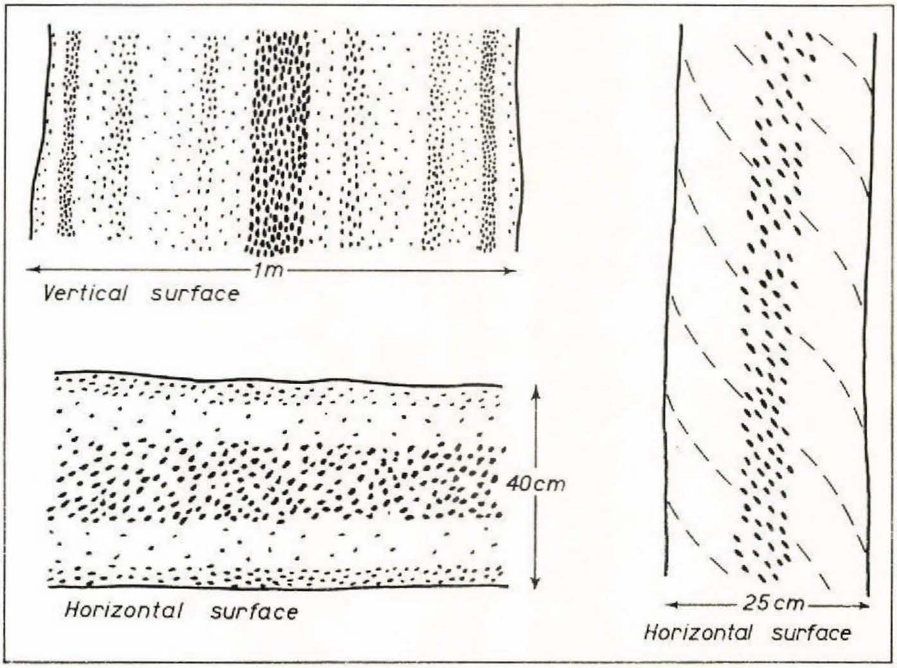


Fig. 14. Diagrammatic sketches of three type-B dykes illustrating variation in both size and distribution of amphibole aggregates.

to the dyke margins. The aggregated amphiboles are larger than those in the groundmass and unlike these show no preferred orientation. The elongation of the aggregates shows up clearly in the field (see fig. 12), but is usually on too large a scale to be a dominant feature in thin sections where the groundmass foliation is more evident.

The net-veining type of inhomogeneity is often found only along short lengths of type-A dykes, the remainder of the dyke showing features typical of the type-B dykes; in some cases, the veining occurs only, or more intensely, where dykes terminate (fig. 2d) or adjacent to places where transverse off-set movements have displaced the dyke (fig. 2e). Apophyses crossing the lines of displacement in such instances, together with apophyses which in some cases consist entirely of the leucocratic component, show that these large scale inhomogeneities are features which originated before consolidation of the dykes. The distribution and petrographic features of the smaller aggregates (see page 39) provide conclusive evidence that these too originated before consolidation, although the ellipsoidal shapes are due to later modification in the period immediately following consolidation.

The conclusions regarding the primary origin of both types of inhomogeneity are confirmed in those instances where they are intersected

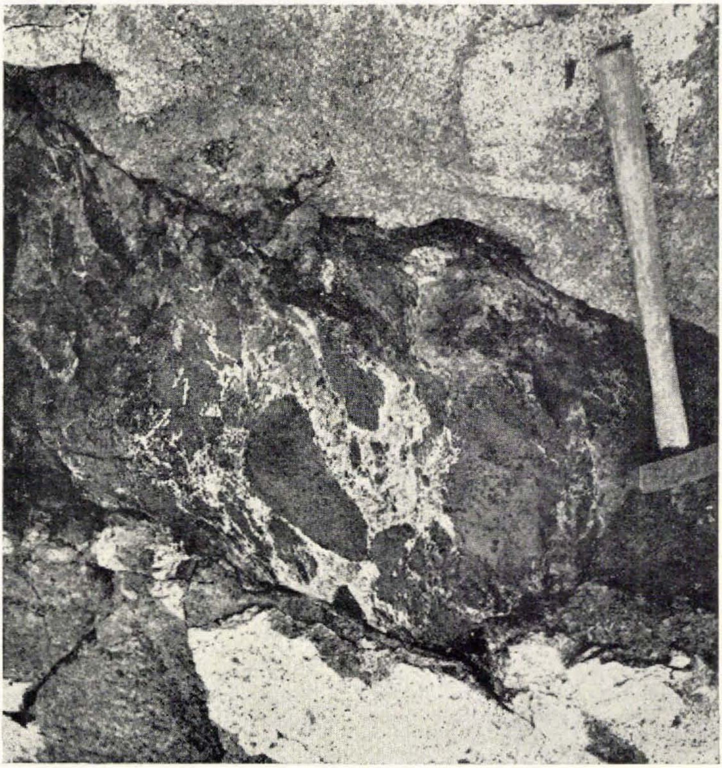


Fig. 15. Extreme textural inhomogeneity in type-A dyke with crude directional structure oblique to dyke margins.

by later dykes of the same suite. Owing to the limited range of strike directions of the dykes, intersections are rare but the four intersections found (see figs. 2a, 17b) are nevertheless of great value in confirming the times of origin of inhomogeneities and foliation derived from other lines of evidence. Details of the textural inhomogeneities are given in section III.

The field evidence strongly suggests that the leucocratic component of type-A dykes was present as a liquid phase when the large mafic aggregates were crystalline. If evidence from type-A dykes alone was available a process of composite intrusion, hybridisation, or mixing of magmas similar to that proposed by READ (1925, 1931) for the A'Chuine hybrids would perhaps seem adequate to account for some of the textural features, but the association with type-B and type-C dykes and the limited extent of veining features in some type-A dykes, suggest that the inhomogeneities are due to the differentiation of an originally homogeneous magma rather than the incomplete mixing together of originally separate components. The structural features of the dykes strongly sug-

Fig. 16. Type-B dyke with felspar phenocrysts, and felspathic vein outlining S-foliation.

gest that this separation was effected by differential movements of the wall-rocks, and the process exactly the same as that aptly described by Bowen (1928) as differentiation by deformation, and now more widely known as filter-pressing.

(iii) Orientation of foliation

The foliation in these dykes typically has a sigmoid pattern, being oblique to the strike of the dyke in the centre and becoming asymptotic towards the margins (figs. 2, 3, 12, 16). This pattern of foliation appears to be an indication of lateral movement along the dyke fissures and where suitable structures are found in the country rocks, displacement can often be seen to have occurred and in the direction expected from the foliation pattern, i.e. S-shaped foliation with dextral displacement and Z-shaped with sinistral displacement. With few exceptions (see page 31) NW dykes have dextral displacement patterns, while NE dykes show indications of sinistral movement. Both sigmoid foliation and evidence for lateral movement are most often found in type-A dykes but there is evidently no regular relationship between intensity of foliation and

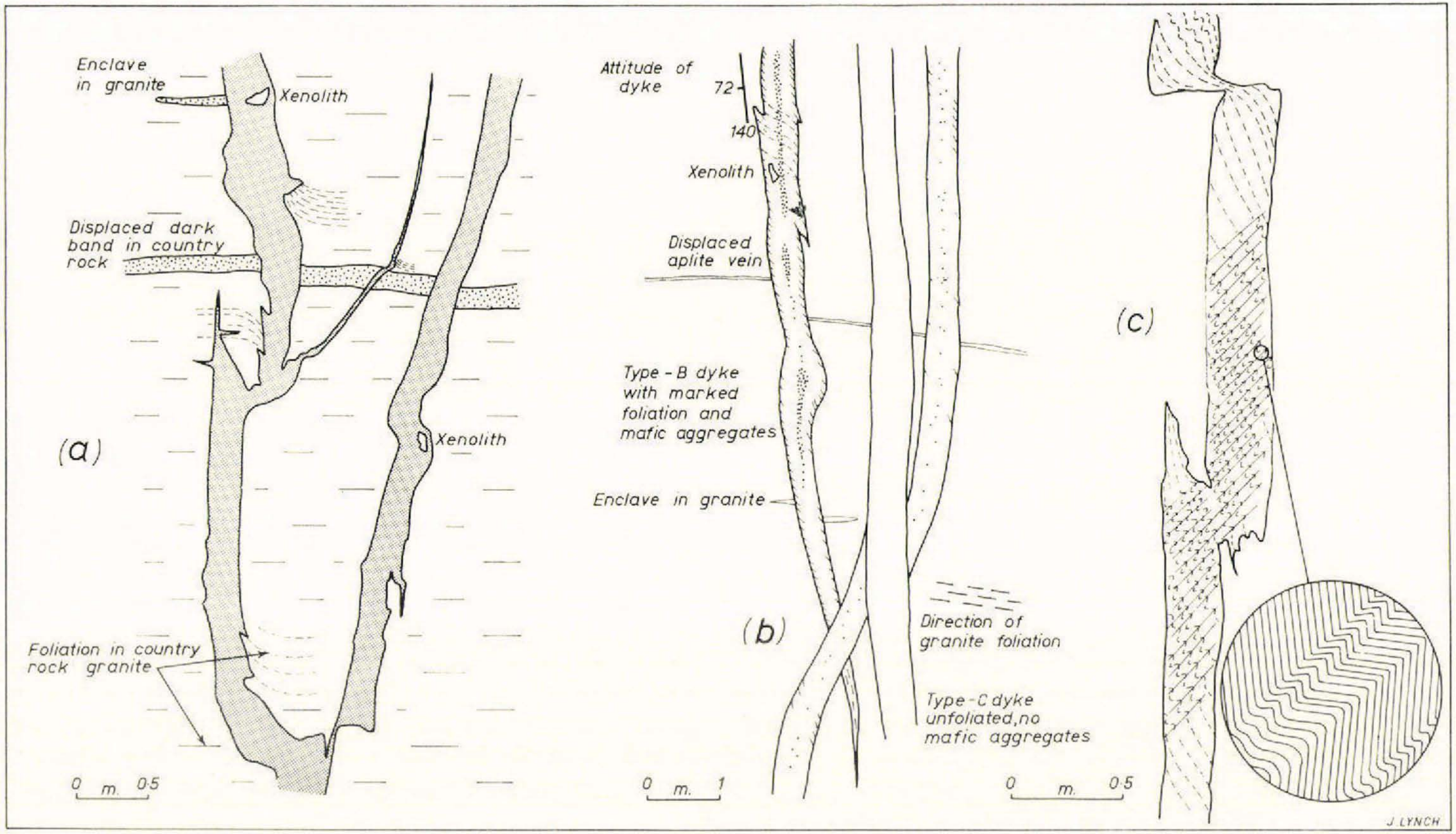


Fig. 17. (a) Type-A dyke showing primary irregularities and deflection of foliation immediately adjacent to country rock consistent with slight displacement of dark band in country rock granite. Foliation and textural inhomogeneity not shown. (b) Type-C dyke (without ornament) cutting later of two type-B dykes. Foliation in earliest dyke cut by second dyke, and slight foliation in second dyke cut by unfoliated type-C dyke. Dextral displacement of country rock structures shown only along first dyke. (c) Type-A dyke with folded foliation (see inset) forming incipient strain-slip structure and beginning of second foliation. Earlier foliation corresponds to dextral movement, later structure to sinistral displacement of wall rocks.

amount of lateral movement. Some dykes with intense foliation and a high degree of textural inhomogeneity show evidence of little or no lateral movement, and the maximum displacement of 5 m was along a dyke with relatively weak foliation. A lateral movement of 1–2 m was found in several cases. In vertical transverse sections through dykes the foliation is in all cases parallel to the margins and no indication was found of vertical displacement along a dyke fissure. In irregular dykes the foliation pattern is a subdued reflection of the irregularities and foliation is found along even the narrowest apophyses, but rarely is it sharply cut off at off-sets (fig. 3d).

In a few dykes the foliation pattern is clearly affected by off-set movements. In such cases (see fig. 3b) there is no indication that the off-set movements took place before consolidation of the dyke. On the other hand the conformity of the foliation with the pattern of displacement, and the absence of cataclastic effects show that the movement was paracrystalline with respect to that crystallisation of the dyke during which the foliation was formed. Intersection of dyke foliation by later dykes of the same swarm again affords the clearest evidence that the foliation was penecontemporaneous with the intrusion and consolidation of the dykes, rather than the result of later movements unconnected with the dyke emplacement (see figs. 2a and 17b). The more precise timing and origin of the foliation is discussed in section III.

In one case two foliations were found within one dyke, the development of the second foliation giving rise to folding of the earlier. In this NW dyke (fig. 17c) the first foliation is in the usual direction with an S pattern indicating dextral displacement, whereas the later oblique foliation is in the direction found otherwise only in NE dykes. The origin of the later foliation is discussed in section VI but it may be noted here that the folds associated with the second foliation are paracrystalline.

Conclusive evidence that the foliation in the dykes is associated with deformational movement rather than other causes is found in a B-type dyke on the west coast of Ikerasârqap nunâ. In this dyke a narrow strip of wall rock is found as a xenolith a few cm from the dyke margin and aligned parallel to it. The strike of the xenolith is thus oblique to the foliation in the dyke and the xenolith is folded on a small scale by folds with axial planes parallel to the foliation (see fig. 3a). This situation is similar to that of the dyke in which the earlier foliation is corrugated by folds with axial planes parallel to a second oblique foliation. It is clear that the directional structures in the dykes cannot be the result of static crystallisation or recrystallisation, or due to any form of magmatic flow.

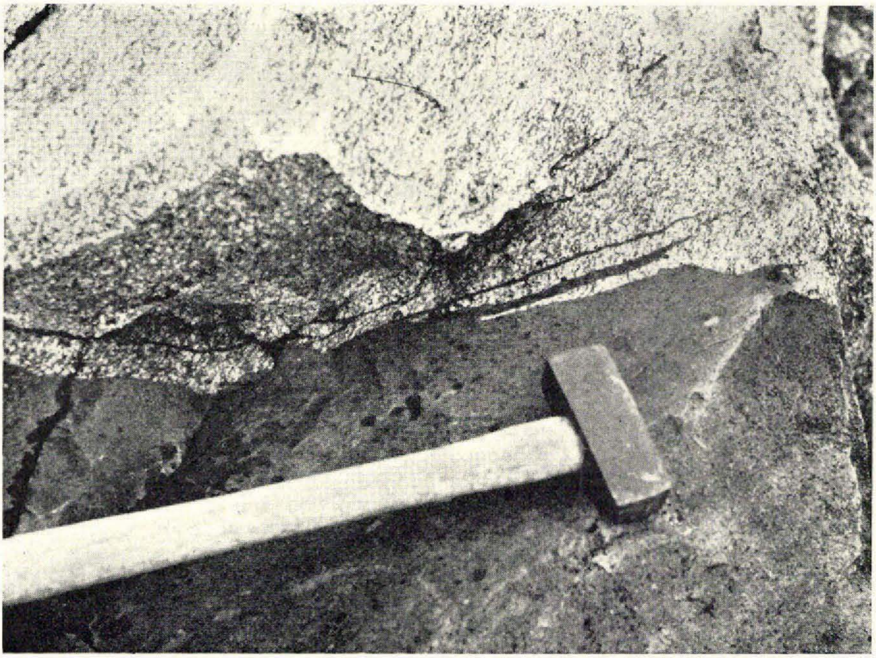


Fig. 18. Margin of type-B dyke showing brittle fractures of country rock invaded by dyke apophyses, and detachment of fragments of country rock (upper left) forming angular xenoliths.

(iv) Xenoliths in the dykes

A common feature of the dykes is the frequent occurrence of xenoliths of country rock. Although difficult to define quantitatively this feature is especially evident in the field because of the occurrence of many other dykes of similar size, both the earlier second period metamorphosed dykes and the later Gardar dolerites, which contain comparatively few xenoliths. In many cases it is evident from the shape of the xenoliths that they are derived from the immediately adjacent wall rocks (fig. 18). In other cases where this is not so the xenoliths are of similar rock type to that of the wall rock and angular in shape, and are unlikely to have been moved very far.

In only one case have rounded xenoliths of various rock types been seen; these are in the microdiorite dyke of Sánerutip imâ which has other distinctive features and is described below.

(v) Border zones of the dykes

In spite of the displacements which have taken place along dyke fissures there is no evidence in any dyke of slip along the contact between dyke and country rock; all post consolidation movement has been accommodated by internal deformation within the dykes. The invariable welding together of dyke and country rock is a further feature distinguishing these dykes from many dykes emplaced under cratogenic conditions, as is the lack of jointing which is usual in the Gardar dolerites of Ilordleq and similar rocks elsewhere.

A small but possibly important feature of some dykes, seen mostly in type-B dykes, is a marginal zone of amphibole usually only 2 mm wide or less, which separates the main body of a dyke from its country rock (see Plate 2c). It is possible that this narrow zone represents the accretionary crystallisation of the dyke, which took place when magma was flowing through the fissure. Accretionary margins are thought by the writer to be common features of many dolerite dykes, especially those which have acted as feeder dykes. The mineral composition of the accretionary zones shows which mineral phases were crystallising together at a particular temperature. If this is so these mafic margins show that crystallisation of plagioclase in the dykes was relatively late. The formation of accretionary zones and their significance will be discussed in a later communication.

(vi) Relative ages of features described

Evidence regarding age of individual features may be summarised as follows:

(1) Irregularity of dyke fissures is due neither to post-dyke disruption nor wholly to existence of irregular pre-dyke fissures. Irregularity of fissures is due, at least in part, to movements contemporaneous with intrusion of dyke magma.

(2) Foliation is due to the same movements as those responsible for lateral displacements of wall rocks, and originated immediately after consolidation of the dykes (see page 27).

(3) Textural inhomogeneities are contemporaneous with or earlier than foliation.

(4) Movements outlasted the period of intrusion of type-A dykes and probably began before intrusion of these dykes.

(5) Type-C dykes were emplaced after cessation of movements.

(6) Absence of cataclastic features in dykes shows that movements did not outlast crystallisation or recrystallisation of type-A and -B dykes (see also section III).

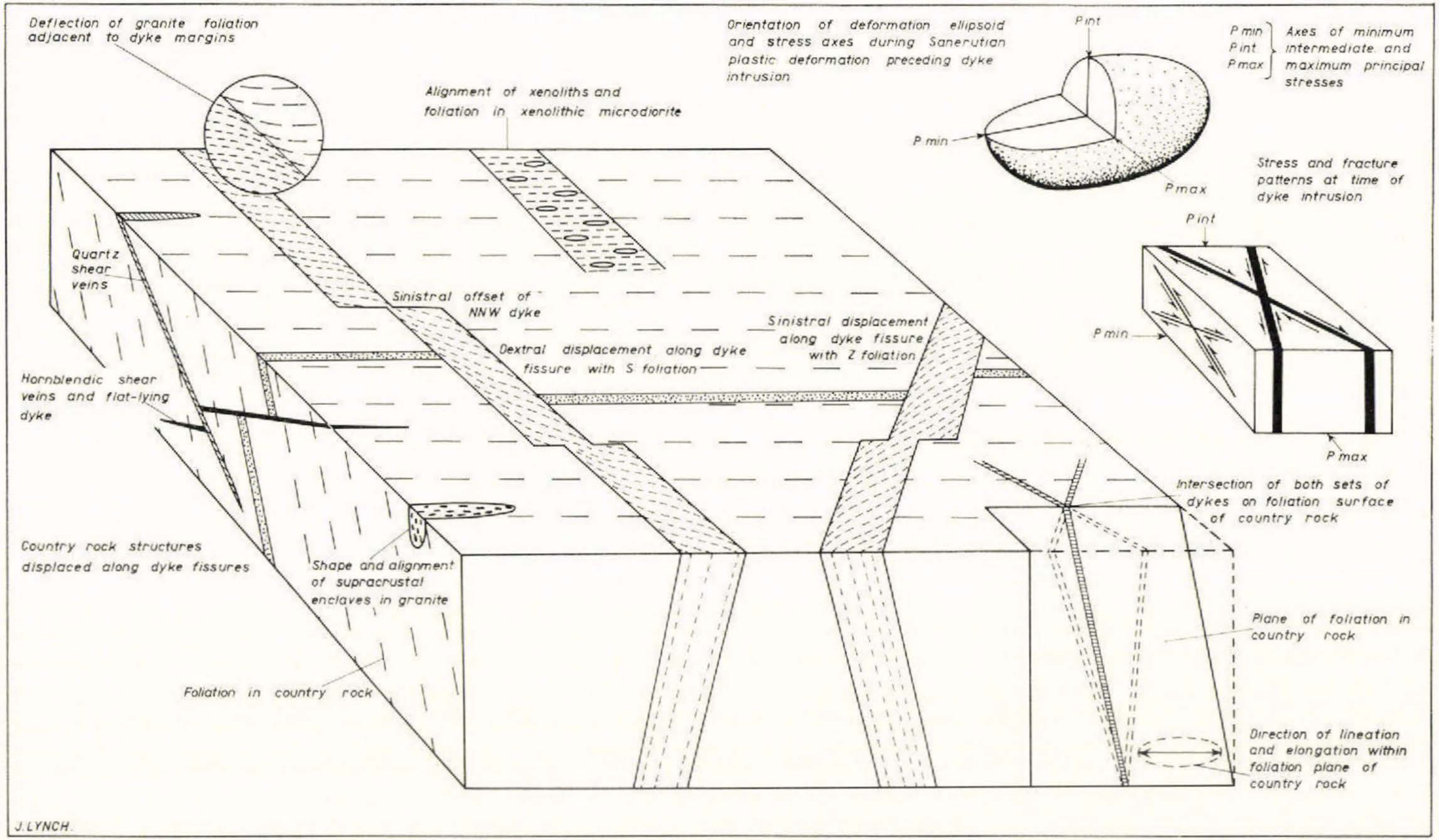


Fig. 19. Schematic structural synthesis and interpretation of collective and individual features of Ilordleq dykes, showing relationship to earlier structures in country rocks, and relationship of stress pattern during dyke emplacement to stress pattern during immediately preceding episode of flow deformation. True angular relationships not shown.

(c) Collective features

(i) Distribution and orientation

Swarms of parallel dykes occur, each swarm including representatives of the three dyke types distinguished. The distribution of dykes is shown in fig. 2 together with the orientation of each dyke. The majority of dykes strike into the NW quadrant and these dykes have other features in common which distinguish them from the NE dykes. Oblique foliation in NW dykes indicates a dextral lateral movement along the dyke fissures and in several cases this is confirmed by displacement of structures in the wall rocks. In addition, transverse off-sets oblique to the strike of these dykes most often show a sinistral pattern, although a dextral pattern is not uncommon and both may be found within the same dyke (fig. 6).

NE dykes have oblique foliation indicating sinistral movement along the dyke fissures and a mainly dextral off-set pattern. Although the number of NE dykes is not large the observations are sufficiently consistent to require explanation. Three dykes have been found which do not conform in respect of foliation pattern. Two NE dykes, one on Sãtukujôq and the other on the coast of Natsît iluat, have S instead of Z foliation patterns. The third case is the dyke previously referred to in which there are two foliations. The amount and direction of dip of the dykes conforms to a fairly regular pattern and the attitude of all dykes is best represented on a stereogram (fig. 1). The strike directions of dykes are not sufficiently separated for the recognition of two groups on the basis of strike directions alone, but two distinct groups are defined when directions of displacement are considered in conjunction with strike directions. The above relationships are shown diagrammatically in fig. 19. No intersection between NE and NW dykes has been found in Ilordleq.

(ii) Relative ages

Evidence for the position of these dykes in the plutonic history of the Ilordleq area has been given in Pt. I. This shows the dykes to have been emplaced after the magmatisation and main deformation of the country rocks due to the Sanerutian plutonic episode and before the unmetamorphosed dolerite dykes of Gardar age. In two cases dykes are cut by undeformed pegmatites similar to those emplaced in the closing stages of Sanerutian plutonism and pre-dating the late-kinematic dykes.

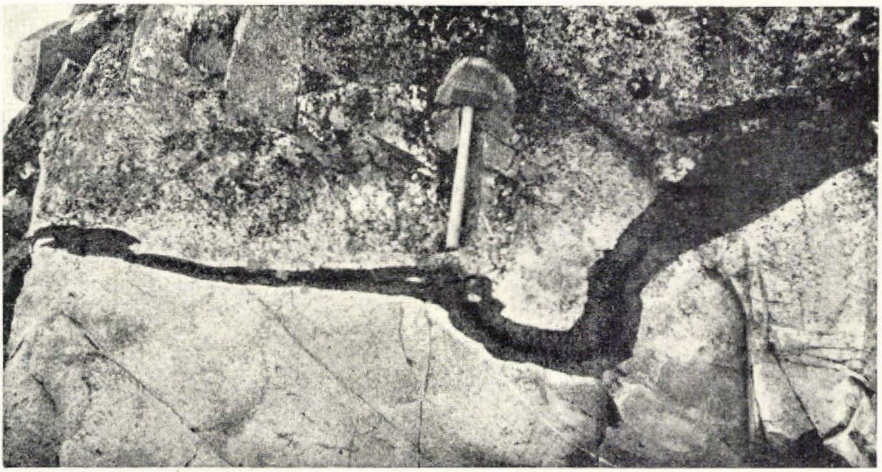


Fig. 20. Flat-lying type-B dykes (see also fig. 2c) with central concentration of mafic aggregates and bleached zones in country rocks immediately adjacent to dyke margins.

(d) Features of the country rocks

(i) Deflection of foliation

The regional foliation in the granite country rocks is oblique to the strike of the dykes (see fig. 19) and in most cases is unaffected by the intrusion of the dykes. Bordering several dykes however, a marked swing in the country rock foliation occurs within a zone 5–10 cm in width on either side of the dykes. This drag effect brings the granite foliation into continuity with the foliation in the marginal parts of the dyke (figs. 17a, 19) and further confirms the existence and sense of movement of transcurrent displacements of the wall rocks. No deflection of bedding and foliation has been seen adjacent to dykes cutting supracrustal rocks.

(ii) Alteration adjacent to dykes

In the field most dykes show no signs of contact metamorphism of the adjacent country rock. This is not unusual with dykes of this size or indeed with much larger dykes when emplaced in crystalline country rocks. The reddened oxidation zones which are often seen bordering dolerite dykes where these are found cutting granite country rocks, in Ilordleq and elsewhere, are not found bordering the late-kinematic dykes. In thin section however a narrow zone of recrystallisation has been found in the granite immediately adjacent to a dyke which has no macroscopic contact effects; this is described on page 45. No other contact of this type has been examined microscopically. Marked contact effects were however evident in the field bordering several type-A and occasional type-B dykes. This is seen as a marked bleached zone, not more than 3 cm wide, in the granite immediately adjacent to the dykes and similar in appearance to adinoles (figs. 6, 20). These are zones of potash metasomatism and thus represent a fenitisation of the granite adjacent to the dykes (see page 46). These bleached zones have not been seen in supracrustal rocks.

(iii) Shear zones in the country rocks

Some indication of the physical state of the country rocks at the time of dyke emplacement is given by the shear zones associated with oblique fault movements which produce off-set patterns in the dykes. Such obvious shear zones are comparatively rare however and in some dykes in which the foliation pattern indicates transcurrent displacement transverse to the dyke, no shear zones are evident in the granite along the lines of displacement. As a high proportion of the transverse fault lines are parallel to the pre-dyke granite foliation it is probable that the fractures have been healed sufficiently for them to be unrecognisable. Those shear zones which are evident can be seen only because the granite foliation has been disturbed by shear movements oblique to it. Microscopically the granite in the shear zones is very similar to that outside (see page 46), and it is apparent that although the granite was capable of brittle fracture to allow intrusion of the dykes (see fig. 18) the evidence of shear zones and deflection of the foliation adjacent to some dykes that it was at the same time capable of plastic deformation, and recrystallisation. These conclusions are in no way contradictory. Over a fairly wide range of conditions, certainly including those of the lower and middle grades of regional metamorphism, the deformation characteristics of granite and other rocks are likely to vary considerably with differing rates of strain.

Shear zones similar to those associated with dyke off-sets are found cutting the granitic rocks of the area; these shear zones dip at low angles to the NNW and although their chronological position has not been established beyond all doubt, they are thought to be penecontemporaneous with the dykes. Several of the shear zones show bleaching of the country rock immediately adjacent to the displacement surfaces, along which veins of amphibole occur (fig. 23).

(e) Xenolithic microdiorite

This occurs as a 1.5 m dyke which is discontinuously exposed over a distance of 15 m. The strike is NNW and the microdiorite cuts a

Fig. 21. Margin of xenolithic microdiorite showing alignment of xenoliths parallel to structures in country rock, and normal to dyke margin.

type-C dyke. The diorite is of particular interest as it is the only member of the suite which contains rounded xenoliths, and also because it is the most leucocratic member of the suite and very similar in appearance and composition to the leucocratic component of the filter-pressed type-A dykes.

The microdiorite itself is a fine to medium grained grey homogeneous rock but containing about $35\,^0/_0$ of xenoliths which vary in size from a maximum of 25 cm down to a few mm. The larger fragments have irregular shapes but with corners rounded off and most of the smaller ones are well rounded. A strange feature of the dyke is the alignment of xenoliths parallel to the foliation in the diorite which is normal to the dyke margins (figs. 21, 22)—a feature unlike that in any other dyke of the suite. The foliation in the diorite is parallel with that in the country rock granite which is normal to the dyke margins. The exposed margins of the dyke show only small scale irregularities (fig. 21).

A small proportion of the xenoliths are of granite identical with that of country rock, and which are no less rounded than the other xenoliths which consist of various types of amphibolite. Both in the field and under the microscope the amphibolite xenoliths resemble the various rock types typical of type-C dykes and are therefore regarded as cognate.

Fig. 22. Central portion of xenolithic microdiorite showing rounding and alignment of both cognate xenoliths (dark) and xenoliths of country rock granite (white).

(f) Summary of conclusions to be drawn from field relationships

Many of the dykes were emplaced in active shear zones along which intermittent movement took place at about the same time as the dykes were emplaced; as a result xenoliths are relatively abundant. The latest dykes, type-C, show no evidence of movement along the dyke fissure and have no foliation. Type-B dykes have been deformed and foliated by lateral displacement of the wall rocks after consolidation of the dykes. The paracrystalline nature of the deformation indicates that these dykes were able to recrystallise after consolidation. Type-A dykes were deformed also during the later stages of consolidation, resulting in a separation of the remaining liquid from the crystallised material. The crystalline component consists largely of mafic minerals; the separated liquid crystallised to form a leucocratic felspar-rich component.

The microdiorite with rounded xenoliths contains fragments of both country rock and cognate inclusions, but is otherwise similar to the leu-

Fig. 23. Hornblendic shear zones cut and displaced by flat-lying quartz vein.

cocratic component of the type-A dykes which was separated by filter-pressing during consolidation.

At the time of emplacement of the dykes the country rock granite was still capable of plastic deformation and recrystallisation, and was evidently at an elevated temperature. Pegmatite formation continued after intrusion of the dykes.

III. MICROSCOPIC FEATURES

In this section a general description of the microscopic characters of the main dyke types is given, together with the conclusions which have been drawn regarding the crystallisation history and mineral facies of consolidation of the dykes.

(a) Descriptions

(i) Type–C dykes

The macroscopic homogeneity of these dykes is reflected in their microscopic characters, and they approach a state of textural equilibrium more closely than either A- or B-type dykes. Absence of foliation and the occurrence of some acicular hornblendes are the only important features which would distinguish these rocks from originally basaltic rocks metamorphosed and completely recrystallised in the almandine-amphibolite facies. The dykes are fine grained and chilled margins have not been seen in the field.

Hornblende, andesine, biotite, epidote and sphene are invariably present and in relatively constant proportions. Opaque ore minerals occur only rarely and are then rimmed by sphene. Andesine comprises 45–50 % of the rocks and is accompanied by hornblende 30–35 %, biotite 10 %, epidote 5–10 %, and small amounts of sphene and traces of apatite.

A small proportion of the hornblende occurs as acicular prisms usually 2–3 mm in length and with centres darkened by dusty inclusions of sphene. Strongly corroded borders are usual and together with rare examples of bent or broken crystals suggest that these acicular hornblendes were present as phenocrysts in the magmatic stage. Biotite is found along fractures in these crystals and a few examples of brown colour further distinguish these from the groundmass hornblendes. Brown phenocrysts contain no granules of sphene and are probably kaersutite. The remainder of the hornblende occurs as short subhedral prisms without preferred orientation, only few of which have dark cores with sphene. These crystals are evenly distributed and together with the plagioclase form the granoblastic groundmass texture which is characteristic of the type-C dykes. The usual grain size is 0.5 mm.

Plagioclase occurs in irregular anhedral or subhedral prisms closely interlocking with hornblende, and frequently untwinned. Normal zoning from An_{45}–An_{35} is common, especially in twinned crystals; unzoned crystals are An_{35} but both zoned and unzoned crystals occasionally have rims of albite. Rare plagioclases of similar size and form to the acicular hornblendes are found in only a few dykes, and these too are sometimes broken and contain biotite along fractures. The large plagioclases are zoned An_{60}–An_{35} and are usually sericitised. Anhedral crystals of epidote are more frequent than the occasional subhedral grains, neither exceeding 0.2 mm in size. Both epidote and sphene are evenly distributed, the latter occasionally forming euhedral wedge shaped crystals; in this respect these dykes differ from typical metabasalts in which epidote is found together with plagioclase and sphene with hornblende. Subhedral flakes of biotite rarely exceed 0.2 mm in size and show cross-cutting relationships only where they occur along fractures in large hornblendes and plagioclases. In none of the type-C dykes is evidence found of retrograde autometamorphic change.

A feature of about half the type-C dykes found is the presence of ocelli, 1–3 mm in diameter, fairly widely spaced and containing variable mineral assemblages distinct from those of the host rocks: the commonest minerals in the ocelli are calcite, epidote and analcite, with occasional prehnite. These ocelli are interpreted as amygdales, and their absence from other than type-C dykes is most likely a result of the post-consolidation deformation and recrystallisation in the type-A and -B dykes.

About six dykes were found which although classified as type-C dykes have some important distinguishing features, and are referred to as leucocratic type-C dykes. The field relations of these dykes are identical with those of the other type-C dykes, but they are readily distinguished in the field by the prismatic habit of the amphiboles (see plate 3a) and a pinkish tinge due to the presence of up to 10 % microcline. The amphiboles are similar to the prismatic amphiboles occurring infrequently in other type-C dykes but almost invariably show fracturing and resorption. The proportion of felspar at 65–75 % is higher than in other dykes of the suite with the exception of the xenolithic microdiorite. No dykes have been found in Ilordleq which are intermediate between the two varieties of type-C dyke, but their several common features suggest that transitional types may be expected to occur elsewhere.

(ii) Type–B dykes

These dykes consist of amphibole aggregates in a fine grained groundmass. The groundmass is similar mineralogically to the type-C dykes described and in many dykes has achieved a similar degree of textural equilibrium. The size, distribution and amount of amphibole aggregates varies considerably from those dykes with numerous large aggregates grading towards type-A dykes, to those with fewer and smaller aggregates which grade towards type-C dykes. The dykes thus show an almost complete textural gradation from A to C which correlates well with other differences such as irregularity of outcrop, degree of foliation and relative ages. The gradation is incomplete insofar as type-A dykes are defined as those showing evidence of physical separation of aggregates and groundmass.

The distribution of aggregates in type-B dykes, although varying from one dyke to another, conforms to a regular pattern within individual dykes. Variation in size and amount of aggregates varies with distance from the dyke margin resulting in an often well-defined banding parallel to the margin (figs. 13, 14). Such banding is symmetrically disposed about the centres of the dykes forming a pattern similar in some respects to that characteristic of multiple intrusion. The gradational nature of the changes and lack of internal contacts suggest that a more gradual process is responsible. Some dykes have aggregates all of similar size evenly distributed, and a common simple pattern is shown in dykes which contain only few small aggregates on the margins, the aggregates increasing in size and number towards the centre. Another common pattern is that shown by dykes in which aggregate-free marginal zones pass into aggregate rich zones which in turn pass into a central zone free of aggregates. Mafic aggregates are found in the marginal parts of some dykes but several of the type-B dykes have fine-grained margins which differ only in grain size from the groundmass of the rest of the dykes. In a large number of dykes a thin layer of amphibole, about 1–2 mm in width separates normal dyke material from country rock (Plate 2c).

A common type of amphibole aggregate consists mainly of several large hornblendes; individual hornblendes rarely exceed 1 mm in size regardless of the size of aggregate. Smaller aggregates may contain only one or two of these hornblendes (Plate 1a) but many more are found in larger aggregates which in type-B dykes range up to 1.5 cm in size (Plate 2a). The aggregates in these dykes do not often exceed about 50 $^0/_0$ of the dyke as a whole but in parts of dykes the proportion may reach 80 $^0/_0$. The origin of the aggregates is indicated by the features shown by the large hornblendes within them. In many cases these hornblendes contain aggregate cores of unoriented fibrous amphibole. The outer margins of the large crystals although irregular on a small scale show subhedral six sided outlines in some cases. Disseminated granules of sphene are concentrated in zones surrounding the fibrous cores but are not found in either the fibrous amphiboles or the margins of the surrounding crystal. The fibrous cores to these hornblendes have all the characteristics of uralite and individual fibrous crystals are of tremolite (fig. 24c and d). This often repeated texture suggests that early pyroxenes were mantled with hornblende during an early, probably magmatic, stage of evolution of these rocks, the mantling hornblende now appearing as the large hornblendes in the aggregates, the pyroxenes surviving for some time as armoured relics before becoming uralitised. The alteration of the pyroxene may have taken place after consolidation of the dykes but the exact stage at which it took place is not important, whereas it is important to establish that the rimming amphibole is not itself pseudomorphous after pyroxene and that it does in fact date from the magmatic stage. Uralisation of pyroxene in metabasalts produces a texture different to that described above and all the uralitic amphibole is of the fibrous type. Extension of the amphibole beyond the confines of the original pyroxene does in some metabosalts produce a narrow rim of optically continuous amphibole surrounding the uralite but to the writer's knowledge these rims are not usual, and are always narrow in relation to the size of the fibrous uralite mass. Hornblendes similar to those found in type-B dyke aggregates are found however in appinitic rocks where there is clear evidence of hornblende rimming pyroxene during the magmatic stage, the pyroxene later being uralitised. Figure 24b shows a large amphibole from an appinitic diorite adjacent to the Ardara granite diapir, Ireland, enclosing a rounded pyroxene. In another amphibole from the same rock, figure 24a, the original enclosed pyroxene has been uralitised. On this evidence alone a primary origin for the large hornblendes in the type-B dykes seems likely. The figured amphiboles from Ardara are phenocrysts, often euhedral, brown in colour (kaersutite) with outer zones of green hornblende. In some of the large hornblendes in type-B dykes, and more commonly in type-A dykes, uralitic cores are either very small or absent; in the latter case the concentrations of sphene granules extends throughout the central parts of the crystals although, as in other cases, they are absent from the margins.

The large hornblendes described do not contribute to the elliptical shapes of the aggregates in which they occur: these are defined by masses of finer grained amphibole which surround and smooth off the irregularly shaped aggregates of larger crystals (fig. 25). The smaller crystals intersect the boundaries of large amphiboles when they are adjacent, and appear to replace them marginally. Large amphiboles occurring singly and not surrounded by smaller crystals are very rare. A few dykes contain aggregates consisting entirely of a fibrous matt of the small amphiboles, which presumably have completely replaced the larger crystals originally forming the aggregate (fig. 26); in these cases the elongation of the aggregates is more pronounced than usual. The smaller

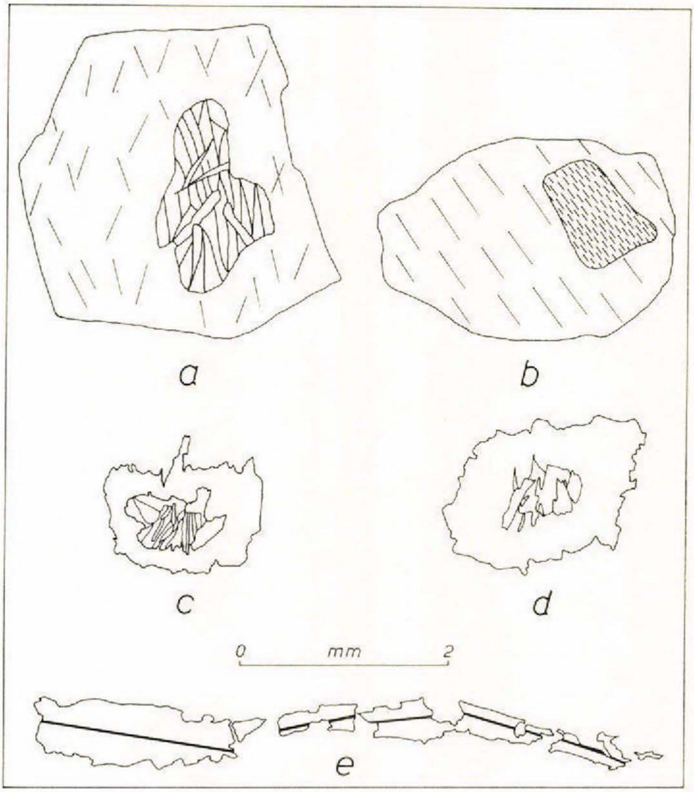


Fig. 24. (a) Brown amphibole with green margins enclosing uralitic core. (b) Brown amphibole with green margins enclosing clinopyroxene. Both from hornblende diorite in appinitic satellite to Ardara diapiric granite, Co. Donegal, Ireland. (c) and (d) Green amphiboles with fibrous uralitic cores from type-B dyke, Ilordleq. Rimming amphiboles have abundant inclusions of granular sphene decreasing towards margins. (e) Disrupted prismatic amphibole with brown core. Type-C dyke, Ilordleq.

amphiboles occurring in the aggregates form irregular laths 0.2 mm or less in size, and are somewhat larger than otherwise similar groundmass amphiboles; they do not contain granular inclusions of sphene. Large crystals of bright yellow epidote are found in many aggregates but their occurrence appears to be capricious.

The groundmass of type-B dykes consists of plagioclase, hornblende, and biotite in proportions 50:35:10, with smaller amounts of sphene, epidote and a little apatite. Epidote may on occasion comprise 5–10 $^0/_0$ of the groundmass. The plagioclase occurs as pellucid polygonal equant grains, which are rarely twinned. The composition of the plagioclase is mostly in the range An_{35}–An_{40} but some oligoclase is found. Hornblende and biotite have a marked preferred orientation parallel to the elongation of the aggregates, but in few cases is this foliation deflected around the aggregates. The stable mineral assemblage at the time of the formation of the paracrystalline foliation was hornblende-andesine-biotite-epidote-sphene.

The occurrence of ovoids of intensely poikilitic scapolite has been noted in the marginal zones of about four type-B dykes: these scapolites appear to be syn-kinematic with respect to the deformation producing the foliation.

(iii) Type–A dykes

The appearance in the field of the extreme textural inhomogeneity which characterises these dykes has been described. The separation into two components, one ultramafic and the other dioritic, differs from that in the type-B dykes in the following two ways: (i) the mafic aggregates in type-A dykes are larger and may reach 20 cm in size. Owing to this difference in scale the type-A dykes may appear more homogeneous in thin section than type-B dykes; (ii) veins of the leucocratic component cut the mafic aggregates and provide conclusive evidence of the time relationship between minerals in the two components.

Ultramafic component: this comprises approximately 50–75 % of individual dykes and may consist entirely of mafic minerals or contain up to 20 % plagioclase. The aggregates in which felspar is absent are most often the smaller ones, but felspar-free aggregates of 20 cm have been found. These felspar-free aggregates are hornblendites containing up to 15 % epidote and small amounts of sphene. Opaque ore is sometimes present in small quantities. The aggregated amphiboles are stubby anhedral prisms without preferred orientation and only rarely with signs of cataclasis, notwithstanding the elongated form of the aggregates. Individual hornblendes are of the same two types as those found in aggregates of the type-B dykes. The larger hornblendes, rarely greater than 2 mm in size, are usually zoned with darker green cores; the dark inner zones contain numerous small granules of sphene which serve to increase the colour contrast of the zoning and have more regular outlines than the outer margins of the crystals. Uralitic cores are much less common in hornblendes of type-A dykes than in those of type-B dykes. The smaller hornblendes in the aggregates are similar to those in the aggregates of type-B dykes and similarly make up varying proportions of the aggregates. The proportion of the large earlier hornblendes in the aggregates is in general much lower than in type-B dykes, and appears to decrease with increasing size of the aggregate. Apart from the minute granules of sphene in the inner zones of the larger hornblendes, larger anhedra of this mineral occur interstitially within the aggregates. When felspar is found in the aggregates it is entirely enclosed by fibrous matts of the smaller hornblendes. The felspar crystals are polygonal and un-

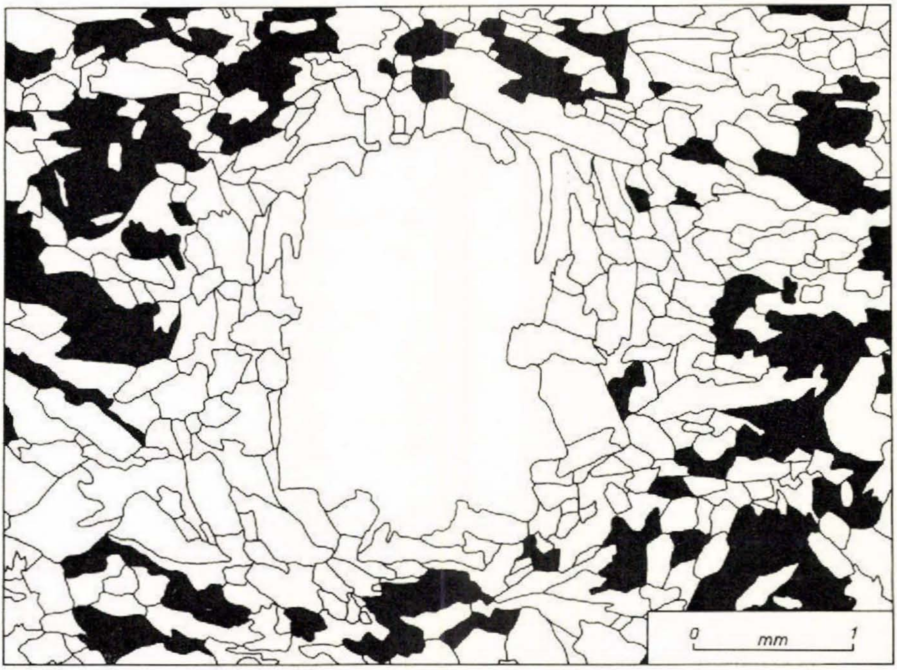


Fig. 25. Amphibole aggregate with single large hornblende, in groundmass of amphibole (plain) and plagioclase (black). Type-B dyke.

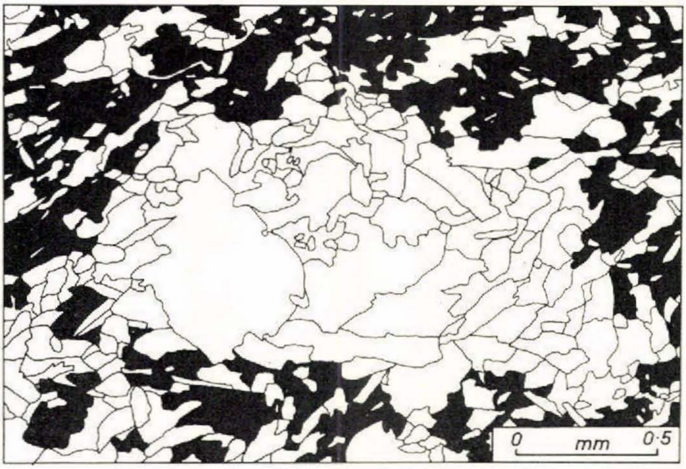


Fig. 26. Amphibole aggregate in groundmass of amphibole (plain) and plagioclase (black). Type-B dyke.

zoned; owing to the absence of lamellar twinning the composition has not been accurately determined but is within the range oligoclase-andesine. It is not known whether there is a systematic variation in the proportion of felspar within individual aggregates.

Leucocratic component: this consists of about 70 % felspar with biotite and hornblende comprising a further 20 %, and epidote and sphene together about 10 %. The proportions are variable and the figures given apply to the most leucocratic of the common types examined. The felspar shows marked evidence of disequilibrium, occurring in two generations the earlier of which is strongly zoned. The composition of the cores of zoned crystals is variable and may be either calcic oligoclase or andesine, while the rims are albite. The later felspars have polygonal outlines which strongly contrast with the irregular prismatic form of the earlier crystals which almost invariably show lamellar twinning. The composition of polygonal felspars is variable (see section on autometamorphism) but none is more calcic than An_{40}. The leucocratic component of type-A dykes is usually foliated but less regularly than is usual in type-B dykes. The veins of the leucocratic component which transect the mafic aggregates is usually similar in all respects to that which surrounds them. Some narrow veins which cut the aggregates consist either of epidote, or of epidote, albite and chlorite.

Important variations from features described in the foregoing generalised accounts are described below.

(iv) Autometamorphic recrystallisation

In about half the type-A and type-B dykes examined microscopically some chlorite is found; only in rare cases is it present in amounts equal to or greater than the other mafic minerals. No chlorite occurs in type-C dykes. In those dykes in which it occurs the chlorite clearly replaces either biotite or amphibole and is most common either in the leucocratic groundmass or on the margins of aggregates. Narrow bands of chlorite have however been seen within a large mafic aggregate in a type-A dyke. The proportion of chlorite to that of other mafic minerals is extremely variable even within the confines of a single thin section. This variability makes it difficult to make a quantitative assessment of concomitant changes, but where it is especially concentrated the chlorite is accompanied by larger proportions of epidote. The only calcite found in the dykes, apart from that found in amygdales, is also closely associated with chlorite.

The formation of chlorite evidently represents the production of a retrogressive assemblage in the dykes. Recrystallisation to this assemblage has taken place only locally within the dykes and quantitatively is of little importance except in a few dykes. The chlorite nowhere is seen to be later than the foliation, but as this could possibly be due to mimetic crystallisation there is no direct evidence that the chlorite assemblage dates from the time of dyke emplacement. It is interpreted as an autometamorphic change (see page 49).

(v) Feldspar phenocrysts

In two of the thin sections examined of type-B dykes are rare euhedral plagioclase phenocrysts. In the field two further dykes were seen containing felspar phenocrysts concentrated towards the centres; in other respects these dykes are type-B dykes with marked foliation (see fig. 16) and some mafic aggregates. The plagioclases are typically igneous with labradorite cores zoned to andesine margins and with lamellar twinning; they are thus more calcic than any other felspars found in the dykes and perhaps because of this are strongly sericitised. In view of the evidently late crystallisation of felspar in the dykes the occurrence of a clearly early magmatic felspar, albeit in small quantity and of restricted distribution, is difficult to account for. A possible explanation is given on page 72.

(vi) Xenolithic microdiorite

The xenolithic fragments of amphibolite in the diorite are texturally indistinguishable from type-C dykes and the only difference between fragments is in the relative proportions of plagioclase and amphibole. The diorite too has textural similarities with type-C dykes and the main difference is in the higher proportion of plagioclase in the microdiorite than in any type-C dyke, and the equal proportions of amphibole and biotite. Amphibole and biotite together comprise 15–20 $^0/_0$ of the rock, the remainder being plagioclase except for the small amounts of sphene and epidote which are always present.

Two types of felspar occur, one of typically igneous aspect, with lamellar twinning, subhedral outlines and usually zoned from about An_{45} to An_{35}. The smaller anhedral, untwinned and unzoned plagioclases intersect the regular outlines of and are later than the twinned felspar; they are slightly more sodic than the marginal parts of the earlier felspar. No preferred orientation of minerals is apparent in the thin sections examined.

(vii) Alteration of country rocks adjacent to dykes

More than half the dykes show no macroscopic signs of contact alteration of their wall rocks. Only one of these contacts has been examined microscopically and in this example evidence of thermal alteration of the granitic country rock is confined a zone 1 mm in width in which the granite has been recrystallised to form a fine grained equilibrium mosaic with plagioclase/plagioclase triple junctions with 120° angles (see Voll, 1960). This slight contact effect is to be expected with such small intrusions and indeed dykes of such size frequently show no contact effects at all when emplaced in country rocks of plutonic origin. In contrast to these slight contact effects leucocratic zones, 0.5–3 cm in width are found bordering several dykes (Plate 3b). Under the microscope this leucocratic zone is seen to consist almost entirely of microcline, often in the form of large porphyroblasts up to 1 cm in size, accompanied by small quantities of epidote and in one case a stellate aggregate of actinolite. The plagioclase, biotite, hornblende and quartz which are present in the unaltered granite are completely absent from this leucocratic zone. Extending for 2–3 times the width of the macroscopically visible zone is a further zone in which plagioclase is strongly sericitised and in which biotite is altered to chlorite. The total width of the zone of contact alteration is thus up to nearly 10 cm. Insufficient material is available to attempt a quantitative assessment of these marginal zones of alteration but it is clear that metasomatic introduction of potash felspar has taken place in the leucocratic zones.

The metasomatic zones are in some respects similar to adinoles but chemically their formation has more in common with that of potash-rich fenites. The alkaline composition of intrusive rocks bordered by fenites leaves little room for doubt regarding the source of potash, but rocks of the composition of the Ilordleq dykes are an unlikely source of potash. It is thought that these zones of metasomatism and alteration do not in fact represent the contact effects of the dykes,, but were formed on either side of the fissures before intrusion of the dyke magma. This suggestion is supported by the occurrence in the neighbouring area of Alángorssuaq, of metasomatically altered areas of the country rock granite which are associated with hot shears in the granite, and dykes similar to those described in this account (see page 93). Although the metasomatism on Alángorssuaq differs from that of Ilordleq in being largely a soda influx, it also involved desilication of the granite, and was therefore described as 'syenitization' by HARRY and OEN (1964). The syenitization is ascribed by HARRY and OEN to the migration along shear zones of pneumatolytic fluids at high temperature (600–700°) and pressure greater than 3000 bars.

(viii) Shear zones in country rocks

The petrographic features of the country rocks into which the dykes were emplaced have been described in Part I (WATTERSON, 1965). Of particular interest are the shear zones in the country rock granite which were contemporaneous with dyke emplacement. The only specimen collected was from the shear zone shown in fig. 27, the unaltered country rock of which is the Sanerutian hornblende granite (*op. cit.*). Both the shear zone and adjacent unaltered granite contain about 15 $^0/_0$ of dark

Fig. 27. Quartz veining along shear zone in country rock in line with dyke off-set (not shown).

minerals, mostly amphibole and biotite with some sphene and epidote. In the unaltered rock biotite and hornblende occur in equal amounts, whereas the shear zone contains about three times as much biotite as amphibole. The grain size of the unaltered and sheared rocks is similar in respect of the quartz and felspars, but myrmekite is found only in the shear zone. A noticeable difference between the two rocks is in the smaller grain size of the dark minerals in the sheared zone, in which both amphibole and biotite are usually less than 0.1 mm in size. This fine grain size is not due to mechanical degradation as crystals of neither amphibole nor biotite show signs of cataclasis, nor is any chlorite found. Although the mineral assemblages in rocks of granitic composition are of little diagnostic value in mineral facies classification, the presence of stable biotite and hornblende in shear zones suggests that temperatures within the metamorphic range prevailed in the country rocks at the time of dyke intrusion. The occurrence of hornblendic shear zones (section II d (iii)) is a further indication that at the time of intrusion of the dykes the stable assemblages in the country rocks may have been of a facies higher than that of lower greenschist facies.

More substantial evidence than is at present available is needed before firm conclusions can be drawn regarding the conditions of the country rocks at the time of dyke intrusion, but in view of the possible importance of such conclusions (see page 50) it is hoped that the necessary information will be obtained either in Greenland or from similar rocks elsewhere.

(b) Conclusions drawn from petrographic features of the dykes

(i) Crystallisation history

The mafic aggregates which comprise up to 75% of type-A dykes and smaller proportions of type-B dykes show that mafic minerals had an extended period of crystallisation before the crystallisation of felspar, which did not begin until about half the dyke magma had crystallised. The most convincing physical evidence of this is shown in dykes in which early formed minerals were separated from the remaining liquid by deformational movements which gave rise to filter-pressing of the type-A dykes. The occurrence of relatively large hornblendes in mafic aggregates, especially in type-B dykes, is a further indication of the early crystallisation of mafic minerals relative to plagioclase, but provides less conclusive evidence because of the necessarily greater interpretive factor involved.

An important feature of the aggregates is the occurrence of hornblendes containing uralitic cores, surrounded by zones containing granules of sphene which are succeeded by clear outer zones. By analogy with similar rocks (page 40) the cores of these crystals are thought to represent the pyroxene which was stable only during the earliest stages of crystallisation of the dyke magma. Succeeding zones crowded with granules of sphene, together with the brown titanium-rich amphibole (kaersutite) which survives in some type-C dykes, suggests that the zone immediately surrounding the pyroxene originally crystallised as brown titanium-rich amphibole from which sphene granules were exsolved when this amphibole became unstable at a later stage in the crystallisation. The outer clear zones of the large amphiboles are similar to the small hornblendes which surround the aggregates and occur in the groundmass, and the crystallisation of this amphibole is thought to coincide with the direct precipitation from the magma of sphene, which occurs interstitially in the amphibole aggregates. The acicular amphibole phenocrysts in the type-C dykes have either brown cores or dark green cores with abundant granules of sphene. No uralitic cores are found in the amphiboles of type-C dykes and any pyroxene formed at an early stage of crystallisation has been entirely resorbed. The succession of mafic phases precipitating from the magma appears to have been:

pyroxene → Ti-rich amphibole → hornblende + sphene. The conclusions drawn regarding the decrease in titanium content of amphibole with decrease in temperature of crystallisation, are consistent with the available chemical data relating TiO_2 content to amphibole paragenesis (LEAKE, 1965).

Biotite is not found in the mafic aggregates and first appeared at about the same stage as plagioclase, or maybe somewhat later. During consolidation of the last 40–50 % approximately of the dyke magma, hornblende, biotite, plagioclase, sphene, epidote and apatite were crystallising together.

Recrystallisation has probably destroyed all traces of the original magmatic textures in the fine-grained portions of foliated dykes, and only in type-C dykes are original textures dominant.

(ii) Mineral facies of consolidation and autometamorphic recrystallisation

Type-C dykes typically have equilibrium assemblages characteristic of almandine amphibolite facies. Although there is evidence suggesting that some amphibole is derived by alteration of a more titanium rich amphibole, in none of the dykes is pyroxene preserved. The absence of pyroxene in rocks of the composition of these dykes (table I) clearly indicates that neither at the time of consolidation of the dykes nor subsequently were conditions suitable for production of an assemblage characteristic of either granulite or pyroxene hornfels facies. The dominant assemblage is hornblende-andesine/oligioclase-epidote-sphene-(biotite). The occurrence of sphene distinguishes this assemblage from that of the hornblende hornfels facies. Only one generation of plagioclase is usual but in some type-C dykes the occurrence of polygonal albites similar to those in type-A and type-B dykes shows the beginning of a recrystallisation in a lower facies.

In type-A and -B dykes the following assemblages are found in addition:

(a) hornblende-albite-epidote-biotite sphene

(b) actinolite-epidote-albite-chlorite-sphene

These are characteristic assemblages of the quartz-albite-epidote-almandine sub-facies (a) and quartz-epidote-biotite sub-facies (b) of the greenschist facies, the former corresponding to the old epidote-amphibolite facies. Occurrence of calcite with some (b) assemblages suggests that limited recrystallization in the lowermost sub-facies (quartz-albite-muscovite-chlorite) of the greenschist facies may have taken place. No rock from an A- or B-type dyke shows an equilibrium assemblage characteristic of any of the above sub-facies. The textures previously described which demonstrate the age relationships of some minerals do show however that progressively lower temperature assemblages were being formed in these dykes. Type-C dykes, which are the latest, show little or no sign of recrystallisation to lower temperature assemblages. The interpretation put forward to account for the features summarised above is a simple one suggested by the field evidence.

An important characteristic of both magmatic and metamorphic rocks is the "freezing" of high temperature assemblages, and the comparative rarity of autometamorphic and retrograde assemblages characteristic of the progressively lower temperatures through which the rocks must pass during their cooling. As this is due to the slow rates of reactions necessary for the production of the new assemblages, the rate of cooling is the most obvious factor to be taken into consideration. Although the rate of cooling of the Ilordleq dykes is likely to have been less than that of more typical minor intrusives, no significant difference is likely in the rate of cooling of type-C dykes, which show little or no autometamorphic changes, when compared with that of type-A and -B dykes. Of the factors which have been suggested as being likely to influence rates of reaction (see Fyfe, Turner and Verhoogen, 1958, Chapter III) which include pressure, water content and water pressure, stress history is the only one for which a significant difference between dyke types is likely. The importance of stress in promoting recrystallisation is well known in areas of regional metamorphism where recrystallisation of competent rocks lags behind that of incompetent rocks. Type-C dykes resemble typical cratogenic magmatic rocks, insofar as they retain the assemblage stable at the time of consolidation and have more or less normal field characteristics. Type-A and -B dykes on the other hand were subject to deformational stress for some time subsequent to their consolidation, but which ceased before intrusion of type-C dykes. It is to be expected therefore that type-A and -B dykes should show a closer correlation between mineral assemblages and the progressively lower temperatures of post-consolidation cooling i.e. the high temperature consolidation assemblage is less likely to remain "frozen". The cooling history of both A- and B-, and C-type dykes is thus very similar and not responsible for the differences in mineralogy which are likely to be due entirely to differences in stress history.

The occurrence of lower greenschist facies assemblages in type-A and -B dykes suggests a means of determining an upper limit for the temperature of the country rocks at the time of intrusion of the dykes. The dykes would not cool below the temperature of their country rocks which therefore was less than the maximum temperature at which greenschist facies assemblages can be stabilised, although due to differences in other factors, possibly P_{H_2O}, the stable assemblage in the country rocks was probably that of amphibolite facies (see p. 48).

IV. INTERPRETATION OF FIELD AND PETROGRAPHIC DATA

(a) Physico-chemical conditions of dyke emplacement

The following conclusions have been drawn from the field and petrographic data available.

(i) the mineral assemblages at the time of consolidation of the dykes was that of almandine amphibolite facies.

(ii) incomplete synkinematic recrystallisation affected type-A and type-B dykes subsequent to consolidation. Most of this recrystallisation took place in the consolidation facies i.e. almandine amphibolite, but limited recrystallisation in a lower (greenschist) facies is evident in some dykes, especially type-A.

(iii) autometamorphic recrystallisation producing minerals characteristic of greenschist facies took place in type-A and type-B dykes, before the intrusion and consolidation of type-C dykes with almandine amphibolite facies assemblages.

(iv) differentiation of type-A dykes by filter-pressing shows that hornblende (and pyroxene) had an extensive period of crystallisation before plagioclase started to crystallise. The residual liquid crystallised 60–80 % plagioclase.

(v) at no time subsequent to consolidation did the dykes have an assemblage characteristic of either granulite facies or pyroxene hornfels facies.

In assuming that the mineral assemblage at the time of consolidation indicates the consolidation facies of the dykes, and that recrystallisation can take place in the same facies, the writer follows Eskola 1921 p. 146: "a mineral facies comprises all the rocks that have originated under temperature and pressure conditions so similar that a definite chemical composition has resulted in the same set of minerals, quite regardless of their mode of crystallisation, whether from magma or aqueous solution or gas, and whether by direct crystallisation from solution (primary crystallisation) or by gradual change of earlier minerals (metamorphic recrystallisation)." However, in this account of the Ilordleq dykes a primary mineral (as opposed to a primary crystal) must be defined as one belonging to the mineral facies (or to a higher facies in the case of metastable relics) in which the rock crystallised, whether formed by direct precipitation from the magma or by autometamorphic recrystallisation. Any further limitation would be difficult to apply not only in the Ilordleq dykes but in the many igneous rocks in which post-consolidation textural readjustments are suspected; in fact in most coarse grained igneous rocks (WAGER, BROWN and WADSWORTH, 1960; VOLL, 1960).

The controlling factor in the primary crystallisation of hornblende from basic magmas was for many years the subject of speculation. The early view (KENNEDY, 1935) that composition of the magma was the principal factor lost favour and the water content of the magma was increasingly regarded as being of prime importance. The role of water was thought to be that of a flux which lowered the crystallisation temperature of the melt (VINCENT, 1953; WELLS and BISHOP, 1955; DEER, HOWIE and ZUSSMAN, 1962). The subject was reviewed by BAILEY (1958) who concluded that compositional differences between hornblende-bearing Devonian rocks and augite-bearing Carboniferous and Tertiary in Scotland, were insufficient to account for their mineralogical differences, and that these differences were most likely due to the presence of 'volatiles, probably in large part water.' (*op. cit.* p. 18). The data presented by YODER and TILLEY (1956, 1962) showed that water pressure could be a decisive factor in determining the primary mineral assemblage in basic igneous rocks, not only in its effect on the crystallisation temperature of the magma but by its effect on the stability fields of the major mineral phases in systems of basaltic composition. The change in emphasis from water content to water pressure was also important, insofar as the interdependence of these parameters is regulated by other geologically important variables such as temperature, total pressure, and presence of other volatile components, which are referred to in the following pages.

Figure 28 shows a projection of the natural olivine tholeiite—water system (YODER and TILLEY, 1962, fig. 27) with the addition of the hypothetical boundary between the almandine amphibolite—hornblende hornfels facies and the granulite—pyroxene hornfels facies tentatively proposed by FYFE, TURNER and VERHOOGEN, 1958 (fig. 107).

With the reservations regarding interpretation of their experimental data suggested by YODER and TILLEY (*op. cit.*) it seems likely that with P_{H_2O} greater than 1300 bars hornblende will be a primary mineral in melts of the stated composition. With increasing water pressure the temperature of the upper stability limit of hornblende in a basic melt of

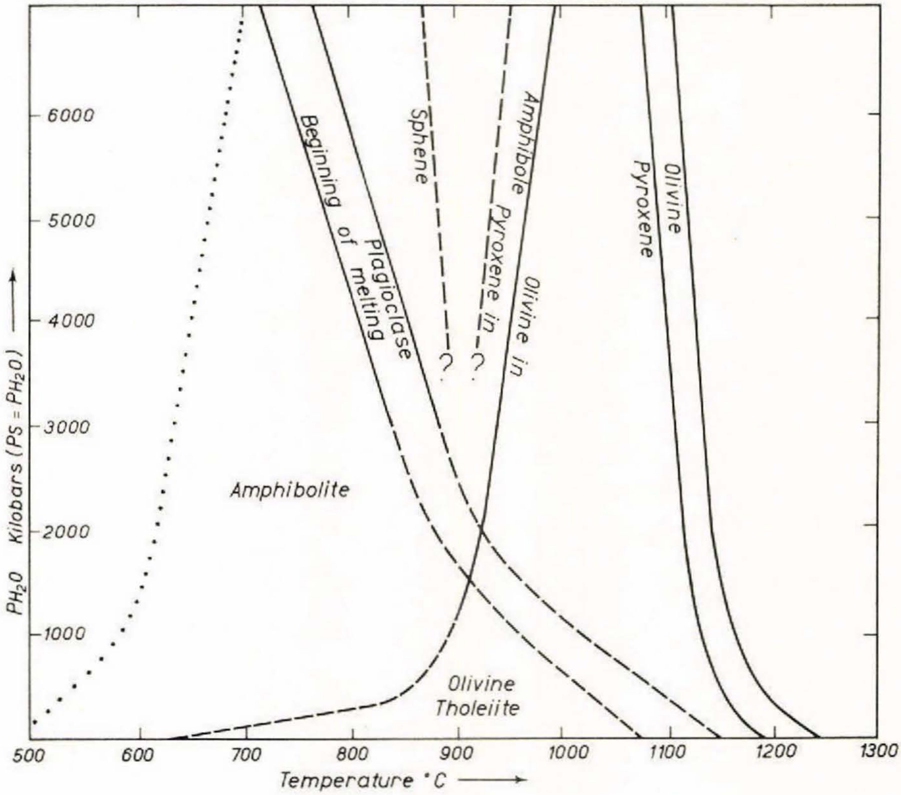


Fig. 28. Projection of natural olivine theoleiite-water system, mineral stable on side of curve along which name is printed. From YODER and TILLEY, 1962, fig. 27. Dotted line shows tentative boundary between amphibolite and granulite facies from FYFE, TURNER, and VERHOOGEN, 1958, fig. 107.

this composition increases, as do temperatures of the lower stability limits of pyroxene and olivine.

In the dykes being considered, the limitations are as follows:—

(i) the periods of crystallisation of pyroxene and felspar do not overlap.

(ii) plagioclase did not begin to crystallise until a large proportion of the amphibole had crystallised.

(iii) sphene was stabilised only after about half the amphibole had precipitated, but before the beginning of crystallisation of the felspar.

From figure 28, it is likely that the lowest P_{H_2O} at which these conditions can be met is in the range 3500–4500 bars. As described below, P_{H_2O} is unlikely to have been constant throughout the period of consolidation of the dykes.

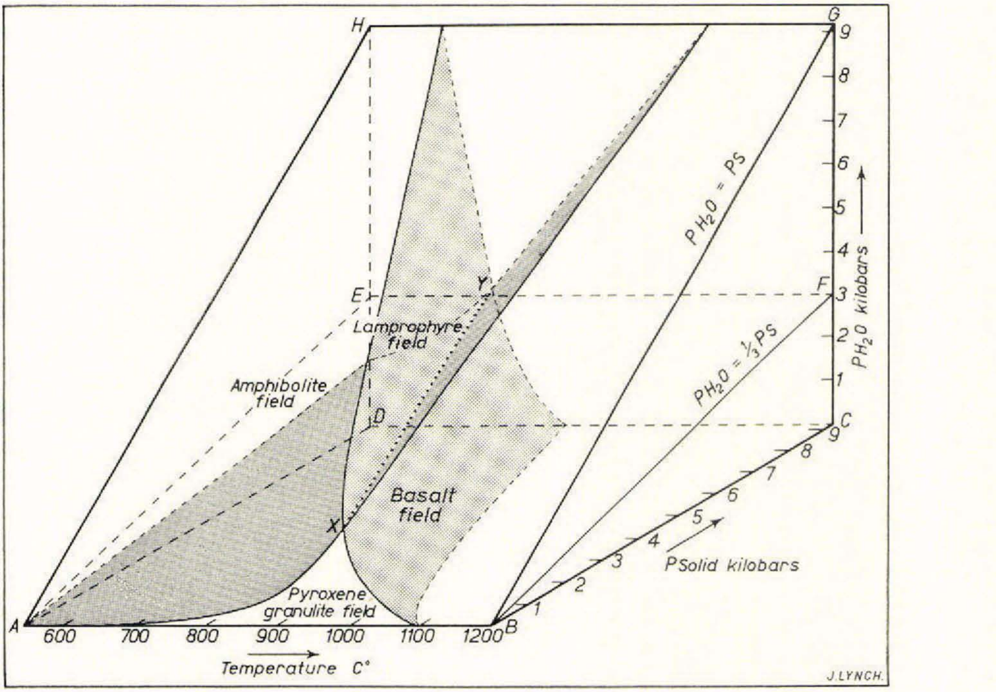


Fig. 29. Relationships, partly conjectural, between beginning of melting of tholeiitic basalt (lightly stippled plane) and upper stability limit of amphibole (heavily stippled plane) in rock and melts of basaltic composition, with variation in temperature, solid pressure, and water vapour pressure. For further explanation see text. Quantitative data from YODER and TILLEY (1962, fig. 27) and tentative field boundaries on plane $P_{H_2O} = \frac{1}{3} P_S$ from FYFE, TURNER and VERHOOGEN, 1958, fig. 107.

Having proposed a lower limit for the (maximum) P_{H_2O} attained during consolidation, it should be possible to set an upper limit determined by the fact that consolidation was completed before greenschist facies conditions were encountered. As can be seen from fig. 28 however, the tentative facies boundaries are not consistent with the experimental data, which indicate pyroxene as unstable throughout much of the suggested fields of the granulite and pyroxene hornfels facies. The tentative and schematic nature of the facies boundaries was emphasised by FYFE, TURNER and VERHOOGEN (*op. cit.*) who also noted that the boundaries were drawn on the assumption that $P_{H_2O} = P_{load}$ in regional metamorphism. It may be that the facies boundaries are broadly correct with respect to solid pressure estimated from field occurrences, and that the discrepancy can be in part resolved by concluding that the assemblages considered by FYFE, TURNER and VERHOOGEN were formed under conditions in which P_{H_2O} was considerably less than P_{solid}.

Figure 29 shows schematically the form of the field boundaries which might be expected when P_{H_2O} and P_{solid} are taken as independent variables. The projection on the surface ABHG ($P_{H_2O} = P_s$) shows the experimentally determined upper stability limit of amphibole and the curve for beginning of melting of basalt (from fig. 28). The upper stability limit of amphibole on the plane $P_{H_2O} = \frac{1}{3} P_s$ is the almandine amphibolite-granulite facies boundary of FYFE, TURNER and VERHOOGEN in respect of temperature and P_s. This should not correspond exactly with the upper stability of amphibole which is stable in the hornblende granulite facies; neither is it suggested that conditions of $P_{H_2O} = \frac{1}{3} P_s$ are characteristic of regional metamorphism; but these approximations are adequate for purposes of illustration. The field boundaries do not extend into the upper half of the cube space as P_{H_2O} cannot exceed P_s. The diagram illustrates in a qualitative way the relationships between the four fields important for consideration of the Ilordleq dykes. These fields are (i) that through which dolerite crystallises (basalt field); (ii) that through which hornblende dolerite crystallises (lamprophyre field); (iii) pyroxene granulite field; (iv) almandine amphibolite field. It is probable that the field boundaries are more nearly parallel to the P_s axis than to the P_{H_2O} axis and that small changes in P_{H_2O} are likely to be of greater significance than corresponding changes in P_s.

The occurrence of vesicles in some of the type-C dykes shows that in the later stages of consolidation P_{H_2O} approached P_1 and hence P_s (see IV (b)) and it is suggested that at the time of consolidation P_{H_2O} and P_s were approximately 3500–4500 bars and the temperature about 800–850°.

(b) Depth of emplacement of the dykes

The preservation of ocelli or infilled vesicles in some type-C dykes (Section III, a, (i)) allows an estimate to be made of the depth of consolidation of the dykes.

Bubbles form in a magma when the (fictive) vapour pressure of the dissolved gas phase (P_g) exceeds the liquid or hydrostatic pressure (P_1) on the magma, and are likely to survive as vesicles in the consolidated rock only if the condition $P_g = P_1$ is maintained throughout consolidation of the magma.

In a confined dyke the condition $P_g > P_1$ cannot be sustained because a rise in P_g is countered by an equal and opposite reaction from the confining walls which allows P_1 to increase in step with P_g. Pressure of the confining walls may be relaxed for short periods due to tectonic or other events and allow bubbles to form, when stable conditions again prevail the condition $P_g = P_1$ will again be achieved and bubbles previously formed would disappear.

In an unconfined dyke with access to the surface, the maximum P_l which can be obtained or induced is limited by the hydrostatic pressure exerted by the overlying magma column. Under such conditions a rise in P_g to a higher value than P_l is prevented not by a rise in P_l but by the formation of bubbles, which are likely to persist only in such unconfined magmas. As a general rule it can be suggested that when vesicles are formed $P_g = P_l$ = hydrostatic pressure exerted by the overlying magma column. The decrease in number and size of vesicles in Hawaiian pillow lavas with increase in depth of overlying water (MOORE, 1965) provides an illustration of the relationship between vesiculation and confining pressure.

Applying this reasoning to the Ilordleq dykes, if it is provisionally assumed that $P_g = P_{H_2O}$, the hydrostatic pressure must have equalled P_g = 3500–4500 bars (see page 53). Such a hydrostatic pressure can be exerted, in the present gravitational field of the earth and neglecting possible viscosity effects, by a basaltic magma column 9–11 km in height (KENNEDY, 1955).

If components other than water are present in the gas phase the estimated height of the magma column must be increased in proportion to the ratio P_{gas}: partial pressure H_2O. For magmas in which CO_2 is not an important component of the gas phase, partial pressure of water is not likely to be less than 80 % of P_g (SHEPHERD, 1948). The magma column overlying the Ilordleq dykes at the time of their formation is likely to have been 10–12 km in height, and it is proposed that the dykes crystallised at about this depth in the crust. The important assumption must be made that volatile components, other than water, which are present do not significantly affect either the consolidation temperature of the rock or the stability fields of constituent minerals. A further inference may be drawn from the supposed depth of crystallisation of the Ilordleq dykes. A similar magma may rise to a higher level in the crust with P_{H_2O} maintained at a high level because of lack of connection with the surface. If connection with the surface is eventually achieved, the consequent rapid decrease in P_{H_2O} would result in explosive vesiculation and release of water vapour. Viewed in this light, the common association of diatremes and gas-drilling phenomena, such as the xenolithic microdiorite of Ilordleq, with lamprophyric and appinitic (e.g. PITCHER and READ, 1952) rocks similar to the Ilordleq dykes may be better understood.

It should be noted that the solubility of water in basaltic melts at 4000 bars under saturated conditions ($P_{H_2O} = P_l$) is about 7 % at 1100° (HAMILTON *et. al.*, 1964), probably reducing to about 6 % at 800°. Even if all the water in the original melt is retained in the consolidated rock, it is not necessary to assume that only in rocks containing 7 % water could P_{H_2O} reach 4000 bars during consolidation. If water is not taken up by the early formed mineral phases the proportion of water, and hence P_{H_2O}, will increase during crystallisation. This increase in P_g is regarded by RITTMAN (1962) as an important mechanism of vulcanicity. In view of this the experimental results of KHITAROV *et al.* (1959) are of great practical importance. Solubility of water in a liquid + crystal system of basaltic composition at 900°, and about 3000 bars is 3.2 $^0/_0$. The comparatively low water contents of the Ilordleq dykes give no indication, therefore, of the water content of the liquid during the various stages of crystallisation. It is clear that any suggested figure for P_{H_2O} during crystallisation can refer only to that at one particular stage in the crystallisation. In the Ilordleq dykes the maximum P_{H_2O} was probably achieved immediately before the crystallisation of hornblende.

V. CHEMICAL FEATURES OF THE DYKES

(a) Analyses

Chemical investigation of the dyke suite was initially undertaken in order to provide evidence on whether or not contamination had taken place during the emplacement of the dykes into what were thought to have been 'active' country rocks. The numerous xenoliths in the dykes also indicated the possibility of assimilation of granitic country rock.

Analyses were first made of six dykes, three type-A, one type-B, and two type-C dykes. In the case of the inhomogeneous type-A dykes, specimens were taken across the full width of narrow dykes in an attempt to obtain the composition of whole dykes and thus overcome the effects of in situ filter pressing.

It was evident from these analyses (table I, 1–6) that the wide variation in composition was unlikely to be due to assimilation of granitic country rock, as both silica and potash are relatively constant. Diffusion of volatile components from 'active' country rocks was unlikely in view of the small variation in potash content. On the other hand, variation in magnesia and alumina in these first six analysed dykes suggested that the differences in dyke composition could be due at least in part to differentiation by crystal fractionation. In order to confirm preliminary conclusions based on these first six analyses, four further analyses were obtained, two of typical leucocratic members of the suite (table I, 7 and 8) and a further two of the separated mafic and leucocratic components of an inhomogeneous type-A dyke (table I, 9 and 10). A further analysis has kindly been made available by Mr D. Bridgwater (table I, 11); this is of a dacitic member of the same dyke suite, more acid than any found in Ilordleq, collected from the neighbouring Isortoq area.

The analyses provide a clear illustration of the difficulties of nomenclature in rocks in the basalt-andesite range, due to poor correlation between classifications based on mineralogy on the one hand and chemical composition on the other. The A-, B-, and C-type dykes, although consisting of 'andesitic' minerals, nevertheless have 'basaltic' silica contents. The difficulties are due entirely to the assumption, implicit in

Table I.

G. G. U.	1	2	3	4	5	6	7	8	9	10	11	12
No.	52526	52568	52536	52541	52542	52544	31680	32136	32157A	32157B	25102	51304
SiO_2	49.93	48.69	49.57	49.88	49.22	49.47	52.65	58.63	44.78	52.84	65.43	49.8
Al_2O_3 ...	12.18	12.64	14.15	16.71	15.34	17.17	17.70	17.65	9.19	21.00	15.68	17.7
Fe_2O_3 ...	2.74	3.25	3.02	2.62	2.74	3.13	3.00	2.26	3.28	2.43	1.57	0.6
FeO	7.54	4.91	6.39	5.52	5.54	6.38	5.63	3.46	9.94	3.64	2.62	8.4
MgO	10.30	10.10	8.82	6.99	8.78	5.27	3.21	2.80	15.80	3.12	0.75	8.6
CaO	8.74	11.94	8.95	9.25	9.88	8.83	6.69	6.53	9.13	6.64	2.21	9.0
Na_2O ...	2.27	1.58	1.89	3.26	2.32	3.31	5.73	4.48	0.56	5.61	4.50	2.6
K_2O	1.98	1.58	1.98	1.47	1.27	1.70	1.44	1.58	0.40	2.00	5.49	0.7
H_2O^+ ...	2.30	3.20	3.20	2.40	3.00	2.10	2.01	1.35	5.71	1.95	0.38	0.6
TiO_2	0.71	0.75	0.72	0.74	0.64	1.03	1.17	0.60	0.40	0.47	0.59	0.8
P_2O_5	0.21	0.30	0.21	0.27	0.16	0.47	0.38	0.27	0.17	0.40	0.15	0.3
MnO ...	0.18	0.16	0.16	0.15	0.16	0.16	0.14	0.11	0.29	0.10	0.08	0.2
CO_2	–	–	–	–	–	–	+	+	+	+	–	–
BaO	–	–	–	–	–	–	+	+	+	+	+	+
SrO	0.12	0.14	0.19	0.22	0.17	0.21	+	+	+	+	+	+
ZrO_2	–	0.02	–	tr.	–	0.03	+	+	+	+	+	+
Cr_2O_3 ...	0.07	0.09	0.07	0.02	0.05	tr.	+	+	+	+	+	+
Total ...	99.27	99.35	99.32	99.50	99.27	99.26	99.75	99.72	99.65	100.20	99.45	99.3
NORMS												
qtz	–	–	–	–	–	–	–	10.6	–	–	12.5	
or	11.7	10.0	12.2	8.9	7.8	10.6	8.9	9.4	2.2	11.7	32.8	
ab	19.4	14.2	16.7	28.3	20.4	28.8	44.0	38.8	5.2	40.3	38.2	
an	18.9	23.4	24.7	27.5	28.9	27.8	18.6	24.2	22.8	27.0	6.4	
neph ...	–	–	–	–	–	–	2.8	–	–	4.3		
di	19.9	29.1	16.7	15.8	16.9	11.3	10.4	7.2	21.2	3.2	3.2	
hyp	12.7	11.8	21.6	3.6	19.4	7.2	–	5.3	28.4	–	2.2	
ol	10.5	4.5	2.7	10.1	1.8	6.5	8.7	–	14.2	7.5	–	
mag	4.2	4.9	4.6	3.9	4.2	4.6	4.4	3.2	5.1	3.7	2.3	
ilm	1.4	1.5	1.5	1.5	1.2	2.0	2.1	1.2	0.8	0.9	1.2	
ap	0.3	0.7	0.3	0.7	0.3	1.3	1.0	0.7	0.3	1.0	0.3	
Normative felspar												
Or	23	21	23	14	14	16	12	13	7	15	43	
Ab	39	30	31	44	36	43	62	54	17	51	49	
An	38	49	46	42	50	41	26	33	76	34	8	
Qtz. + Fels. + Neph.	50	37.6	53.6	64.7	57.1	67.2	74.3	83.0	30.8	23.3	89.9	

\+ not determined. – below detectable limit.

Analysts (Geological Survey of Greenland) Bjørn I. Borgen analyses 1–6, 11, 12. Ib Sørensen analyses 7–10.

Norms based on water-free recalculation to 100 %.

Analyses of Ilordleq rocks 1–10.

1–3, Type-A dykes.
4, Type-B dyke.
5, 6, Type-C dykes.
7, Type-C dyke with acicular amphibole microcline.
8, Xenolith-free matrix of xenolithic microdiorite.
9, 10, Separated early and late components of filter-pressed type-A dyke.
11, Margin of dacitic dyke, Isortoq area, collected by D. Bridgwater.
12, Noritic gabbro, Frederiksdal, collected by W. S. Watt.

conventional igneous terminology, that all igneous rocks have crystallised in the same facies; the problem of terminology is referred to in a later section.

As the conditions under which the Ilordleq dykes crystallised are thought to be unusual, it is important to remember that the terms in which differentiation of basic rocks are usually discussed are those which have been devised and found useful for what appears to be a specialised, although common, circumstance, i.e. differentiation of basic magmas crystallising under conditions which favour relatively small crystallisation intervals and a high degree of overlap of the crystallisation intervals of major phases (YODER and TILLEY, 1962).

(b) Differentiation

(i) Series and phase differentiation

Before examining in detail the compositional variation of the Ilordleq dykes it will be useful to review the features which may be expected to distinguish differentiation under the specialised circumstances referred to. To facilitate discussion, two ideal types of fractional crystallisation differentiation are defined below; these will be referred to as *series differentiation* and *phase differentiation.*

Series differentiation is that due to separation and isolation of early formed minerals from remaining liquid when the major phases crystallise together. When this is achieved by a continuous separation mechanism a well defined cryptic layering (in the sense of HESS, 1960) is found within a single intrusion e.g. Skaergaard. This type of variation is effected mainly by progressive changes in composition of minerals within the discontinuous reaction series and continuous reaction series respectively, principally pyroxene and plagioclase. The differentiation is expressed in the same terms as the important differences within each mineral group concerned i.e. MgO:FeO in the mafic minerals, CaO:Na_2O in the plagioclase, and differences in total composition between rocks of a cotectic differentiation series are relatively small.

Phase differentiation is that due to separation of different mineral phases, the separation of plagioclase from the mafic phases being most important. The important differences between rocks of a phase differentiation series are expressed in the same terms as the differences between the separated phases e.g. MgO + FeO:alkalies, or MgO + Feo:Al_2O_3. Phase differentiation may take place in different ways; it is commonly achieved on a small scale in many intrusions by the gravitational separation of contemporaneous phases to form rhythmic layers, and is likely to take place in any magma in which crystallisation intervals of major phases have little or no overlap. Difference in composition between members of a phase differentiation series is relatively great e.g. pyroxenite and anorthosite.

Notwithstanding minor complications introduced by intercumulate crystallisation and differences in the mechanisms by which isolation is achieved, many large basic intrusions (Skaergaard, Stillwater, Bushveld) and probably volcanic suites too, show differentiation trends similar to ideal series differentiation trends. This is to be expected from the characteristics of basalt melts described by YODER and TILLEY (1962); in such melts major phases crystallise together and their wholesale separation on anything other than the local scale of rhythmic units would require an exceptionally effective separating mechanism. Some gravitational separation of early mafic phases from early plagioclase may in some cases be achieved either within a large intrusion or within a magma chamber, but under normal conditions, the phase differentiation is likely to be subordinate to the series differentiation, except in small intrusive units.

When crystallisation of the major phases in a magma is not broadly contemporaneous however, phase differentiation may become the dominant process and series differentiation play only a minor role. Separation and isolation of early formed minerals from the remaining liquid produces variations in the relative proportions of the major phases, and the compositional variations characteristic of phase differentiation therefore become effective on a large scale, rather than on only the small scale of rhythmic units.

The differences between the two circumstances may be illustrated by reference to the expected differences between crystallisation of basalt magma at low P_{H_2O} and high P_{H_2O} (4000 bars). Crystallisation intervals of the major phases in both cases are shown in fig. 30 (data from YODER and TILLEY, 1962) from which the following conclusions may be drawn:—

(1) the same degree of separation of early and late minerals will produce much greater differentiation at high P_{H_2O} than at low P_{H_2O}. At high P_{H_2O} accumulation of the early formed minerals will produce pyroxenite, pyribolite and hornblendite whereas the remaining liquid will crystallise as leuco-diorite, due to phase differentiation. At low P_{H_2O} with series differentiation, the rocks formed will nearly all be gabbroic.

(2) Differentiation at high P_{H_2O} will be expressed mainly by variation in $MgO + FeO$:Alkali or $MgO + FeO:Al_2O_3$ ratios whereas differentiation at low P_{H_2O} will be expressed mainly in terms of $MgO:FeO$ and $CaO:Na_2O$ ratios.

(3) The differentiation potential at hight P_{H_2O} is increased also because of the greater temperature interval between liquidus and solidus which

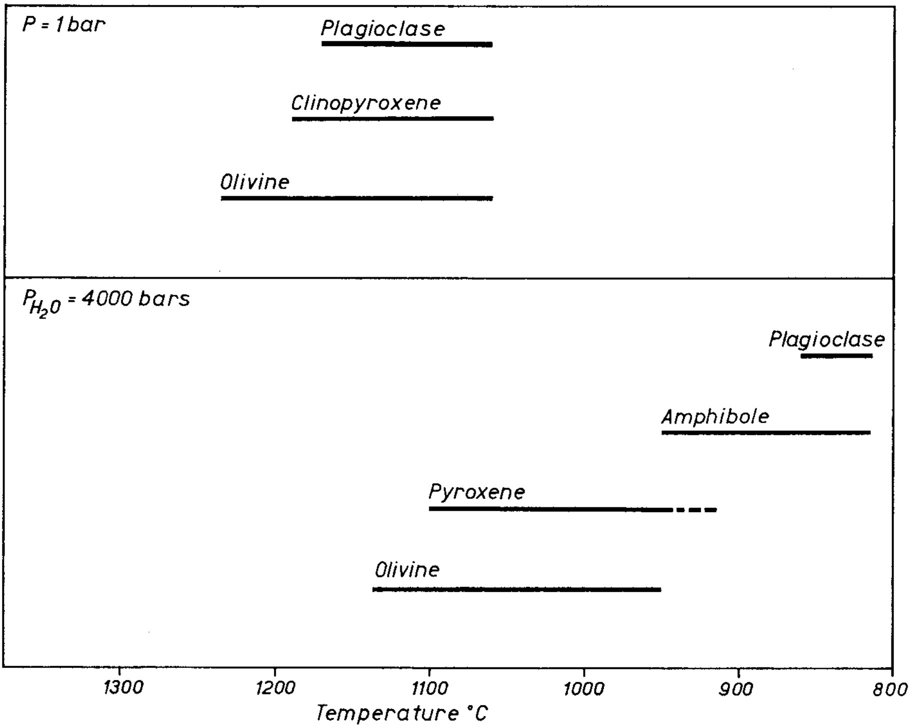


Fig. 30. Crystallisation intervals of major phases in natural olivine theoleiite showing differences in overall crystallisation interval and differences in overlap of crystallisation intervals of major phases at 1 atmosphere and 4000 bars water pressure. (Data from YODER and TILLEY, 1962).

will serve to increase the time interval during which crystallisation proceeds. The temperature interval may however be unimportant in determining the time of crystallisation when compared with other factors such as heat of crystallisation of the minerals and size etc. of the body.

The chemical differences between series and phase differentiation of a basic magma can be expressed in a variety of ways. HESS (1960, plate 11) used FeO:MgO:alkalies ratios to demonstrate the important differences between extreme continuous fractional crystallisation of large lopoliths, and the slight fractional crystallisation of some volcanic suites. This distinction is valid however only if it can be shown that fractionation in both cases is effected by the same minerals in magmas which crystallise in similar ways. Extreme continuous fractionation of basalt at 4000 bars water pressure might give an apparently similar trend, in terms of MgO:FeO:alkalies, to that of slight fractional crystallisation of the same magma at low water pressure. Both the delay in crystallisation of plagioclase and the introduction of hornblende favour this trend.

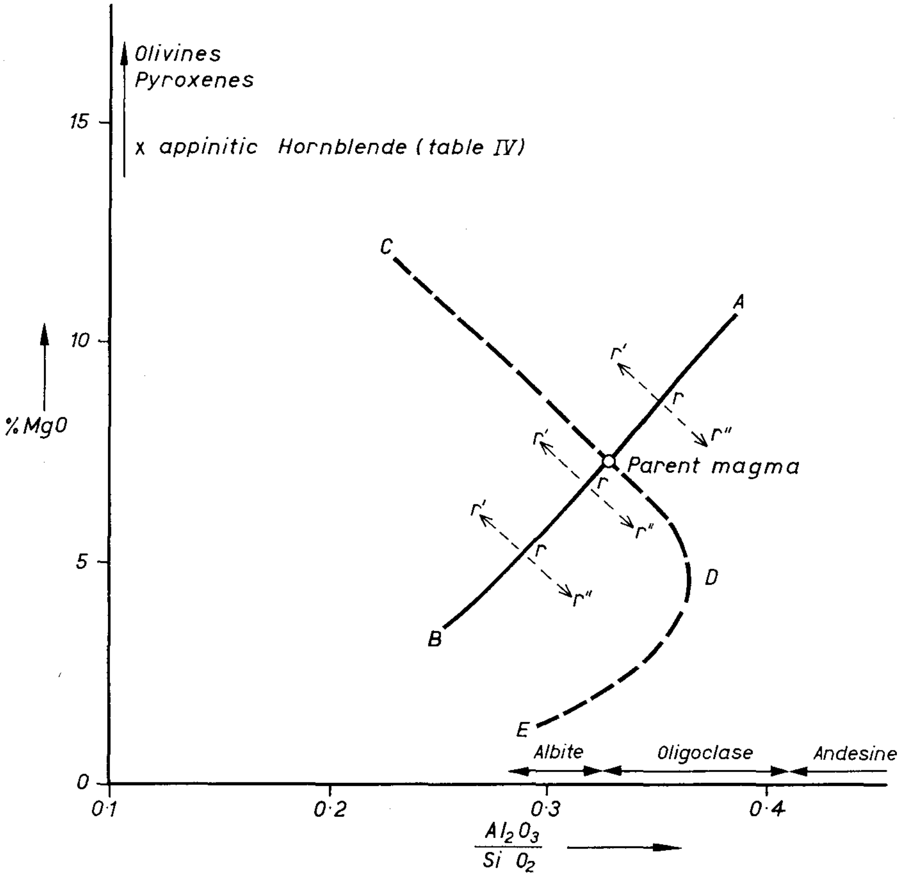


Fig. 31. Schematic $MgO/\frac{Al_2O_3}{SiO_2}$ diagram showing expected differences between differentiation trends produced by ideal series differentiation (A–B) and ideal phase differentiation (C–D–E) of same parent basalt magma. Superimposed trends (r′–r″) on series differentiation trend show expected effects of rhythmic separation at successive stages (r). For further explanation see text.

As the Ilordleq dykes show evidence of having crystallised at high P_{H_2O} it is necessary to allow for the possibility that any differentiation affecting them also took place at high P_{H_2O} i.e. was primarily a phase differentiation. A useful plot for this purpose is $MgO: \frac{Al_2O_3}{SiO_2}$ on which series and phase differentiation can be distinguished. The same parameters were used by Murata (1960) in an attempt to distinguish between tholeiite and alkali-basalt differentiation trends, but as has been shown by Yoder and Tilley (1962) the essential differences between these suites cannot be expressed satisfactorily in this way.

The main features of this plot are shown in fig. 31 in which the expected differentiation trends of basalt at low P_{H_2O} (series differentia-

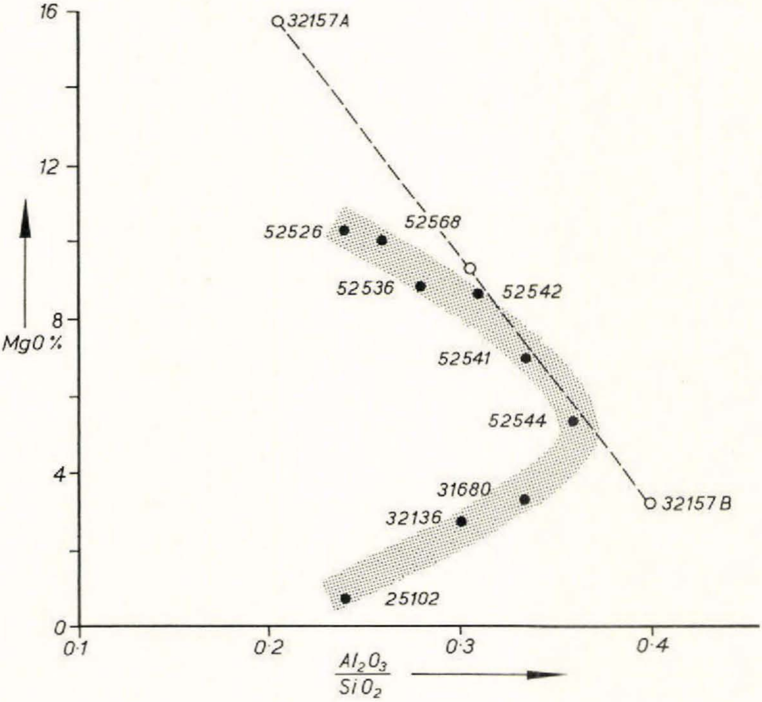


Fig. 32. Compositional variation of Ilordleq rocks in terms of MgO and $\frac{Al_2O_3}{SiO_2}$ ratio. Compositions of separated components of filter-pressed type-A dyke (52537) and calculated bulk composition of this dyke also shown.

tion) and high P_{H_2O} (phase differentiation) are shown schematically. The factors which primarily determine the trend of series differentiation are (i) constant proportions of mafic phases and plagioclase (ii) regular change in plagioclase composition (iii) decrease in MgO content of mafic phases. Dotted lines r–r show trends of local phase differentiation due to rhythmic segregation at various stages. Phase differentiation of the same liquid by continuous fractionation at high water pressure is determined primarily by separation of felspar from mafic phases. Compositional variation of the mafic phases, which now include hornblende, under these conditions is not known but is unlikely to change the negative slope of the trend line. After the beginning of crystallisation of plagioclase the possibility of phase differentiation is much reduced and series differentiation (D–E), as a result of changes in felspar composition, is likely to become dominant.

It is not to be expected that these idealised trends should be exactly reproduced in rock suites, but the series differentiation trend is closely approached by Skaergaard rocks (fig. 33), while the Ilordleq rocks appear to correspond closely to a phase differentiation series (fig. 32).

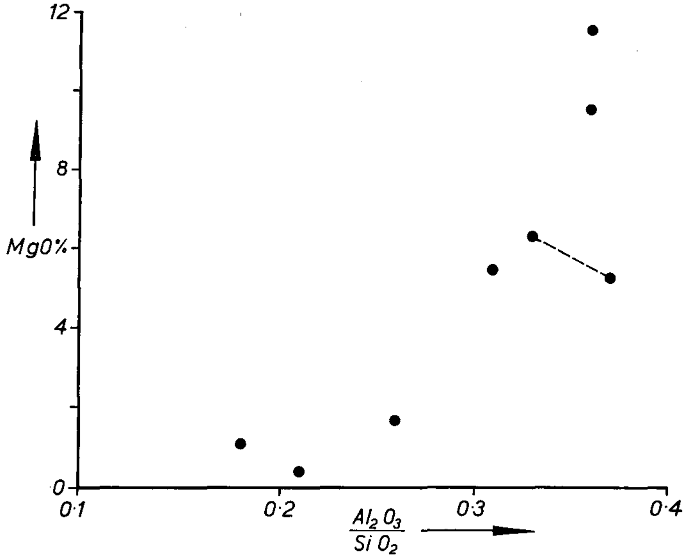


Fig. 33. Compositional variation of rocks of Skaergaard layered series in terms of MgO and $\frac{Al_2O_3}{SiO_2}$. Data from WAGER and DEER (1939).

(ii) Differentiation in terms of MgO / $\frac{Al_2O_3}{SiO_2}$

The six points representing A-, B-, and C-type dykes (fig. 32) show the variation which is thought to include the large majority of dykes in the Ilordleq swarm. The trend of compositional variation shown by these rocks is that which is to be expected of rocks forming a phase differentiation series with separation of plagioclase from mafic phases.

As is usual in such cases the plotting of points on such a diagram shows only the possibility of the rocks being members of a differentiation suite; other lines of evidence must be sought before it can be decided whether or not this is the most likely interpretation. It is thought that the evidence referred to in the following discussion is sufficient to allow acceptance of the compositional variation of the six analysed dykes as being the result of phase differentiation.

The fact that the relative ages of the dyke types is similar to their relative order with respect to degree of differentiation is not necessarily of much significance. In many igneous suites the order of intrusion is independent of position with the supposed differentiation series. A capricious order of emplacement is less likely if the suite contains certain types of cumulate rock which never had independent existence as liquids or crystal-liquid mixtures. Rocks formed by in situ bottom accumulation of crystals or filterpressing are always likely to be post-dated by rocks formed from their respective residual fractions. In these cases rocks more basic than the parent magma are in general likely to be earlier than those less basic than the parent magma. Seen in this light the relative positions of the A-, B-, C-type dykes on the $MgO / \frac{Al_2O_3}{SiO_3}$ plot offers some slight support to the differentiation hypothesis.

A quantitative method of checking the possibility of phase differentiation was suggested by the conclusion that the inhomogeneity of type-A dykes is due to filter-pressing. If the separate components in type-A dykes represent early and late fractions, the difference in composition between these components would show the course likely to be taken by fractional crystallisation differentiation on a larger scale. This would apply whether the separation of early and late fractions on the large scale was achieved by filter-pressing or by some other mechanism such as gravitational settling. Analyses were obtained of the separated components comprising a type-A dyke (analyses 9 and 10, table I) and plotted (32157A, 32157B) on the same diagram as the previous analyses.

If the differentiation which produced the rocks represented by analyses 1–6 (table I) was accomplished by accumulation of a single phase of fixed composition, the points representing these rocks should lie along a straight line which should coincide with the line joining points 32157A and 32157B. However, not only is amphibole unlikely to be the only participant mafic phase, but its composition is likely to vary. Points representing analyses 1–6 should therefore ideally lie along a curve, the line joining 32157A and 32157B being a tangent to this curve; the point at which tangent and curve meet should correspond to the bulk composition of the filter-pressed type-A dyke from which specimens 32157A and 32157B were taken. The open circle (fig. 32) represents the calculated bulk composition of type-A dyke 32157 assuming equal proportions of the two components; in the field the dyke was estimated to comprise equal proportions of mafic and leucocratic components, with the former possibly in excess. The fact that, on this diagram, the calculated bulk composition of the dyke 32157 falls almost precisely on the line joining A and B is strongly suggestive of a simple genetic relationship between the two components. In view of the likely errors in sampling material as inhomogeneous as type-A, and to a lesser extent type-B, dykes, the predicted relationships, for a theoretical ideal, are approached sufficiently closely to lend support to the differentiation hypothesis on which the prediction is based.

A further check on the phase differentiation hypothesis is made possible by the occurrence of more acid rocks which although quantitatively insignificant in Ilordleq are evidently members of the same suite. These comprise the type-C dykes containing microcline, and the xenolithic microdiorite (table I, analyses 7 and 8); these have been plotted on the $MgO / \frac{Al_2O_3}{SiO_2}$ diagram (fig. 32, points 31680 and 32136) together with the dacitic dyke (table I, analysis 11; fig. 32, point 25102) from the Isortoq area. These three points enable the supposed differentiation trend to be continued into the region in which separation of felspars from hornblendes is of less significance than fractionation within the felspar series. The band defined by the nine whole-rock analyses corresponds closely with that which may be theoretically predicted for continuous fractionation achieved primarily by phase differentiation, of the type likely in the differentiation of basic magmas crystallising a high water pressures.

It is clear that a unique solution cannot be substantiated by consideration of the chemical data alone, as conclusions drawn from chemical variation within the suite are necessarily equivocal. In the writer's view the most convincing support for the interpretation put forward derives from the fact that the chemical data are consistent with the conclusions drawn from field and petrographic evidence and closely correspond to the predictions which can be made from those conclusions.

(iii) Differentiation in terms of MgO: $FeO + Fe_2O_3$: Alkalies (AFM)

The compositions of the analysed Ilordleq rocks in terms of these components are shown in figure 34, from which they can be seen to fall within a clearly defined band, showing a distinct trend toward enrichment in alkalies relative to F + M with a slight but continuous enrichment in F relative to M. This trend closely approaches the normal calc-alkaline trend and it is of some interest to determine whether the calc-alkaline trend is necessarily the result of the Ilordleq type of phase differentiation, or whether such differentiation may show a similar trend, in terms of AFM, to differentiation accomplished in some other way.

The MgO:FeO:Alkalies diagram has been used by HESS (1960) to illustrate differences in differentiation trends between, at the one extreme, Skaergaard and the large lopoliths such as Stillwater, and at the other extreme certain volcanic suites; thick sills show trends intermediate between these extremes. The differences are shown diagrammatically in figure 35 which shows the pronounced initial increase in FeO:MgO + Alk. ratio characteristic of the large lopoliths, contrasting with continual decrease in FeO:MgO + Alk. ratios of the volcanic suites—the calc-alkaline trend (HESS, 1960). Hess refers these differences to differing degrees of fractional crystallisation, that of the lopoliths being regarded as extreme and that of the volcanic suites as slight fractional crystallisation.

The previous brief discussion of the differences between phase and series differentiation shows that with extreme phase differentiation characterised by separation of felspar from mafic minerals, variation in the ratio F:M is likely to be subordinated to changes in the M + F:Al_2O_3 and M + F:A ratios; in terms of the AFM diagram the trends of extreme phase differentiation are not likely to be distinguishable from the calc-alkaline trend.

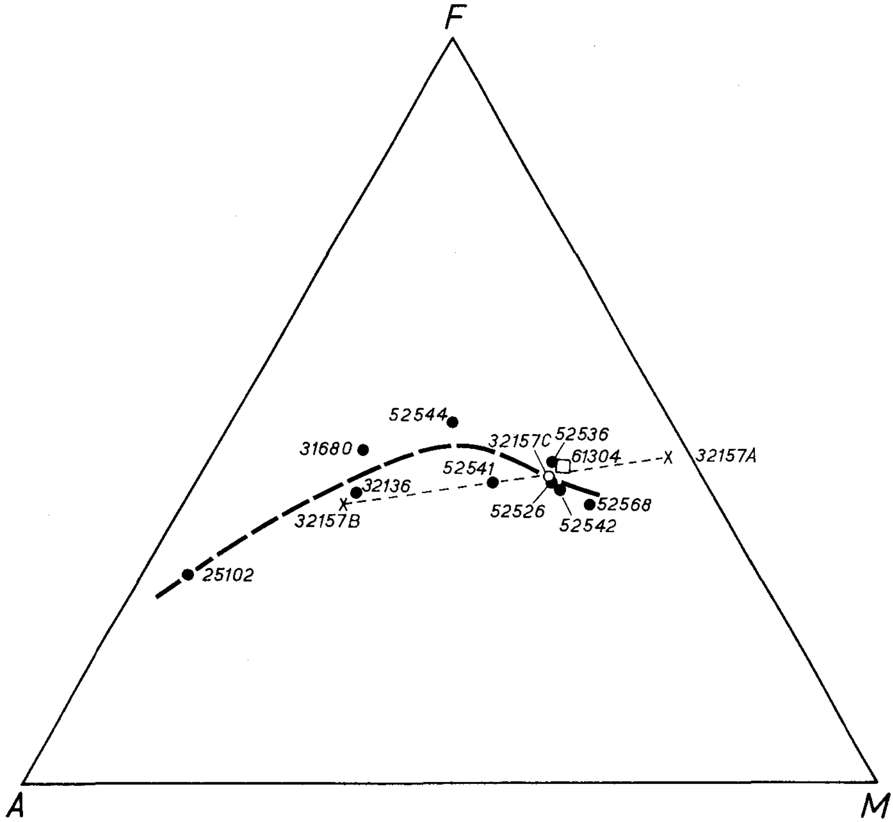


Fig. 34. Compositional variation in Ilordleq suite (solid circles) with respect to Alkalies: FeO + Fe_2O_3:MgO showing supposed differentiation trend (heavy broken line). Separated components of filter-pressed type-A dyke (crosses) together with calculated bulk composition of this dyke (open circle). Norite from Frederiksdal Rapakivi complex (open square) shown for comparison.

As the Skaergaard trend is known to be the result of extreme series differentiation, the intermediate trend shown by thick sills is consistent with, although not necessarily the result of, a combination of phase and series differentiation. In sills which behave as single rhythmic units the vertical variation is likely to be the product of both gravitational accumulation of dense mafic phases and compositional variation within both felspar and mafic minerals i.e. phase and series differentiation taking place independently of one another. A similar intermediate trend could be the result of differentiation at moderate water pressures, again a combination of phase and series differentiation, petrographic evidence for which would be seen in sills but not necessarily in extrusive volcanic rocks.

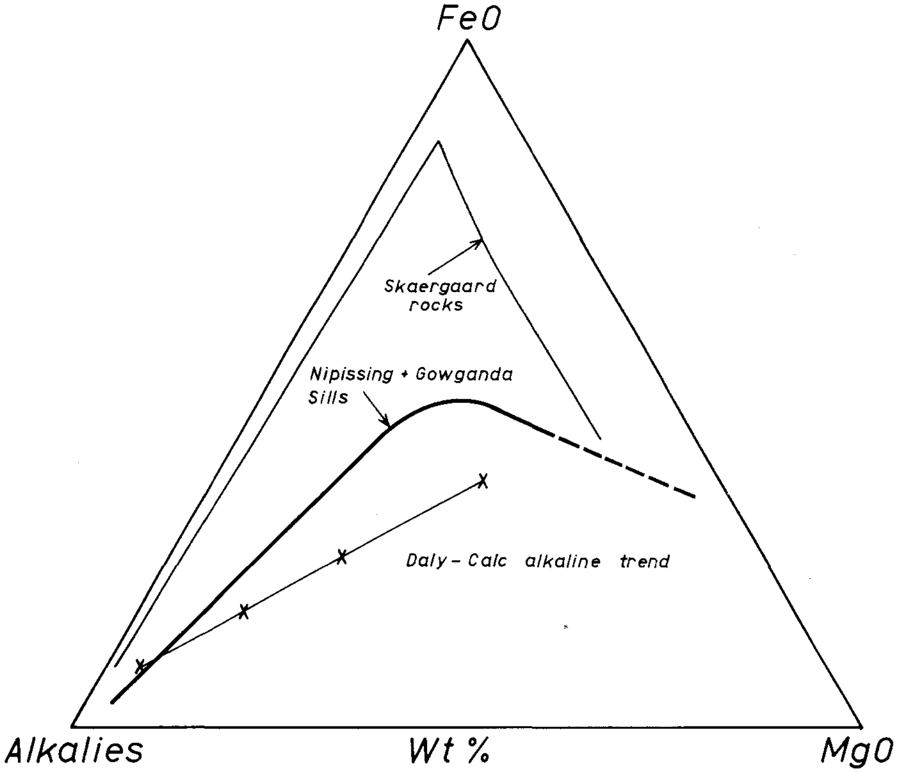


Fig. 35. FeO:MgO:Alkalies diagram showing trends suggested by HESS (1960) as typical of extreme, moderate and slight fractional crystallisation, illustrated here by Skaergaard, Nipissing and Gowganda Sills, and calc-alkaline (DALY's average basalt-andesite-dacite-rhyolite) suites respectively. Data from HESS (1960).

Apart from derivation by slight fractional crystallisation it has also been suggested that the calc-alkaline trend is the result of fractional crystallisation at constant or increasing oxygen partial pressure (OSBORN, 1959). It was suggested that fractional crystallisation with constant oxygen partial pressure, as opposed to constant total composition, would lead to a marked reduction in the degree of iron enrichment of mafic phases and hence a differentiation trend similar to that of the calc-alkaline suites. The differences between the lopolith or Skaergaard trend and the calc-alkaline trend in terms of iron enrichment have perhaps been over-emphasised at the expense of the more marked differences in the F+M:A ratios; after comparable amounts of crystallisation the difference in F:M ratios of the Skaergaard and Ilordleq rocks (fig. 36) is not very great and is attributed to crystallisation of amphibole in place of pyroxene and olivine in the Ilordleq rocks. The difference between F+M:A ratios is considerable however and is clearly due to phase differentiation consequent on the delayed crystallisation of plagioclase; although not suggested as a likely result of crystallisation at constant oxygen partial pressure (OSBORN, 1959), some delay in the crystallisation of plagioclase has since been demonstrated experimentally (HAMILTON, BURNHAM, and OSBORN, 1964).

It seems likely, from consideration of the AFM diagram, that phase differentiation is likely to be responsible for the calc-alkaline type of differentiation, although this phase differentiation could be achieved in some way other than by crystallisation at high water pressure: discussion of the origin of the orogenic volcanic rocks (section V, c (iii)) suggests the many other characteristics of these rocks require the operation of high water pressures during differentiation.

The available evidence does not allow better than approximate definition of the parent magma of the Ilordleq suite. In terms of $MgO/\frac{Al_2O_3}{SiO_2}$ the parent magma cannot be defined more closely than as lying within the band shown (fig. 32), with 8–10% MgO; the type-B and type-C dykes are limiting factors as they are unlikely to be more mafic than the parent. A close definition of the parent magma in terms of AFM is also impossible but it seems unlikely to be very different from the calculated bulk composition of the filter-pressed type-A dyke (fig. 34, open circle 32157C). A noritic gabbro from the Frederiksdal Rapakivi massif has been plotted for comparison (fig. 34, open square 61304).

(c) Bearing of Ilordleq dyke differentiation on related problems

The chemical characteristics of the Ilordleq dykes are relevant to discussion of the origin of high-alumina basalt (TILLEY, 1950), and the related problem concerning the origin of those rocks comprising the orogenic basalt-andesite-rhyolite volcanic association. Much of the discussion of these problems has been of a theoretical and general nature owing to the lack of field evidence with a direct bearing on them. As the field relationships of the Ilordleq dykes provide essential clues to the interpretation of their chemical characteristics, the limited chemical data have perhaps greater significance than would otherwise be the case.

(i) Origin of high-alumina basalt

Opinions have differed as to whether the high-alumina character of some non-porphyritic basalt magmas is of primary origin (Kuno, 1960) or a derived feature (Yoder and Tilley, 1962) and, if derived, whether it is a result of simple crystal fractionation or resorption of accumulated plagioclase.

Table II.

	(i)	(ii)
SiO_2	49.47	50
Al_2O_3	17.17	18
Fe_2O_3	3.13	9
FeO	6.38	
MgO	5.27	5
CaO	8.83	10
Na_2O	3.31	2.5
K_2O	1.70	0.4
TiO_2	1.03	1.0

(i) Type-C Ilordleq dyke, No. 52544.
(ii) Porphyritic Central type basalt, Mull (from Tilley, 1950, table II).

The differentiation of the six Ilordleq dykes of basaltic composition shows a marked trend towards Al-enrichment, culminating in a type-C dyke which is chemically equivalent to a high-alumina basalt. Despite its non-porphyritic character this dyke shows a close chemical resemblance to the Porphyritic Central type basalt of Mull and analyses of the two are shown for comparison in table II. In the Ilordleq dykes the increase in Al_2O_3, both in absolute terms and relatively with respect to silica, is interpreted as being mainly the result of delayed crystallisation of plagioclase due to high water pressure: recourse to any other mechanism is clearly unnecessary. The course of differentiation is well illustrated by the ratio of normative felspar:mafic minerals in the dyke referred to above of 2.5:1, compared with that of 1:1 in the most mafic dykes. Also illustrating the trend toward Al-enrichment is the leucocratic component separated from a type-A dyke. Compositionally this residual fraction is equivalent to an andesitic basalt or basaltic andesite and contains 21 % Al_2O_3. As would be expected, those dykes which are compositionally equivalent to andesitic basalt and andesite (31680, 32136, and 25102) also have high contents of Al_2O_3 and are further discussed in a following section.

It is clear that the conditions under which the Ilordleq rocks crystallised were extremely favourable to the production of high-alumina magmas by fractional crystallisation differentiation, without either resorption of accumulated plagioclase or necessity for a parent magma of unusual composition. This evidence alone is insufficient to allow general conclusions to be drawn regarding the origin of high-alumina magmas elsewhere, but provides firm support for the proposals of YODER (1955), and YODER and TILLEY (1962), who concluded that "... relatively high water pressure may bring about the production of high-alumina magmas" (*op. cit.* p. 422).

The fact that mineral assemblages of most high-alumina basalts give no indication of crystallisation from a magma derived by differentiation at high P_{H_2O}, is of little significance. In discussions of lines of magmatic evolution in igneous rock suites it is commonly assumed that the present mineral assemblages of the rocks concerned necessarily include the phases likely to have been involved in the differentiation giving rise to the observed variation in rock composition. This assumption is undoubtedly valid for those rock suites in which differentiation took place at the same level, or at least under approximately the same physico-chemical conditions, as the final crystallisation of the suite examined; as for example, in the large lopoliths. Differentiation of a magmatic suite may however take place under conditions different from those obtaining at the time of final crystallisation, especially if this final crystallisation takes place at or near the surface; the assumption referred to is therefore least likely to be valid in the case of extrusive volcanic suites.

Significant changes in water pressure are likely during the ascent of a magma through the crust; as has been pointed out in an earlier section, the maximum water pressure in a magma is a function not only of the water content, but also of the confining pressure which can be exerted or, more correctly, sustained by the surrounding medium. The maximum water pressure which can be maintained even in thick lava flows or shallow intrusions is only a fraction of that which obtained during crystallisation of the Ilordleq dykes. Had the magmas which crystallised to form these dykes completed their passage to the surface, the resulting lavas would have differed petrologically from the dykes in the following important respects.

1. The gradual reduction in P_{H_2O} on ascent would have resulted in a radical change in equilibrium mineral assemblage at the time of consolidation, with production of an assemblage characteristic of the 'basalt facies' i.e. pyroxene, plagioclase, in ideal cases. Had ascent of the magma taken place sufficiently slowly for crystal/liquid equilibrium to have been maintained at all times, phenocrysts of plagioclase would have developed in those magmas relatively enriched in plagioclase components by the earlier differentiation. If ascent was too rapid for crystal/

liquid equilibrium to be maintained with changing P_{H_2O}, the preservation of unstable relic phases would be likely, and perhaps provide some clue as to the conditions under which differentiation took place.

2. Reduction of P_{H_2O} during ascent of the magma must be accomplished by reduction in the amount of water dissolved in (saturated) magma, and result in bubbling-off of water vapour. Consequently lavas formed from magmas initially identical with those which formed the Ilordleq dykes would be likely to contain appreciably lower amounts of water than do the dykes. For some comparative purposes therefore the recalculation of Ilordleq analyses on a reduced-water or water-free basis is to be preferred (see table III).

Table III. Composition of Ilordleq dykes with extrusive volcanic rocks.

	I	1	II	2	III	3	IV	4
SiO_2	51.8	51.9	47.7	47.0	51.1	52.4	59.6	60.1
Al_2O_3	14.8	15.1	9.8	9.1	17.8	17.8	18.0	17.9
Fe_2O_3	3.1	3.4	3.5	1.4	3.3	1.5	2.3	2.1
FeO	6.6	7.6	10.6	10.4	6.7	6.8	3.5	3.5
MgO	9.2	7.7	16.8	20.2	5.5	6.9	2.8	3.5
CaO	9.3	9.2	9.7	7.7	9.2	8.9	6.6	6.3
Na_2O	2.0	2.9	0.6	1.5	3.5	3.4	4.6	4.2
K_2O	2.1	0.4	0.4	0.3	1.7	0.7	1.6	1.4
rest	1.1	2.8	0.9	2.4	1.4	1.6	1.0	1.0

I Type-A dyke, 52536.
1 Tholeiitic average basalt (hypersthene basalt) of Koolau Series, Oahu, Hawaii (WENTWORTH and WINCHELL, 1947).

II Early crystallising component of filter pressed type-A dyke, 32157A.
2 Reheated picrite-basalt with new hypersthene, ejected block (1924), Kilauea, Hawaii (TILLEY, 1950).

III Type-C dyke, 52544.
3 Olivine basalt of Cascade Province, Outerson Mt., Oregon (THAYER, 1937).

IV Xenolith-free matrix of xenolithic microdiorite, 32136.
4 Hypersthene Andesite of Cascade Province, Crater Lake, Oregon. (WILLIAMS, 1942).

N.B. All analyses recalculated water-free to 100 %.

In table III analyses of Ilordleq rocks are compared with compositionally similar rocks from effusive volcanic suites; it may reasonably be surmised that rocks with mineral assemblages similar to those of the volcanic rocks of Table III would be associated with the Ilordleq dykes at higher levels in the crust.

(ii) Genesis of orogenic basalt-andesite-rhyolite volcanic association

A close relationship between rocks comprising this association and the Ilordleq dyke swarm is indicated by two independent lines of evidence. As described in Section VII, the Ilordleq dyke suite forms only a small part of an extensive array of intrusive rocks in South Greenland, here referred to as the Rapakivi suite. These rocks were emplaced following or during the closing stages of a period of intense plutonic activity; comparison with similar suites elsewhere makes it likely that at the time these rocks were being emplaced, effusive rocks of the orogenic volcanic association were accumulating at the surface. This conclusion can best be substantiated by comparing the South Greenland intrusive suite with that of a region in which a similar intrusive suite can be directly correlated with its complementary extrusives. A well documented example is that afforded by the Palaeozoic late-Caledonian magmatic suite of the British Isles, of which recent summaries are available (READ, 1961; MERCY, 1965). The similarity of the South Greenland Rapakivi suite to the late-Caledonian magmatic suite is already sufficiently well established (WALTON, 1965) for further detailed comparison to be unnecessary here. The Caledonian intrusive suite can be directly correlated with a complementary extrusive suite which in Wales and NW England comprises a variety of basaltic, andesitic and rhyolitic rocks, including a high proportion of pyroclastics, analogous in all important respects with late-orogenic volcanic suites in North America and elsewhere. It may reasonably be assumed that a similar effusive suite complemented the Rapakivi suite in South Greenland but is not preserved at the present erosional level.

The second line of evidence derives from the occurrence in the Ilordleq dyke suite of petrographic and chemical features which also characterise rocks of the orogenic volcanic suite. Characters common to both suites include those which in the Ilordleq rocks are regarded as indicating, or consistent with, differentiation and crystallisation at high water pressures.

The petrogenesis of the orogenic volcanic association has been reviewed by TURNER and VERHOOGEN (1960). Current theories include fractional crystallisation of basalt magma at depth, contamination of basaltic magma by sialic material, differential fusion of crustal rocks with or without subsequent mixing or differentiation of the initial magmas, and fractionation of basalt under strongly oxidising conditions. O'HARA (1965) has cited experimental evidence in support of the suggestion that orogenic andesittes are likely derivatives of liquids generated by melting of peridotite mantle in the presence of water vapour, or of basalts in contact with peridotite which becomes saturated with water vapour. In both instances the liquids are likely to be rich in silica and therefore committed, even at lower pressures, to a fractionation trend of pronounced enrichment in silica. JOPLIN (1959, 1960) has proposed a process involving hybridisation and remelting of early orogenic basic rocks, to account for the large quantities of intermediate rocks which form an important part of the late-orogenic intrusive suite.

It is suggested here that the characteristic features of the orogenic volcanic suite are consistent with derivation by fractional crystallisation of basalt magma under conditions of high water pressure. These characteristics are considered below under three headings, (1) chemical features, (2) petrographic and mineralogical features, (3) features of a more general nature.

(1) Chemical characteristics of the suite

These have been summarised by TILLEY (1950) and TURNER and VERHOOGEN (1960). Basaltic members are characterised by a high alumina content and "are strongly reminiscent of the porphyritic central type of Mull" (TURNER and VERHOOGEN, *op. cit.* p. 282). As described previously, these characteristics are consistent with derivation by fractional crystallisation at high P_{H_2O} and it is unlikely that such basalts represent parent magmas of the suite. More likely candidates for this title are the normal tholeiitic basalts represented in many provinces. The apparent lack of continuity or systematic variation, shown by basaltic members of the suite on silica variation diagrams, has led to doubts as to whether these rocks are related by any systematic differentiation mechanism such as fractional crystallisation. The constant silica content of the basaltic Ilordleq dykes shows that under the conditions suggested, silica enrichment is a feature only of the later stages of differentiation and that silica variation diagrams are of limited value. The high alumina contents of andesitic members of the orogenic suite may, by comparison with the andesitic rocks of the Ilordleq suite, be seen as consistent with derivation under the conditions suggested.

TILLEY (1950) has demonstrated the distinctively low $FeO + Fe_2O_3/MgO$ ratios of orogenic andesites compared with the 'normal' fractionation products of tholeiitic basalt magmas, by reference to the AFM diagram (*op. cit.* fig. 2, p. 48). These differences have been discussed previously in respect of the Ilordleq dykes, where it was shown that late separation of plagioclase due to high P_{H_2O} could result in compositional variation, in terms of MgO-$FeO + Fe_2O_3$-Alkalies, characteristic of the calc-alkaline igneous suite. This trend of differentiation of the dykes was established from two lines of evidence, namely, differences in composition between individual dykes, and differences in composition between early and late components of a filter-pressed dyke. Although emphasis has been placed on delayed crystallisation of plagioclase, the crystallisation of hornblende may be a contributory factor in determining the Ilordleq trend. TILLEY (*op. cit.*) has suggested that the appearance of hornblende is not a unique determinant of the course of liquid variation in the orogenic volcanics, on the grounds that pyroxene is the dominant mafic mineral of the andesite suite. As pointed out previously, mineral assemblages stable at or near the surface may be quite different from those stable at the depths of differentiation.

By comparison with the Ilordleq dykes, the chemical features of individual members of the orogenic volcanic association, and the compositional variation of the suite as a whole, can be seen as fully consistent with derivation from a magma of 'normal' tholeiitic composition by differentiation at high P_{H_2O}.

(2) Petrographic and mineralogical features

A common though by no means universal character of orogenic basalts is a porphyritic character. A porphyritic habit is in many rocks the result of crystal accumulation; this is unlikely in the orogenic basalts because of the wide occurrence of compositionally identical rocks with a non-porphyritic character. If, as seems likely, these basalts are themselves products of fractional crystallisation, a porphyritic character strongly suggests a profound difference between the physico-chemical conditions under which the magmas were derived, and those under which the magma finally crystallised. Under constant conditions, felspar phenocrysts cannot develop during fractional crystallisation trending toward enrichment in alumina.

A widespread petrographic feature of andesites is the occurrence of disequilibrium mineral assemblages, seen in both mafic and felsic phases, or as expressed by TURNER and VERHOOGEN (1960, p. 276) in reference to rocks of the San Juan province (LARSEN *et al.*, 1937), assemblages which "express a tendency for mutual association of minerals belonging to different stages of magmatic evolution". The association of minerals in these disequilibrium assemblages frequently shows the reverse order of crystallisation from that of BOWEN's reaction series, as with the alteration of hornblende and biotite to aggregates of iron ore, pyroxene, and plagioclase reported by LARSEN *et al.* (1937). Similar relationships are described by WILLIAMS (1931) from cognate inclusions in the Lassen Peak dacites, which feature replacement of hornblende by pyroxene and are further characterised by a tendency toward "a diabasic or lamprophyric texture and by their vesicularity" (*op. cit.* p. 395) and also by WAGER (1962). The only other suite of magmatic rocks which regularly exhibit comparable features are appinitic and lamprophyric rocks which form a part of the intrusive suite which complements the extrusive orogenic volcanics.

These petrographic features alone strongly suggest that changes in physico-chemical conditions constitute an important element in the development of the orogenic andesites and dacites, and are consistent with the view that such changes are those due to the ascent through the crust of an initially water-saturated magma. This view findes further support in two minor characteristics of the suite, namely the abundance of pyroclastic rocks previously referred to, and the occurrence in andesitic lavas of hydrothermal secondary alteration, probably to a greater degree than any rock group other than spilites and related rocks of the ophiolite suite. The reduction of confining pressure consequent on the ascent through the crust will result in a decrease in the amount of water dissolved in an initially saturated magma; excess water which does not escape completely will be retained within the consolidated rock, in vesicles and elsewhere, and is likely to give rise to hydrothermal alteration during the post-consolidation cooling of the rock.

(3) General characteristics

An important difficulty in accounting for the genesis of the orogenic volcanic series by fractional crystallisation of a parent basalt, lies in accounting for the large proportions of andesitic, dacitic and rhyolitic differentiates; this has indeed been an important factor in the acceptance of theories requiring assimilation or partial melting of continental rocks. For the reasons given below it is suggested that by fractional crystallisation of a parent basalt at high P_{H_2O}, greater volumes of intermediate differentiates are to be expected than with differentiation of a similar basalt at low P_{H_2O} or under dry conditions.

Differentiation of a magma by fractional crystallisation is the result of two distinct and independent factors. One of these, which may be called the separation factor, is dependant on a mechanism whereby crystals become separated and effectively isolated from the magma, or that part of the magma, from which they crystallise. The effectiveness of a separating mechanism—gravitational settling or filter-pressing, for example—is dependant on the properties of the magma only insofar as it is affected by physical properties such as viscosity and density.

The other factor consists of two components, the more important of which is dependant on the chemical characteristics of the magma. One of these factors is the time interval, between appearance of the first crystalline phase and consolidation of the magma, during which the separating factor may operate. This time is to some extent dependant on the temperature interval between liquidus and solidus, but the importance of this is greatly reduced by the effects of latent heat of crystallisation, size of the magma body and temperature of the country rocks. The other component of the chemical factor of differentiation is however likely to be of great importance and concerns the relative periods of crystallisation of major phases.

The qualitative aspects of this chemical factor have been referred to in the discussion of series and phase differentiation and put forward as a likely explanation for the differing trends of differentiation in the Ilordleq and Skaergaard suites.

The quantitative effect of the chemical factor on differentiation, could be demonstrated by drawing trend profiles of the two suites, in which compositional trend lines are integrated in a cumulative curve with data on the amounts of each differentiate; unfortunately the necessary data on relative amounts of differentiates are not available for the Ilordleq suite. An acceptable alternative however is comparison of residual liquid compositions in the cifferent suites after crystallisation of known proportions of the parent magmas. The composition of the residual liquid after about 50–60 $^0/_0$ crystallisation of a magma similar to the Ilordleq parent magma is known from analyses of separated components of the type-A dyke. The composition of the 40–50 $^0/_0$ Ilordleq residuum can thus be compared with the 40 $^0/_0$ residual liquids calculated for Skaergaard and Stillwater (fig. 36). Plotted in terms of AFM, these data clearly demonstrate that comparatively large volumes of andesitic differentiates are produced by fractional crystallisation at high P_{H_2O}, while a similar degree of differentiation of basalt at low P_{H_2O} produces no andesitic liquid. Confusion appears to have arisen mainly because andesites represent quite different stages in the differentiation of the calcalkaline suite on the one hand and Skaergaard type of suite on the other. Under conditions of continuous fractionation, andesites are produced in the Ilordleq, and probably calc-alkaline, type of differentiation at the same stage, and in the same proportions, as slightly iron enriched gabbros in the Skaergaard or Stillwater type of differentiation. Factors which have contributed to this confusion include the great difficulty of classifying intermediate rocks in a genetically useful way, and the fact that correlation of differentiation trends with crystallisation processes has been carried out almost invariably in high-level intrusions; it is evident that the conditions obtaining in such intrusions cannot be assumed to be those obtaining during differentiation of all volcanic suites.

If the orogenic volcanic rocks are produced by fractional crystallisation at high water pressures, it can be seen that optimum conditions are achieved for operation of the chemical factor in differentiation and consequent production of relatively large volumes of non-basaltic differentiates: these conditions are (i) restricted overlap in crystallisation of major phases, (ii) slower rate of cooling in orogenic root zones than elsewhere, (iii) large temperature interval between liquidus and solidus.

An important difficulty in deriving surface lavas by differentiation at depth under high water pressure, is that this differentiation is likely to take place at a temperature below that of the solidus of the dry magma. Reduction of P_{H_2O} on approach to the surface in such a case may cause the magma to crystallise rather than continue its passage to the surface. If the ascent of magma is relatively rapid it may be possible for a relatively high P_{H_2O} to be maintained until the surface is reached, as is suggested by resorption of hornblende and biotite in the San Juan lavas (Larsen *et al.*, 1937), which occurred after eruption.

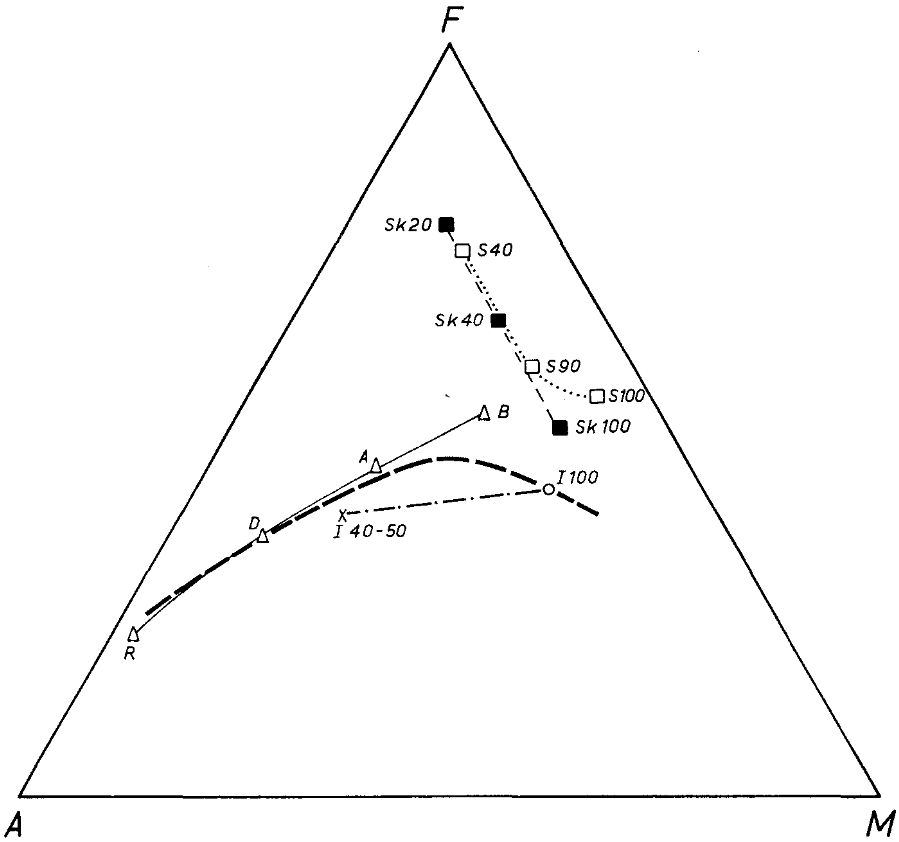


Fig. 36. Calculated compositions of residual liquids at various stages of crystallisation in Skaergaard (Sk, solid squares), Stillwater (S, open squares) and Ilordleq (I, open circle and cross). Figures refer to percentage of liquid remaining at each stage i.e. parent magma = 100. Compositional variation of Ilordleq rocks (broken line) from fig. 34, and calc-alkaline trend (Daly's averages) shown for comparison. Skaergaard data from Wager and Deer (1939), Stillwater data from Hess (1960).

A more important factor however in reducing the likelihood of an isothermal crystallisation, is the effect of latent heat of crystallisation. Crystallisation of early phases due to a decrease in P_{H_2O} is likely to effect an increase in temperature of the magma; it has been suggested (TUTTLE and BOWEN, 1958) that a temperature rise of possibly 100–300°C may result from the adiabatic crystallisation of a hydrous granitic liquid, assuming no heat is lost from the system. Adiabatic crystallisation is likely not only to result in reversals of the discontinuous reaction series but seems a likely cause of the complex zoning of felspars which characterises many andesitic and dacitic lavas.

(4) Conclusions

If the suggestions put forward above are broadly correct it is clear that the intrusive rocks of the orogenic suite may provide more useful evidence regarding genesis of their complementary effusives than is the case with any other intrusive suite. Unfortunately however this group of intrusive rocks is probably less well known than any other group of corresponding size or importance, rarely receiving passing mention even in otherwise comprehensive petrological texts. Appinites such as those of the British Caledonides appear to be important hypabbysal representatives of late-orogenic volcanicity (see JOPLIN, 1959, 1960). In the small number of these intrusions which have been described, the strong evidence of high gas pressure and the frequent occurrence of hornblende as the stable phase in basic rocks, point to the possibility of crystallisation under conditions of high P_{H_2O}. Ultramafic rocks, which must be formed in considerable quantity if orogenic andesites represent differentiation products of basalt magmas, are found in the hornblendites, pyroxenites and other ultramafic types of the appinite complexes.

At a deeper level the information on this suite is even more scanty, possibly because the Precambrian shield areas have not yet been investtigated in sufficient detail, and perhaps too because of the possibility of confusion of igneous rocks initially crystallising at high P_{H_2O} with those crystallised by normal processes of regional metamorphism.

No evidence is available with which to support speculation regarding the separating mechanism responsible for the differentiation proposed. The operation of large scale filter-pressing in an orogenic environment (see PHILPOTTS, 1966) seems to offer excellent possibilities for differentiation. A difference between the effects of filter-pressing and gravitational differentiation processes, which may be significant, is in the mobility of material in which early formed minerals are concentrated. Gravitational sorting allows the formation of lavas more basic than the parent magma by concentration of these minerals in particular parts of the magma reservoir. Liquid, or mobile, products of filter-pressing must always be deficient in early phases, and differentiation series of eruptive rocks formed in this way are likely to show a compositional gap between parent magma and first mobile differentiates. (See TURNER and VERHOOGEN, 1960, pp. 286–287).

The conclusions reached above regarding the origin of the orogenic volcanic suite are similar in many respects to those of OSBORN (1959) and OSBORN and ROEDER (1960) which derived from a theoretical consideration of the effects of oxygen partial pressure on the crystallisation and differentiation of basalt.

OSBORN (1960), concluding that constant or increasing oxygen partial pressure during crystallisation was likely to favour a calc-alkaline differentiation trend, suggested that these conditions were most likely to be achieved during crystallisation of a hydrous magma. Accordingly he ascribed the characteristic differentiation of orogenic basaltic rocks to the presence of small amounts of water in the magma, this water being absorbed from geosynclinal sediments.

Whether or not the effect of high water pressures on the crystallisation of basalt, as observed experimentally (YODER and TILLEY, 1962) and in the dykes of Ilordleq, is in fact due to the influence of water on the partial pressure of oxygen is still conjectural. This question is not, however, of immediate importance unless a comparable effect on oxygen partial pressure may also be achieved, in crystallising magmas, in some way other than by the presence of water.

Limited experimental data (HAMILTON, BURNHAM and OSBORN, 1964) appears to indicate that the role of water in basalt melts is not limited to its effect on oxidation, and the maintainance of constant or increasing oxygen partial pressure during the development of a magmatic rock suite has not yet been demonstrated. The evidence bearing on these problems afforded by the Ilordleq dykes is limited by the possibility of changes in oxidation during the auto-metamorphic stage and will be discussed elsewhere.

(iii) Variation in degree of silica saturation

The table of normative constituents (table I) of analysed rocks shows interesting variations in silica saturation during the supposed differentiation of the Ilordleq dykes, which may have some bearing on the relationships of alkali basalts and tholeiites to their respective lines of liquid descent. Conclusions of general application cannot be drawn from the limited evidence available, which is discussed only in order to show the possibly important information which may be obtained from a detailed study of the Ilordleq or similar suites. It must be remembered too that calculated norms may be significantly affected by changes in oxidation state (see YODER and TILLEY, 1962, p. 375) which may have taken place together with the other autometamorphic changes in these rocks.

Dykes which are regarded as being similar in composition to the initial Ilordleq magma, contain normative hypersthene + olivine and can thus be regarded as undersaturated tholeiites in the sense of YODER and TILLEY (1962). The initial course of differentiation was toward increasing undersaturation with production of nepheline-normative rocks (analyses 7 and 10, table I); this is shown particularly well by analyses (9 and 10, table I) of the filter-pressed dyke. The field and petrographic evidence strongly suggest that fractionation of hornblende was a critical factor in the early stages of differentiation.

The effects of amphibole accumulation and resorption on the course of differentiation of basic magmas was considered by BOWEN (1926) by reference to normative compositions of hornblendites; most of these were nepheline-normative and capable of producing undersaturated liquids only by resorption rather than by means of a fractionation process such as that envisaged for Ilordleq. Compositions of amphiboles vary widely and analyses of amphiboles recast in terms of normative constituents may fall in any space in the idealised basalt tetrahedron (YODER and TILLEY, 1962). When considering the effects of amphibole fractionation it is clearly necessary to consider amphibole compositions appropriate to this particular type of magmatic suite. No analysis is

Table IV.

	(i)	(ii)	Norms	(i)	(ii)
SiO_2	48.92	34.96	quartz	0.9	–
TiO_2	1.21	3.99	orthoclase	4.5	–
Al_2O_3	5.88	15.29	albite	10.6	–
Fe_2O_3	6,5	2.90	anorthite	8.7	5.7
FeO	7.79	18.30	nepheline	–	1.7
MnO	0.17	0.39	leucite	–	32.0
MgO	14.32	10.42	kaliophilite	–	5.1
CaO	11.37	1.11	corundum	–	4.3
Na_2O	1.2	0.41	diopside	36.8	–
K_2O	0.71	7.99	hypersthene	26.3	–
rest	0.16	1.01	olivine	–	39.5
H_2O^+	1.37	3.07	magnetite	9.8	4.4
H_2O^-	**0.18**	**0.41**	ilmenite	2.4	7.9
	99.78	100.25			

(i) Hornblende, appinite, Glen Tilt, Scotland (DEER, 1938).
(ii) Biotite, hornblende hybrid (dioritic), Cairnsmore of Carsphairn, Scotland (DEER, 1937).
N.B. Norms based on recalculation of ten major oxides to $100\,^{0}/_{0}$.

available of any Ilordleq amphibole, but the composition of a hornblende from a similar suite is given in table IV. This appinitic hornblende shows a slight degree of silica over-saturation, and fractionation dominated by removal of similar amphiboles could give rise to undersaturated liquids.

It is evident however that the trend to undersaturation was not maintained throughout the Ilordleq differentiation, as later differentiates (analyses 8 and 11, table I) contain normative hypersthene + quartz. This reversal may provisionally be ascribed to the advent of biotite and its inclusion in the fractionation process; it can be seen from the normative composition of the biotite shown in table IV that fractionation of modest amounts of biotite may have relatively great effects, in terms of silica saturation, on residual liquids.

The suggestions above are intended to illustrate the possible important of future detailed studies of the Ilordleq suite or similar suites elsewhere. The object of this work should be to determine the compositions of minerals, in particular amphiboles, which have been stabilised at successive stages in the crystallisation of basic melts at high water pressures. A major difficulty in this work may be the relatively rapid achievement of chemical equilibrium at high water pressure in crystal-liquid mixtures and possibly also during post-consolidation cooling.

VI. STRUCTURAL FEATURES OF THE DYKES

(a) Features shown by individual dykes

(i) Foliation in the dykes

The internal foliation of the dykes is clearly related to relative displacement of dyke walls, and thus affords a good opportunity for observing structures produced by clearly defined external movements, or the forces associated with incipient or actual movement.

Movement before consolidation of dykes probably accounts for the observed lack of correlation between amount of displacement and intensity of deformation. Foliation is unlikely to be produced by movements which took place while fissures were occupied by magma, and must be regarded as the result of differential stress sustained by and transmitted through crystalline material. Nevertheless the foliation is in most dykes defined by primary minerals (see page 52) and the same mineral assemblages may be found in foliated type-B dykes as in the unfoliated type-C dykes.

The time during which foliation could have developed can be divided into the three following periods:—

(1) from the time when sufficient material had crystallised for a dyke to behave as a solid body, until consolidation was completed; this probably is the time during which the last 30–50 $^0/_0$ of the dyke crystallised. Deformation during this period would be critical insofar as filter-pressing would almost inevitably accompany the development of foliation. Dykes in which this occurred are type-A dykes.

(2) from the time of consolidation of a dyke until the physico-chemical conditions of the consolidation facies no longer prevailed. If the rate of strain during deformation was high relative to the rate at which the minerals could recrystallise, a cataclasis would result instead of the reconstructive transformations characteristic of synkinematic recrystallisation. Dykes deformed during this period include both type-A and type-B dykes.

(3) the period following (2) during which reconstructive transformations were possible under conditions different from those of the consolidation

facies i.e. recrystallisation in greenschist facies. Several examples of both type-A and type-B dykes underwent a limited recrystallisation and deformation during this period.

Foliation in the dykes consists of two distinct parallel components (i) shape and alignment of amphibole aggregates, and (ii) orientation of individual micas and hornblendes in the groundmass. As the outcrop of foliation is in vertical sections parallel to dyke margins, the three-dimensional pattern of deformation can be established.

Deformation of a dyke by lateral relative displacement of wall-rocks can be regarded as a problem of rotational homogeneous strain or simple shear. The former term is preferred as an indication of the *external* movement pattern, because shear used in this context is liable to confusion with shear as an *internal* mechanism of deformation; internal shear played no part in the development of the Ilordleq dykes which deformed by flow (see FLINN, 1962, p. 386). Deformation of dykes by relative displacement of more or less rigid wall-rocks, provides one of the closest approaches possible in geology to deformation in which it may be assumed that neither shortening nor elongation took place parallel to the intermediate principal strain axes (axis Y in fig. 37a), i.e. the deformation path k = 1 (FLINN, 1962). In this circumstance both discussion and illustration of deformation are greatly simplified as the problem is effectively reduced to two dimensions.

Before comparing structures in the dykes with those likely to be produced by rotational homogeneous strain, it is first necessary to define the important characteristics of this type of deformation. The conventional strain pattern expected is shown by reference to deformation of a cube in fig. 37, a–c (see also RAMBERG, 1959). This strain pattern relates only to the finite strain, the maximum and minimum principal axes of which undergo progressive rotation. Consideration of finite strain patterns shows the progressive re-alignment of passive planes and lines, and changes in shape of passive geometric forms such as the circle shown in fig. 37. The relationship between this re-alignment, amount of deformation, and various deformation paths, has been established by FLINN (1962) for cases of irrotational homogeneous deformation; similar relationships apply also to rotational deformation and are further complicated only insofar as the principal axes of finite strain rotate during progressive deformation. In rocks passive planes or lines may be defined by colour banding, lines of mineral grains or small enclaves, or any similar inhomogeneity which does not affect, on the scale considered, the homogeneity of the rock in respect of its deformational characteristics.

Often of greater importance, however, when considering internal structures of rock deformed by homogeneous strain, are the dispositions

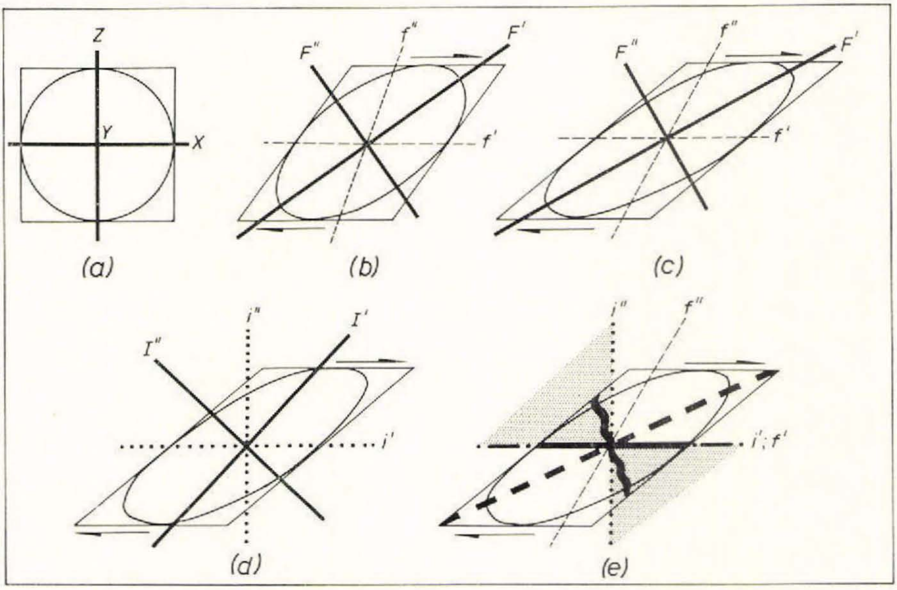


Fig. 37. (a)–(c) Rotational homogeneous deformation of cube, for k = 1, showing reference axes X, Y and Z, ZX section of strain ellipsoid, and progressive re-alignment of maximum and minimum principal axes of finite strain (F′; F″) and planes of no finite strain (f′; f″). (d) static maximum and minimum principal axes of infinitesimal strain (I′; I″) and planes of no infinitesimal strain (i′; i″). All planes are parallel to Y axis for k = 1. (e) illustration of folding, boudinage, and no deformation, of competent layers in relation to planes of no finite and no infinitesimal strain, according to RAMBERG (1959) and FLINN (1962). For further explanation see text.

of principal axes of infinitesimal strain and of stress. The difference between infinitesimal strain and finite strain may be briefly summarised as follows. Infinitesimal strain is an expression of the small increments of strain, the combined effects of which are seen as finite strain. Infinitesimal strain is the product of the movement or flow pattern within the deforming body at any one time; this pattern is in turn a consequence of the prevailing stress system. Whether the stress system should be regarded as controlling the infinitesimal strain or vice versa need not be considered here (see Pt. III); in plastic materials the principal axes of stress and infinitesimal strain will coincide.

The behaviour of included bodies acted upon by the flow regime within a homogeneously deforming body must be considered in relation to the infinitesimal strain ellipsoid rather than the finite strain ellipsoid. For the limited purpose of discussion of the Ilordleq dykes it is sufficient to define such included bodies as being of elongate form, consisting of material competent relative to that of the host, small in size relative to the dimensions of the host and large relative to the deformation unit cell of the host. The deformation unit cell is the smallest unit of a ho-

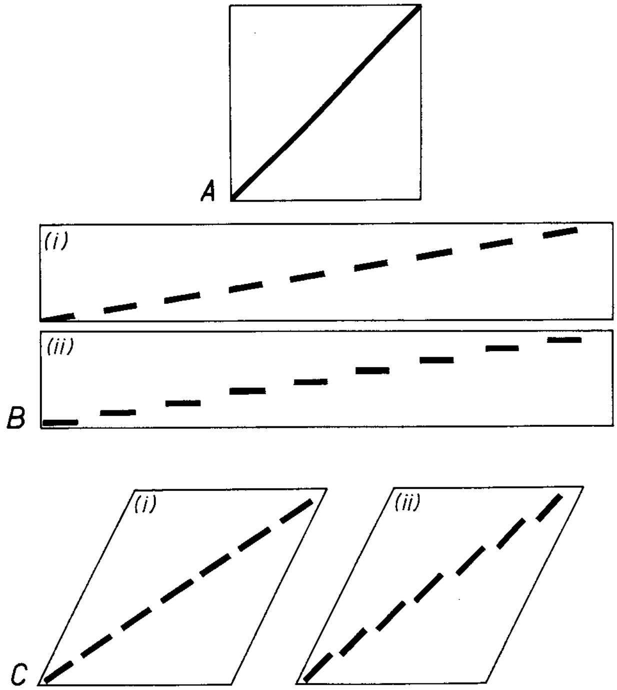


Fig. 38. Simplified illustration showing effects of homogeneous deformation (deformation path k = 1) of host with competent layer (A). B (i) shows irrotational homogeneous strain with re-orientation and boudinage of competent layer. B (ii) as B (i) with rotation of isolated fragments of boudine layer parallel to long axis of infinitesimal strain ellipsoid. C (i) shows rotational homogeneous strain with re-orientation and boudinage of competent layer. C (ii) as C (i) with isolated fragments of boudine layer remaining parallel to long axis of infinitesimal strain ellipsoid. For further explanation see text.

mogeneously deforming material with the same deformation characteristics as the body as a whole. During progressive homogeneous strain there will usually be a tendency for such bodies to become oriented or re-oriented by flow to alignment parallel with the maximum (extensive) principal axis of infinitesimal strain. The circumstances and rates at which this alignment is likely to be achieved are considered in Pt. III. A clear distinction must be recognised between the re-orientation of such included bodies and the re-orientation of passive lines or planes, the latter conforming to the finite strain pattern. The distinction is simply illustrated in two dimensions for a case of progressive rotational homogeneous strain in fig. 38c, which shows the progressive re-orientation of a line of inclusions, while individual inclusions maintain a constant alignment parallel to the maximum principal axis of infinitesimal strain. It is unfortunate that the term rotation has previously been used to refer to the re-orientation of passive planes and lines, as this is liable to cause confusion with rotation of inclusions which are individually rotated by a shear couple imposed by the flowing host; to avoid confusion, the term rotation is used below only in reference to re-alignment of inclusions, and re-orientation used for the re-alignment of passive planes and lines.

The significance of the distinction made above is most easily seen in rotational strain because in this type of deformation principal axes of finite strain undergo progressive re-orientation, while the principal axes of infinitesimal strain maintain a constant orientation (RAMBERG, 1959). In irrotational strain principal axes of infinitesimal and finite strain coincide and maintain a constant orientation; the distinction is still of importance, however, in that re-orientation of passive planes or lines, and rotation of inclusions, take place independently of one another. A simplified illustration of a possible example of this independence in the case of a boudine layer is shown in fig. 38b. The effects of infinitesimal strain may be summarised as resulting in alignment of included bodies in a direction normal to the maximum principal stress axis, i.e. parallel to the alignment of prismatic or tabular synkinematic minerals and hence to the foliation in the rock.

Application of these conclusions to dykes deformed by lateral displacement of wall-rocks, in which a deformation path $k = 1$ is to be expected, affords an explanation, albeit an over-simplified one, of some features of the Ilordleq dykes. As shown by RAMBERG (1959), for rotational strain with $k = 1$, the minimum and maximum principal axes of infinitesimal strain lie at an angle of 45° to the X and Z axes (fig. 37). With the deformation model outlined above it would be anticipated that a synkinematic foliation would develop and remain throughout the deformation at an angle of 45° to dyke margins; included bodies (hornblende aggregates) would not only be flattened within the plane of foliation but would have no tendency to rotate away from this alignment. This explanation of the fabric of the Ilordleq dykes appears to be more consistent with the observed phenomena than explanations based on other deformation models currently available.

Insofar as a foliation defined by the alignment of individual crystals will not comprise discrete planes or folia, there will be no tendency for the foliation pattern to re-orientate with increasing deformation. If discrete planes were to form at any stage parallel to the mineral alignment, such as those originating in some rocks by metamorphic differentiation and defined by compositional differences, these planes would undergo progressive re-orientation in accord with increasing finite strain. Such planes were not developed, or at least did not survive, in the Ilordleq dykes.

No account has yet been taken of the sigmoid curvature of the dyke foliation. This 'drag' of the foliation in the marginal zones of the dykes is of particular interest as it demonstrates the influence of boundary layer effects, which represent a departure from homogeneous strain which may be of importance in the generation of similar folds. This problem is considered in more detail in Part III, and it is necessary here only to outline the main factors affecting the formation and extent of the boundary layer. The regular pattern of progressive strain shown in figure 37 illustrates the behaviour of a perfectly plastic solid. The concept of a perfectly plastic solid is one which has only limited geological application as it does not allow consideration of the effects, on stress differences and om deformation paths, of varying strain rates. A comprehensive view of the relationship between deformation and the rates of strain is best obtained by a theoretical approach, which is attempted in Pt. III, but an empirical comparison is sufficient to illustrate the factors which determined the foliation pattern in the dykes.

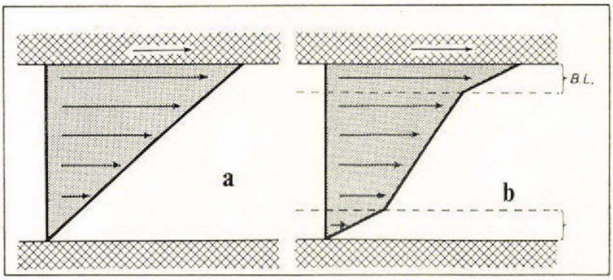


Fig. 39. (a) Velocity gradient, or strain rate, in ideal Newtonian fluid between moving parallel plates. (b) Velocity gradient, or strain rate, in non-ideal fluid with boundary layer (B.L.) effect. After Reiner (1960).

Figure 39a shows the velocity gradient, or variation in strain rate, in an ideal fluid between parallel plates, when one plate is moved in its own plane (Reiner, 1960). The absence of boundary layer effects is shown by the straight line velocity distribution. Figure 39b shows the velocity distribution in viscous liquids or plastic solids with boundary layer effects adjacent to the plates, a situation closely analogous to that in the Ilordleq dykes. The width of the boundary layer in fluids is primarily a function of the viscosity of the fluid, but with plastic material having a fundamental strength, the stress difference within the solid, which is a function of the rate of strain (Heard, 1963), is also important. In general however a high rate of strain, large stress differences, and a high viscosity will increase the proportion of the movement taking place within the boundary layer. The marginal shear zones in metabasaltic and other dykes may be seen as the result of lower temperatures, giving higher effective viscosities, (see HEARD, 1963) and higher stress differences than obtained in the Ilordleq dykes.

(ii) Deflection of country rock foliation

Deflection of the earlier granite foliation in a narrow zone on the borders of some dykes shows that the wall rocks did not behave as completely rigid bodies. The width of the affected zone is however little wider than that which may have been termally affected by the dykes, and the deflection does not therefore provide a certain indication of the rheological state of the main body of country rock at the time of dyke intrusion. The direction of the deflection is nevertheless useful insofar as it confirms the overall movement pattern inferred from other lines of evidence.

(iii) Folded xenoliths

The type-B dyke containing folded strips of country rock granite has already been described (page 27 and figure 3a). As interest in this dyke attaches to the relationship between deformation, foliation and folding rather than petrogenesis of the dykes only brief comment is necessary.

The xenoliths are aligned parallel to the dyke margins and therefore to one of the planes of no infinitesimal strain of the strain ellipsoid (RAMBERG, 1959). This orientation is critical in that with the mechanism of internal deformation envisaged by RAMBERG (*op. cit.*) and FLINN (1962) competent sheets parallel to this plane should have undergone neither stretching (boundinage) nor folding. Figure 37e is a simplified illustration of the relationship, as advocated by the above authors, between folding and boudinage of competent layers and rotational homogeneous strain, with k = 1.

Planes of no finite strain (f′; f″) correspond to circular sections of the finite strain ellipsoid which separate sectors in which planes or lines are shorter (oblique angles f′–f″) and longer (acute angles f′–f″) than the originals, corresponding to sectors in which competent layers are folded and boudine respectively. Planes of no infinitesimal strain (i′; i″) separate sectors in which shortening (shaded angles i′–i″) or lengthening (unshaded angles i′–i″) of planes or lines takes place, irrespective of whether they are shorter or longer than the originals. In sectors i″–f″ layers are shorter than originally but undergoing lengthening, and in shaded sectors layers are shorter than originally and undergoing further shortening. According to this hypothesis planes originally parallel to the plane containing the X and Y reference axes are planes of no finite strain, and planes of no infinitesimal strain, which remain parallel to the

XY plane throughout the deformation and undergo neither shortening nor lengthening; competent layers parallel to the XY plane should consequently undergo neither folding nor boudinage. The folding of the xenoliths in the dyke referred to is thus inconsistent with this mechanism of folding.

It is suggested that this discrepancy is not due to an unusual mechanism of deformation either in this particular dyke or in the Ilordleq dykes in general. The oblique orientation of the xenolith strips relative to the dyke foliation has served to demonstrate the existence of local variations in the amount of strain within the dyke. Such variations are likely to be present not only in all the dykes, where they are not seen because of the lack of earlier structures oblique to the plane of foliation, but in all deformed plutonic rocks where they are an important factor in the generation of folds with axial planes parallel to the foliation. The xenoliths cannot be regarded as playing an active role in the formation of the folds nor are they ptygmatic veins.

Supporting evidence for the conclusions drawn from this single example in Ilordleq has been recently obtained during examination of similar dykes in the Julianehåb area of South Greenland. In this area late-kinematic dykes with wall-rock displacements and foliation patterns similar to those recorded in Ilordleq, are cut by numerous penecontemporaneous granitic veins; the deformation and folding of these veins is inconsistent with the relationship between homogeneous deformation and folding envisaged by RAMBERG (1959) and FLINN (1962). It is not suggested that the concept of homogeneous strain is not applicable to plutonic rocks, but rather that departures from it are important in a way different from that previously proposed.

(iv) Folded foliation

This has been seen only in one dyke (page 27, fig. 17c and Plate 1b). The folding of the earlier foliation is paracrystalline with respect to amphibolite facies minerals and recrystallisation of biotite and hornblende parallel to the axial of the planes folds define a second foliation at right angles to the earlier one. It is probable that the second foliation developed as a result of a final displacement in a reverse direction i.e. sinistral, to that which produced the first foliation. In this dyke too the folded structure i.e. the plane of the earlier foliation, can be regarded as playing no active role in the genesis of the fold structure and its only function has been that of showing up the variations in amounts of strain parallel to the second foliation.

It is conceivable that the second foliation is due not to sinistral displacement along the dyke but to continued dextral displacement, which is accommodated by internal movement along planes of maximum shearing stress in the strain ellipsoid. Activation of these planes is unlikely, however, when the dyke is able to recrystallise readily, and would in any case produce structures indicating transverse relative displacement (dextral) and monoclinal folds, rather than the symmetrical folds which are found.

(b) Collective features of the dykes

The structural characteristics of the dyke suite as a whole are shown diagrammatically in fig. 19 in which the dyke fractures are interpreted as a conjugate set of shear fractures. This interpretation is based primarily on the directions of displacement along the dykes because, as the stereographic projection in fig. 19 shows, the directions of the dykes do not fall into two clearly separated groups.

The overall pattern of fracturing and displacement is consistent with brittle fracture by sub-horizontal compression with the maximum principal stress approximately N–S, and sub-vertical intermediate stress parallel to the line of intersection of the dykes. Drag features associated with a gently dipping dyke (figs. 2c, 20) and hornblendic shear veins (fig. 23), both of which dip to the NNW, indicate reverse fault or overthrust movement toward SSE, whereas quartz veins dipping to the SSE are emplaced along fractures which indicate overthrust movement to the NNW. One of these quartz veins is seen to cut a hornblende shear zone (fig. 23). Only few observations have been made of such displacements, but it can provisionally be suggested that they represent a subsidiary set of conjugate shear fractures which may develop when the value of the minimum principal stress approaches that of the intermediate principal stress. A fracture zone outcropping for 300 m on the NW coast of Ikerasârqap nunâ, dipping 20°–30° to the SE, may have been formed by movement along such a shear fracture; the relative movement in this zone is not known.

Although the strike directions alone do not allow a convincing separation into two groups, the sense of displacement along dyke fissures is clearly related to strike direction. In addition, the lines of intersection of the large majority of dykes are fairly consistent, plunging at about 65° to 215°. As the line of intersection is taken to be the intermediate principal stress direction, this is more clearly defined than the azimuth directions of minimum and maximum principal stresses. The spread of strike directions is concentrated within the sector containing the minimum principal stress axis, approximately E–W as determined from displacements along dyke fissures. The direction of the maximum principal stress axis is estimated to be about 010°. The spread of strike directions is too great to determine whether the maximum principal stress direction lies within an acute, or within an obtuse angle between the supposed shear directions.

It is possible that the present attitudes of the dykes are not original but due to later tilting: assuming that the line of intersection of the dykes was originally vertical, the usual case in dyke swarms, a tilting of 25° towards ENE must have taken place, at some time subsequent to the emplacement of the late-kinematic dykes and before intrusion of the first Gardar dykes.

Possibly related to the hornblende shear zones referred to previously, are ubiquitous amphibole coated joint surfaces found throughout the area; small displacements can be seen on many of these joints but neither these nor the joint directions were recorded systematically. The occurrence of amphibole in shear zones and along joint surfaces may point a connection between the movements associated with the intrusion of the Ilordleq dykes and the mineralisation on Alángorssuaq, a peninsula immediately to the west of Ilordleq (HARRY and OEN, 1964). Of particular interest are the hot shear zones associated with syenitization of the country rock granites on Alángorssuaq. Dykes described by the above authors as having been regionally metamorphosed have many features in common with the late-kinematic Ilordleq dykes, including sigmoid foliation defined by hornblende aggregates indicating sinistral movements along N–S and NNE striking dykes, some of which have "vague ramifying areas paler and richer in felspar than the enclosing rock" (*op. cit.* p. 28). The period of fracturing giving rise to hot shear zones in the granite preceded the main mineralisation which HARRY and OEN (*op. cit.* p. 61) regard as having taken place at a maximum depth of 3 km, but at fluid pressures greatly in excess of 'load' pressure.

The suggested orientations of regional principal stress axes are similar to those which prevailed during the preceding plutonic Sanerutian activity. The structures developed during this plutonic episode indicate a homogeneous pattern of strain throughout much of the area, with the maximum principal stress normal to the regional foliation and lineation (elongation) direction, and the minimum principal stress parallel to the latter which is sub-horizontal (see Parts I and III). The foliation and lineation directions are shown in fig. 19 together with the orientation of the inferred strain ellipsoid. The accuracy of determination of the axes during either period is not sufficient for an attempt to demonstrate an exact fit, but even without this it is clear that there were no marked changes in the tectonic pattern throughout the Sanerutian period. It is even conceivable that conditions during the period of plutonic activity differed from those during the period of intrusion of the dykes only in that the rate of strain was more rapid during the latter.

VII. REGIONAL CONTEXT OF THE DYKES

Since the Ilordleq dykes were recognised as a distinctive suite, more or less identical dykes occupying a similar chronological position have been found to occur throughout a wide area of South Greenland (Allaart, 1964). A further characteristic intrusive suite, not found in Ilordleq, consists of flat-lying net-veined sheets (Windley, 1965) which are widely distributed in the Julianehåb area. These sheets post-date the late-kinematic dykes in the Julianehåb area but are also thought to have been emplaced during the later stages of Sanerutian reactivation. In addition, larger intrusions of dominantly basic rocks of appinitic type have been described from north of Narssarssuaq (Walton, 1965). These intrusions are known to be cut by dykes similar to those of Ilordleq and have been described as being intruded "immediately following the second period dykes" (Bridgwater and Walton, 1964). This assertion can however be supported only by the fact that, in the area north of Narssarssuaq, no significant geological event intervened between emplacement of the second period dykes and the appinites. Notwithstanding present uncertainties regarding the age of the appinites relative to plutonic reactivation in Ilordleq, which preceded emplacement of the Ilordleq late-kinematic dykes, it is apparent that the Ilordleq dykes, the net-veined diorite sheets, and the appinitic intrusions, represent a well defined suite of basic and intermediate rocks emplaced during the closing stages of a period of intense plutonic activity. Whether this major plutonic event should be thought of as being the Sanerutian alone, or as including both Ketilidian and Sanerutian, or even as extending into the pre-Ketilidian, does not greatly affect interpretation of the Ilordleq dykes. It is probable that the suite of basic and intermediate rocks described forms only a small part of a more extensive suite which includes the large masses of granitic rocks collectively referred to as New Granites. The main features of the New Granites have been reviewed by Bridgwater (1963); and Dawes (1966) has shown that at least some have the petrographic, in addition to the environmental, characteristics of Rapakivi granites. These granites and associated intermediate and basic intrusives occur mainly between Julianehåb and Kap Farvel on the west coast, also extending northwards from Kap Farvel on the east coast. Recent work has shown rocks of this association to be even more extensive than shown on the most recently published map (BRIDGWATER, 1963) and their total areal extent is upwards of 3000 km^2. The granitic rocks are everywhere associated with basic and intermediate rocks similar to those found north of Julianehåb which are associated with only small amounts of granite.

The Ilordleq dykes therefore form only a very small part of a very extensive group of rocks which at the present erosional level in South Greenland collectively form the Rapakivi suite. No far-reaching conclusions regarding this suite can be arrived at by investigation of the small fraction of it comprising the Ilordleq dykes, although conclusions reached regarding conditions of crystallisation, depth of emplacement, and the relationship of the dykes to surface volcanic activity may apply to the suite as a whole.

VIII. CONCLUDING REMARKS

(a) Comparisons with rocks showing similar features

The oblique foliation pattern in the Ilordleq dykes has been shown to be consistent with deformation of the dykes by lateral relative displacement of rigid wall-rocks. A similar foliation characterises many other lamprophyric dyke suites (KAITARO, 1953; BLYTH, 1949; BALK and GROUT, 1934; ELDERS, 1957; MOORE and HOPSON, 1961). The oblique shears in the porphyritic dykes of Galloway (Scotland) have been interpreted by BLYTH (1949) as having been formed by lateral movement recurring after emplacement of the dykes along transcurrent movement fractures. As in the Ilordleq area the structures in individual dykes conforms to a regional pattern (see also MOORE and HOPSON, 1961). No evidence for the sense of relative movement of the wall-rocks is cited for the Galloway dykes and the shear structures are explained by means of a brittle fracture hypothesis; as a result the relationship between the oblique structures in the dykes and directions of relative displacement of wall-rocks is the reverse of that which is thought to have applied in Ilordleq. It may be however that the oblique structures in the Galloway dykes are not comparable with the foliation in the Ilordleq dykes.

The radial suite of lamprophyric dykes associated with the Åva granite, SW Finland, (KAITARO, 1953) show a relationship between oblique foliation and wall-rock displacement identical with that proposed for the Ilordleq dykes: interpretation in the two areas differs only in regard to the mechanism of deformation of the dyke material, the present writer regarding the theory of brittle fracture inappropriate. Similarity of many features in contrasting swarms of dykes such as those of Ilordleq and Åva, suggests that a study of the transcurrent movement directions along dyke fissures in a radial swarm would be of great interest.

The conjugate fracture system which controlled the emplacement of the Ilordleq dykes can probably be regarded as analogous to conjugate fold systems which develop in rocks less homogeneous than those of Ilordleq. The regional stress pattern thought to be responsible for the formation of the fracture system in Ilordleq is the same as that thought by RAMSAY (1962) to control the development of conjugate folds; these folds are found in rocks deformed during late phases of orogenic development and are often related in space and time with development of faults, thrusts and joints (*op. cit.*). Dykes similar to those of Ilordleq have in fact been shown to be associated with late-Caledonian conjugate folds in NW Scotland, (SOPER and BROWN, 1965), and suggest the possibility of a detailed comparison of comparable events and phenomena at the different tectonic levels represented in Scotland and South Greenland.

The important petrographic features of the Ilordleq dykes are those which indicate primary crystallisation in amphibolite facies followed in many dykes by extensive post-consolidation recrystallisation. Descriptions of comparable features are widespread in the literature on lamprophyric rocks and have on occasion led to conclusions similar to those arrived at in Ilordleq, which tend to confirm that 'the deadlock reached with regard to these troublesome rocks is due to a rigid belief in orthomagmatic crystallisation'. (SMITH, 1946, p. 170). Individual features which constantly recur in lamprophyre descriptions and which are thought to be of genetic importance in the Ilordleq rocks include titaniferous brown amphiboles (CHALLIS, 1963; CAMPBELL and SCHENK, 1950; RAMSAY, 1955; WALKER and ROSS, 1954; JAFFE, 1953) and the occurrence of amygdales or ocelli (WILLIAMS, 1923; WOODLAND, 1962; CAMPBELL and SCHENK, 1950; RAMSAY, 1955; WALKER and ROSS, 1954; JAFFE, 1953; KNOPF, 1936; REYNOLDS, 1931).

Abundant xenoliths of both cognate and accidental origin are features which point to common factors in the genesis and conditions of emplacement of a large number of lamprophyric dykes of diverse type: in Ilordleq the abundance of xenoliths is regarded as a result of high gas pressure and emplacement along active transcurrent fissures.

The apparent similarity between the crystallisation and deformational history of many lamprophyric dyke suites and that of the Ilordleq rocks, suggests that filter-pressing may be more common than has been previously acknowledged. Some examples of filter-pressing have been described and interpreted as such (WILLIAMS, 1923; KAITARO, 1953; WOODLAND, 1962), while descriptions of inhomogeneities in many other suites, of which the A'chuine hybrids (READ, 1925, 1931) are an example, may indicate the operation of a similar mechanism.

The felspathisation of wall-rocks of some of the dyke fissures before intrusion of the dykes has obvious similarities with the formation of such well-known rocks as fenites and adinoles. The combination of basic dykes and potash metasomatism seems however to be an unusual one; an example which has been fully described (KENNEDY and READ, 1936) relates to a dyke which is probably a member of the Scottish swarm referred to earlier (BLYTH, 1949). Extensive potash metasomatism adjacent to this dyke has been established by chemical analysis, and the potash content of the dyke rock exceeds that of the basaltic Ilordleq dykes by less than 1 %. Similar bleaching of brecciated country rocks adjacent to sills has been described by TWETO (1951). The close relationship of the late-kinematic dykes with alkaline fluids, which in a neighbouring area are associated with hydrothermal sulphide mineralisation (see page 93), suggests that the Rapakivi suite in South Greenland is of potential economic interest.

(b) Ilordleq dykes in relation to the lamprophyre problem

It is clear that the Ilordleq dykes have features in common with many dyke suites elsewhere which have been described as lamprophyres, and this term could indeed have been used for these dykes. An attempt has been made to show that the Ilordleq dykes were derived from a magma of commonplace composition, probably theoleiitic, and that their unusual features, chemical, mineralogical, and others, are due entirely to two factors; (i) crystallisation at high P_{H_2O}, and (ii) external conditions at the time of emplacement. Insofar as crystallisation at high P_{H_2O} appears to be a common feature of late-plutonic basic rocks, it is probably correct to regard external conditions as wholly responsible for the characteristic features of the dykes.

If this is the case, the differences between the Ilordleq dyke suite and a normal tholeiitic or calc-alkaline dyke suite must be regarded in the same way as, for example, the differences between rocks metamorphosed in different grades of regional metamorphism. Although wide differences in composition may exist the primary division of metamorphic rocks is one based on differences which are interpreted as being due to variation in the conditions under which the rocks crystallised. Although these distinctions have been used mainly in the study of metamorphic rocks, the application of the facies concept to magmatic rocks was clearly envisaged by ESKOLA in his original definition of mineral facies (page 51). If rocks such as those of Ilordleq are regarded as the products of crystallisation in a particular facies, the difficulties over nomenclature and classification of these and similar rocks can be at least circumvented, if not resolved. Furthermore, the primary classification of such rocks on the basis of often minor differences between mineral assemblages, a large proportion of which cannot even be regarded as equilibrium assemblages, will then be seen to be as inappropriate and pointless as would a similar classification of metamorphic rocks.

On the basis of the limited evidence available, there is no reason to suppose any significant differences in the equilibrium mineral assemblages, and hence physico-chemical conditions, between the facies in which the dykes crystallised and the almandine-amphibolite facies of regional metamorphism. It could be, however, that the suspected differences in, for example, the relationship between fluid and solid pressures (see page 55), would not significantly affect mineral assemblages in basic rocks but would effect significant differences in mineral assemblages in rocks of a different composition. Either because of this, or simply as a matter of convenience, it could be argued that a separate facies terminology should be used for the consolidation facies of magmatic rocks. The Ilordleq rocks could then simply be described as basic rocks crystallised in the lamprophyre facies as opposed to the basalt facies. Further subdivisions could be made when it becomes apparent that they are required; it could be, although it is not suggested so here, that all magmatic rocks can be satisfactorily divided into only two facies. It is not suggested that all lamprophyres and associated rocks can be regarded as having crystallised under the same conditions as those prevailing during crystallisation of the Ilordleq dykes; as has been emphasised by FYFE, TURNER and VERHOOGEN (1958), a facies classification is not a rigid system, but one which is of an essentially pragmatic nature, and which may be re-adjusted either as a result of new information, or on grounds of practical convenience. The writer is at present investigating the mineral facies of a variety of magmatic rocks with the object of determining the subdivisions which may be of practical use, and whether some or all of these subdivisions differ significantly from the subdivisions of metamorphic facies.

Perhaps the greatest use of a separate terminology would be the impetus which would be given to the recognition of conditions of consolidation as being of equal importance with rock composition in determining the mineral assemblages of magmatic rocks.

(c) Source of water in the Ilordleq dyke magna

The water content of the parent magma of the dykes was the critical factor which made possible the development of the high water pressures which influenced both their differentiation and crystallisation. It is important to determine whether this high water content is of primary origin or whether due to influx of water at some time subsequent to the formation of the magma: if the latter it is of interest to know whether the water was of juvenile or connate origin.

If the high water content was congenital it must be supposed that the magma originated under conditions of high P_{H_2O}. If this were the case and if the magma were derived by partial fusion of a non-basaltic source, the composition of the magma would be quite different from that of magmas derived by partial melting of the same source at low

P_{H_2O}; as this is not the case it is probable that the water content is not an original feature of the magma. The close relationship, in both space and time, between magmatic suites in which high water content is an important character and plutonic activity, seems sufficiently well established to justify a prima facie conclusion that the water content of such magmatic rocks derives from the penecontemporaneous plutonic rocks. The progressive depletion of water in plutonic rocks with increasing grade of metamorphism has long been recognised, but there is also convincing evidence for the migration of alkalies, particularly potash, in the higher grades of metamorphism. A metamorphic source seems possible for the alkaline fluids which preceded the basic magma along the dyke fissures in Ilordleq, and perhaps also for the regional alkali influx associated with the emplacement of the Rapakivi suite (ALLAART, 1964; DAWES, 1966).

If rocks undergoing granulite facies metamorphism are depleted in water and alkalies (RAMBERG, 1951), it may provisionally be suggested that the compositional changes undergone by plutonic rocks during such metamorphism are complementary to compositional changes in contemporaneous basic magmas, which effect profound changes in the subsequent evolution of such magmas. This process is analogous to the formation of spilitic rocks by the migration of water and soda into basalt magmas, from enclosing marine sediments or sea-water. It might even be suggested that in some circumstances both the development of granulite facies assemblages and related compositional changes are dependent on the proximity of basic magmas.

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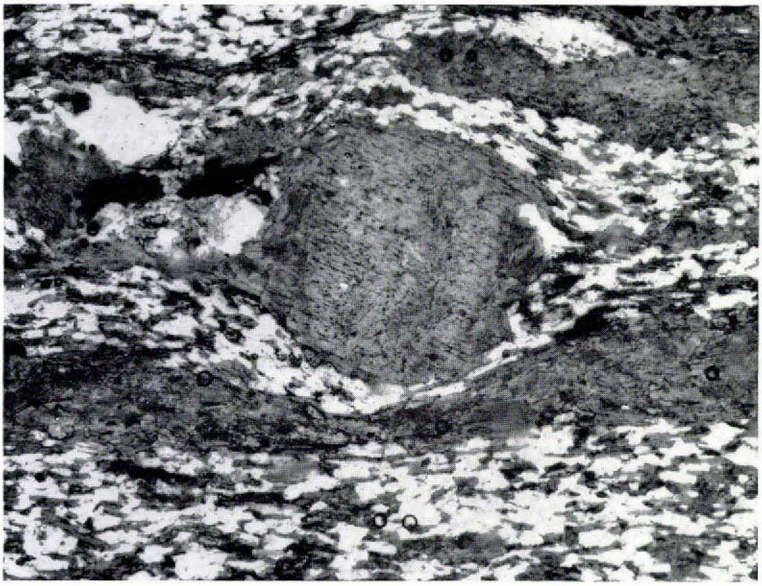
PLATES

Plate 1

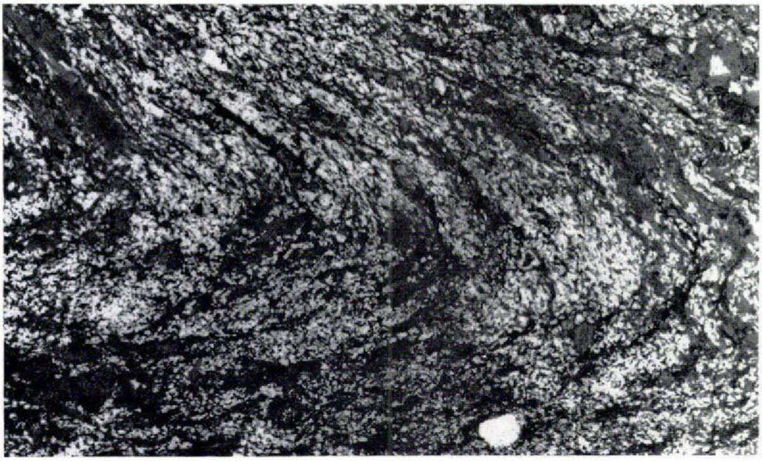
(a) Mafic aggregate in type-B dyke, consisting mainly of single undeformed amphibole crystal. P.P.L., (×28), G.G.U. 31464.

(b) Folded foliation in type-B dyke showing incipient strain-slip structure parallel to axial plane of folds. P.P.L., (×6.5), G.G.U. 52526.

(c) Inhomogeneity in type-A dyke with leucocratic material separating mafic-rich aggregates. P.P.L., (×3), G.G.U. 32157.



a



b

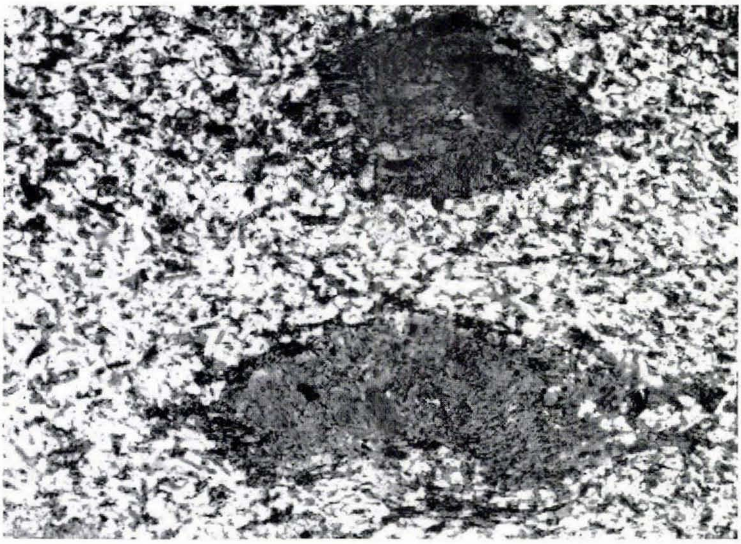
c

Plate 2

(a) Amphibole aggregates drawn out and aligned parallel to foliation in plagioclase-hornblende groundmass of type-B dyke. P.P.L., (×16), G.G.U. 32535.

(b) Disrupted zoned prismatic brown amphibole in microcline bearing type-C dyke. P.P.L., (×24), G.G.U. 31680.

(c) Amphibole concentration along margin of type-B dyke (right) adjacent to country rock granite (left). P.P.L., (×16), G.G.U. 52540.



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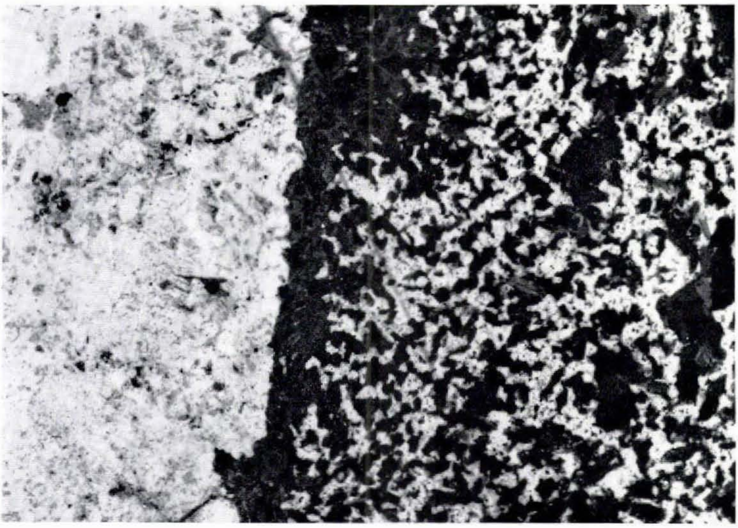
b

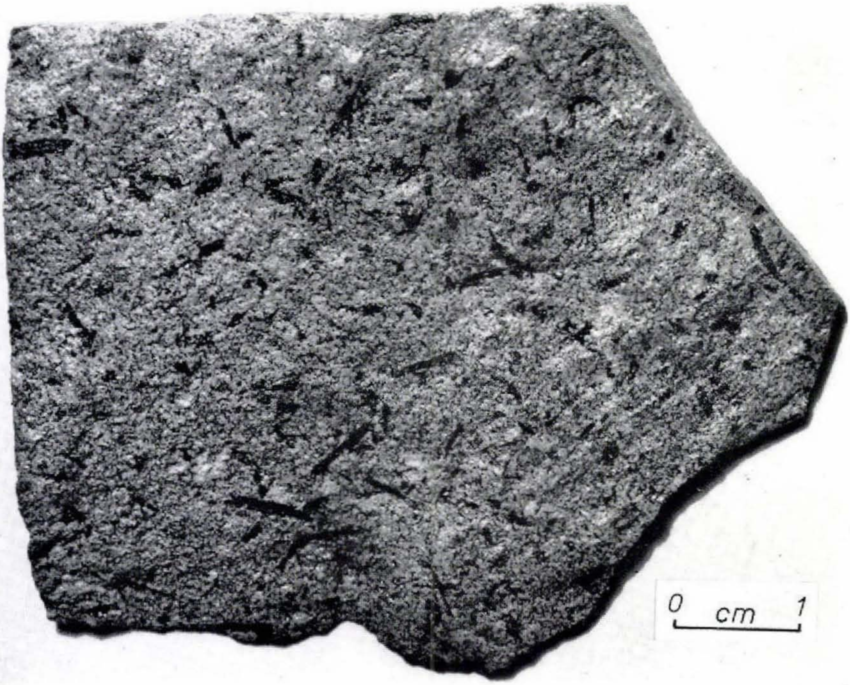


c

Plate 3

(a) Prismatic amphiboles on weathered surface of microcline-bearing type-C dyke.

(b) Zone of metasomatic alteration of country rock granite (right) bordering type-B dyke (left). Polished surface.



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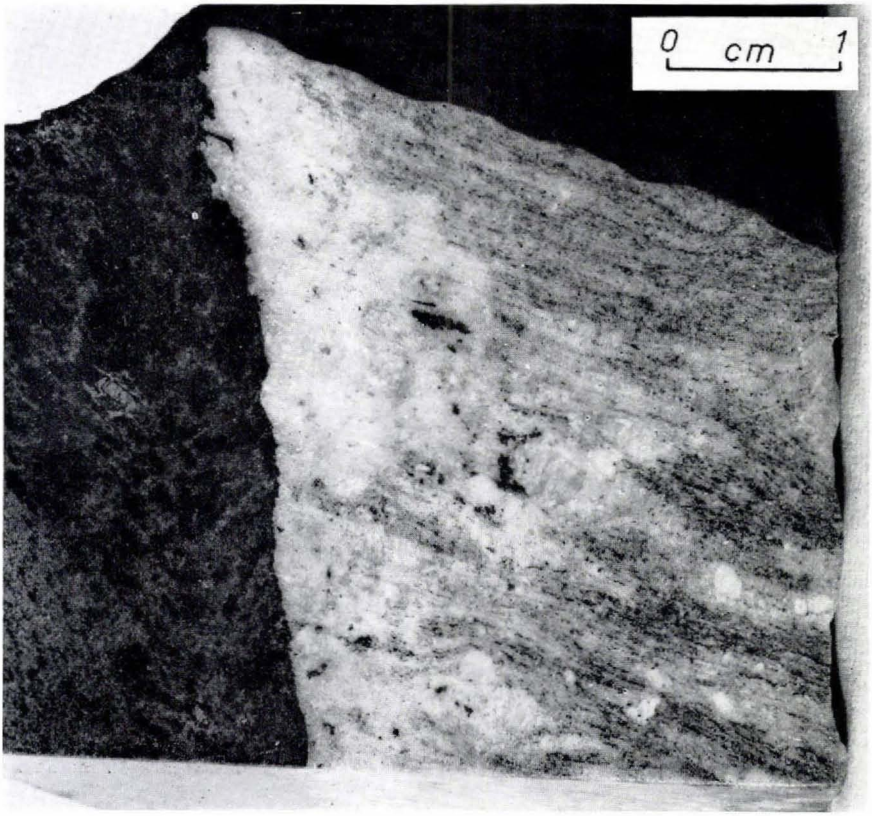
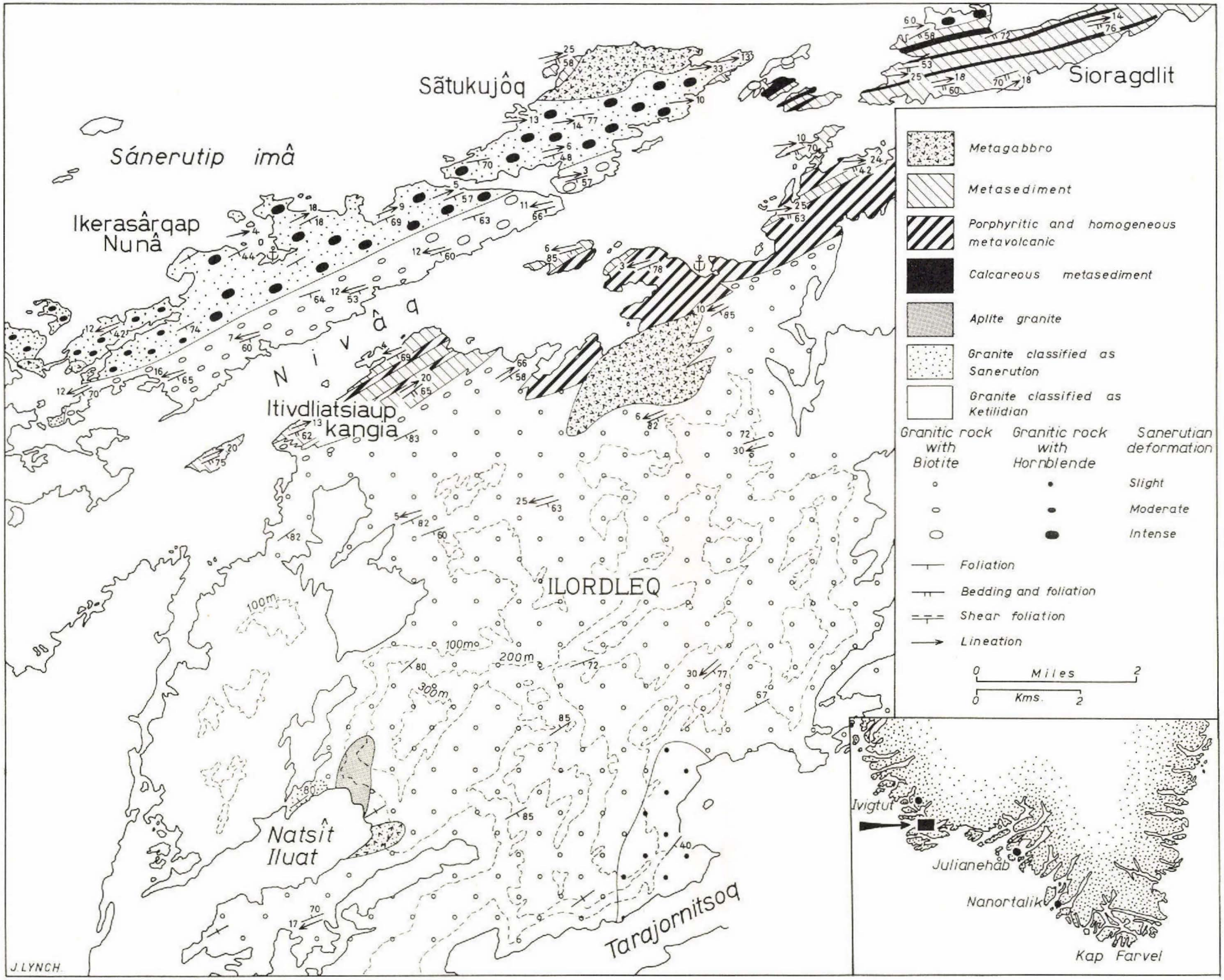


b

Plate 4

Geological sketch map and location of the Ilordleq area.


Sãtukujôq
Sioragdlit
Sánerutip imâ
Ikerasârqap Nunâ
N i v â q
Itivdliatsiaup kangia
ILORDLEQ
100m
200m
300m
Natsît Iluat
Tarajornitsoq
J. LYNCH
Metagabbro
Metasediment
Porphyritic and homogeneous metavolcanic
Calcareous metasediment
Aplite granite
Granite classified as Sanerutian
Granite classified as Ketilidian
Granitic rock with Biotite
Granitic rock with Hornblende
Sanerutian deformation
Slight
Moderate
Intense
Foliation
Bedding and foliation
Shear foliation
Lineation
0 Miles 2
0 Kms. 2
Ivigtut
Julianehåb
Nanortalik
Kap Farvel