Petrology of the Scourie dyke, Sutherland.

(With Plate XVIII.)

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Summary. Chemical data are given for four rocks from the Scourie dyke, Sutherland, and for the constituent minerals. Three of the specimens are unsheared and represent stages in a continuous variation from a one-pyroxene (subcalcic ferroaugite) dolerite through partially amphibolized two-pyroxene dolerite to garnet–plagioclase amphibolite. These changes are not accompanied by conspicuous changes in bulk composition. The garnetiferous varieties represent a border facies of the dyke, which is in contact with little-altered pyroxene-bearing gneisses of the Lewisian complex. The fourth specimen is a hornblende schist formed from the dolerite by shearing. This change also involves little change in bulk composition, and affects impartially the three types of dolerite referred to above. Mineral relations are discussed and a hypothesis advanced to account for the garnetiferous border facies of the intrusion, invoking intrusion while the country rock was at relatively high temperature and pressure.

THE petrology of the dyke at Scourie was first described by Teall (1885) who demonstrated that in its least altered state the dyke was composed of an iron-rich quartz-dolerite containing one pyroxene, and that this dolerite was converted to hornblende schist without major change in bulk composition. This conversion was ascribed to dynamic metamorphism at 'ordinary' temperature, a view which was later modified (Teall, 1918) to dynamic metamorphism at 'comparatively low' temperature, i.e. less than that required for fusion. Detailed accounts of the field relations and regional setting of the Scourie dyke and other similar dykes in Sutherland and Wester Ross have been published elsewhere (Clough, Teall, *et al.*, 1907; Sutton and Watson, 1951 *a* and *b*) and need not be recapitulated here.

The clouded feldspars of the Scourie dyke have been commented on by Macgregor (1931) and several aspects of their petrography were examined by Bailey (1951). Four facts not recorded by previous workers are: first, that garnet is abundant in the Scourie dyke at both localities where it is well exposed on the north shore of Scourie Bay (Creag a'

Mhail and Poll Eorna on the 6-in. map, national grid references 29/145458 and 29/150455 respectively); the garnet is restricted to the finer-grained border facies of the dyke, and is absent from any rock that has suffered shearing.

Secondly, undisturbed junctions between dyke and country rock are exposed at Creag a' Mhail (northern contact immediately west of the only convenient access to the dyke hollow), and Poll Eorna (northern contact under shingle near high-water mark a few feet west of a well-exposed bollard of country rock). The dolerite at the contact is a fine-grained rock with a layering of light and dark components parallel to the junction, suggesting flow-banding. This layering persists for a few inches only into the dyke, and is due to segregation of garnet and amphibole. The country rock is a quartz–andesine–augite–hypersthene gneiss that shows no evidence of shearing, even in contact with the layered dolerite. The mineralogy and attitude of the gneiss demonstrate that it belongs to the early Lewisian metamorphic complex with little or no modification due to the late Lewisian metamorphism (Sutton and Watson (1951*a*)).

Thirdly, all of the southern contact and most of the northern contact are affected by shearing, which also affects parts of the centre of the dyke within narrow transgressive zones. Within these zones the dolerite is everywhere converted to a lineated hornblende schist of uniform appearance. At Creag a' Mhail the shearing is seen to be later than the formation of garnet in the border facies. Sutton and Watson (1951*a*) have correlated the shearing with the period of the late Lewisian metamorphism on reliable evidence.

Fourthly, no unmodified chilled contact exists between the Scourie dyke and the gneiss, nor can any normal chilled contact be found between any member of the swarm of similar dykes and the gneiss anywhere in the region between Laxford and Lochinver, nor in Torridon.

Petrology.

One-pyroxene dolerite [84249] (numbers in brackets refer to catalogue numbers in the Harker Collection, Dept. of Mineralogy and Petrology, Cambridge). This material is comparable to that described, analysed, and figured by Teall (1885). The only source of this material appears to be the branch that diverges to the south of the main dyke immediately east of the beach at Poll Eorna. An analysis and mode of this rock are given in table I. The norm yields: Qu 0·1, Or 4·4, Ab 20·3, An 23·8, Di 18·4, Hy 23·5, Il 4·6, Mt 3·8, Ap 0·4, Rest 0·7. Mode and norm agree closely

TABLE I. Chemical and modal analyses of rocks from the Scourie dyke.

	1	2	3	4	5	6
SiO_2 ...	48·58	47·45	48·26	48·23	48·30	49·78
TiO_2 ...	2·43	1·47	2·56	2·96	2·83	2·22
Al_2O_3 ...	13·48	14·83	13·52	13·22	13·34	13·13
Fe_2O_3 ...	2·62	2·47	2·65	4·56	3·93	4·35
FeO ...	14·07	14·71	13·15	12·62	12·45	11·71
MnO ...	0·22	n.d.	0·24	0·30	0·21	0·27
MgO ...	5·11	5·00	5·41	5·20	5·43	5·40
CaO ...	9·48	8·87	10·11	8·61	9·52	8·92
Na_2O ...	2·40	2·97	2·35	1·97	2·40	2·39
K_2O ...	0·75	0·99	0·66	0·96	0·73	1·05
P_2O_5 ...	0·23	n.d	0·12	0·04	0·23	n.d.
H_2O^+ ...	0·55	1·00	0·89	1·53	0·76	1·14
H_2O^- ...	0·24		0·04	0·12	0·12	
CO_2 ...	n.d.	0·36	n.d.	n.d.	n.d.	0·10
Total ...	100·16	100·12	99·96	100·32	100·25	100·46

Modal analyses (vol. %)

	1	2	3	4	5
Clinopyroxene ...	43·6	—	24·7	6·0	—
Orthopyroxene ...	—	—	6·4	—	—
Amphibole ...	5·7	—	25·6	47·3	70·4
Plagioclase ...	40·9	—	34·8	24·2	22·7
Quartz ...	3·6	—	2·3	—	—
Orthoclase ...					
Garnet ...	—	—	—	15·0	—
Biotite ...	—	—	—	0·6	—
Iron ore ...	5·2	—	5·2	6·9	5·7
Sphene ...	—	—	—	—	0·6
Apatite ...	1·0	—	1·0	tr.	0·6

Trace elements (parts per million)

	1	2	3	4	5
Cr ...	100	—	100	40	45
Ni ...	80	—	45	30	40
Co ...	45	—	45	30	45
V ...	320	—	500	450	450
Li ...	3	—	6	22	10
Sr ...	125	—	100	650	125
Ba ...	220	—	160	150	240
Rb ...	25	—	30	30	20
Ga ...	15	—	20	15	15
Yt ...	45	—	25	50	45
Zr ...	220	—	140	220	140
Sc ...	45	—	55	45	45

1. 84249 Fresh dolerite, Poll Eorna.
2. Fresh dolerite, Scourie dyke (Teall, 1885).
3. 84248. Altered dolerite, Poll Eorna.
4. 84059. Marginal garnet-plagioclase amphibolite, Creag a' Mhail.
5. 84218. Hornblende schist, Creag a' Mhail.
6. Hornblende schist, Creag a' Mhail (Teall, 1885).

Analyst: 1, 3, 4, and 5, M. J. O'Hara. Trace element determinations by R. Allen, Department of Mineralogy and Petrology, Cambridge.

with the exception that in the mode normative hypersthene appears together with diopside as a single clinopyroxene. The rock is a medium-grained non-porphyritic unfoliated dolerite. In thin section both the pyroxene and the plagioclase are seen to be clouded by multitudes of small inclusions.

The plagioclase forms tablets that are often partly enclosed by the pyroxene. Zoning is apparent, the range of which has been determined by universal stage measurements (Turner, 1947) as from cores of labradorite (An_{63}) to margins at least as sodic as andesine (An_{36}). Reversals of zoning are rare. Albite and pericline twinning are frequent, Carlsbad and Manebach laws are rarely observed. Many of the tablets are bent. The clouding is due to very fine particles, which are concentrated towards the grain centres, and more particularly into the (010) twin planes. Particles vary in size, and the largest can just be resolved as stumpy rod-like forms of pale green material with high relief, perhaps amphibole.

The pyroxene forms euhedral prismatic crystals. Clouding by what appear to be minute opaque particles is general, but varies in intensity in zones concentric about [001] and is most conspicuous in the outer parts of the grains. In sections parallel to (010) the particles are parallel to the $\{h0l\}$ trace, the angular relationship suggesting that they may be parallel to (001). Twinning on (100) about the normal to (100) is common. The optical properties are: optic axial plane $\|$ (010); $2V_\gamma$ 10° (cores) to 46° (margins) extreme limits of zoning; β 1·711, no detected variation with zoning; γ:[001] 45°; very slight pleochroism in shades of pale brown. An analysis (table II) of the separated zoned crystals shows this to be a sub-calcic ferroaugite, which is probably zoned from pigeonite cores towards ferroaugite margins as indicated by the optical data.

X-ray single-crystal examination by the method of Bown and Gay (1959) showed that the pyroxene is an intergrowth of two clinopyroxenes in approximately equal proportions, the two phases having (001) and [010] in common. It is probable that the two phases are ferropigeonite and ferroaugite. No reflections corresponding with orthopyroxene, amphibole, iron ore, or spinel were found. Similar photographs, differing only in the unit-cell dimensions of the phases, were obtained from almost unclouded and intensely clouded fragments, suggesting that the clouding is due to the exsolution of two phases from the original subcalcic ferroaugite, and that variation in size of the exsolution bodies is the predominant cause of variation in intensity of the clouding.

The iron ore forms skeletal masses and is composed of ilmenite with subordinate magnetite, which is intergrown with the ilmenite as coarse lamellae parallel to one extinction direction of the ilmenite. Alkali feldspar, quartz, and apatite occur interstitially between the plagioclase

TABLE II. Analyses of minerals from the Scourie dyke.

	7	8	9	10	11	12	13	14	15
SiO_2 ...	47·80	48·46	48·33	48·02	44·54	51·51	41·73	36·75	41·25
TiO_2 ...	1·04	0·75	0·83	0·97	1·00	0·92	1·55	1·37	2·43
Al_2O_3 ...	4·65	5·34	4·48	2·49	9·18	1·90	11·85	21·09	13·02
Fe_2O_3 ...	1·75	1·24	2·23	2·24	5·07	2·87	5·98	4·10	4·14
FeO ...	22·42	18·15	18·51	30·78	17·82	9·26	14·00	25·12	15·94
MnO ...	0·42	0·12	0·26	0·62	0·28	0·13	0·11	1·52	0·26
MgO ...	9·66	10·78	10·60	12·33	7·64	11·41	8·13	2·39	7·22
CaO ...	11·31	14·03	14·07	2·02	11·03	21·91	11·63	8·12	11·30
Na_2O ...	0·51	0·62	0·63	0·22	1·20	0·58	1·39	n.d.	1·64
K_2O ...	0·28	0·28	0·25	0·18	1·26	0·05	1·09	n.d.	0·92
P_2O_5 ...	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·05
H_2O^+ ...	n.d.	0·26	n.d.	n.d.	1·35	n.d.	2·03	n.d.	0·85
H_2O^- ...	n.d.		n.d.	n.d.	nil	n.d.	0·09	n.d.	0·07
Total ...	99·84	100·03	100·19	99·87	100·37	100·54	99·58	100·46	100·09
Si ...	7·47	7·44	7·46	7·61	6·80	7·74	6·32	5·81	6·28
$Al^{[4]}$ ...	0·53	0·56	0·54	0·39	1·20	0·26	1·68	3·92	1·72
$Al^{[6]}$ ...	0·35	0·41	0·27	0·07	0·45	0·08	0·43		0·61
Fe^{3+} ...	0·20	0·18	0·26	0·27	0·59	0·32	0·68	0·49	0·47
Fe^{2+} ...	2·92	2·32	2·38	4·08	2·27	1·16	1·77	3·31	1·93
Ti ...	0·12	0·08	0·10	0·12	0·12	0·10	0·18	0·16	0·28
Mn ...	0·06	0·02	0·03	0·08	0·04	0·02	0·01	0·20	0·03
Mg ...	2·24	2·46	2·43	2·91	1·73	2·55	1·83	0·56	1·63
Ca ...	1·90	2·31	2·32	0·34	1·80	3·53	1·88	1·38	1·84
Na ...	0·16	0·18	0·19	0·07	0·36	0·17	0·41	—	0·18
K ...	0·06	0·06	0·05	0·04	0·25	0·01	0·21	—	0·06
O ...	24·0	24·0	24·0	24·0	24·0	24·0	24·0	24·0	24·0
H ...	—	—	—	—	1·37	—	2·05	—	1·86
Trace elements (parts per million)									
Cr ...	120	180	—	40	75	220	80	5	45
Ni ...	70	35	—	45	45	32	22	*	40
Co ...	60	60	—	60	45	55	30	*	45
V ...	550	600	—	220	500	600	1000	220	1000
Li ...	12	22	—	3	16	20	22	2	10
Sr ...	10	*	—	*	5	30	22	*	25
Ba ...	65	45	—	200	150	5	150	45	200
Rb ...	*	*	—	*	30	*	*	*	20
Ga ...	8	10	—	15	15	10	20	15	15
Yt ...	45	45	—	*	50	140	45	*	25
Zr ...	120	100	—	100	120	100	45	120	120
Sc ...	100	120	—	*	70	*	100	120	45

* Below limit of sensitivity.

	Opt. data, page
7. Subcalcic ferroaugite from fresh dolerite. 84249.	851
8 and 9. Ferroaugites from altered dolerite. 84248.	854
10. Ferrohypersthene from altered dolerite. 84248.	
11. Amphibole from altered dolerite. 84248.	853
12. Augite from garnet–plagioclase amphibolite. 84059.	855
13. Amphibole from garnet–plagioclase amphibolite. 84059.	
14. Garnet from garnet–plagioclase amphibolite. 84059	
15. Amphibole from hornblende schist. 84218.	856

Analyst: M. J. O'Hara. Trace element determinations by R. Allen.

tablets, and represent a late crystallized portion of the magma. The alkali feldspar has $2V_\alpha$ 49°, α 1·522, γ 1·529, consistent with a high-temperature-state orthoclase of composition about $Or_{60}Ab_{40}$ (Tuttle, 1952). Although optically homogeneous, an X-ray single-crystal study (method of Mackenzie and Smith, 1955) shows this to be an intergrowth of subsidiary amounts of albite-twinned sodic feldspar and dominant orthoclase. The orientation of the two components is that expected in an exsolution intergrowth, and the material is presumably cryptoperthitic.

Amphibole is present in very small amounts, as rims about iron ore and pyroxene. It is never euhedral and appears to be secondary. Minor scapolite and sericite are present as alteration products of plagioclase. A few samples from this locality show less amphibole and less conspicuous clouding of pyroxene and plagioclase than the specimen described.

Two-pyroxene dolerite [84248]. Similar material may be collected from the centre of the main dyke at either locality, the specimen described here coming from Poll Eorna. An analysis and mode are given in table I. Although chemically very similar to the one-pyroxene dolerite there are five principal distinctions: a higher combined water content and higher Fe_2O_3/FeO ratio are noted; this is not connected with a higher content of modal iron ore. Clouding of plagioclase is less conspicuous due to the presence of fewer rod-like inclusions, which are, however, larger than those described from the one pyroxene dolerite, but otherwise similar.

Thirdly, amphibole is abundant, mantling all pyroxene and iron ore grains; the optic properties are α yellow-green, β 1·691 deep olive, γ 1·699 deep blue-green; an analysis is given in table II. The amphibole occurs as one or more individuals mantling a single pyroxene grain, frequently with the [001] axes of the two minerals parallel. A little iron ore is enclosed within the amphibole, but quartz is not observed in association with these mantles.

Fourthly, the pyroxene grains have the same external form as in the one-pyroxene dolerite, but two pyroxenes are now present. The majority of the material is a pale green clinopyroxene with fibrous or vermicular appearance due to the abundance of lamellae parallel to (100). Twinning on (100) is present but the clouding noted in the pyroxene of the one-pyroxene dolerite is absent. The optical properties of the host are β 1·706, $2V_\gamma$ 50°, indicating a composition $Ca_{39}Mg_{32}Fe_{29}$ (Hess, 1949; Tröger, 1956). X-ray single-crystal studies show clinopyroxene with abundant orthopyroxene intergrown with (100) and [001] common to the two structures, the orientation found in intergrowths attributed to exsolution (Bown and Gay, 1959). Some amphibole is present also.

Analyses of two portions of the clinopyroxene differing in density and magnetic properties are given in table II. These are bulk compositions representing the host ferroaugite plus the orthopyroxene lamellae.

Also present are patches of orthopyroxene varying in form from coarse blebs enclosed in the augite and elongated parallel to the trace of (001) of the augite through ragged areas marginal to large augite grains to apparently independent crystals. The optical properties are α 1·726 pale red, β yellow-green, γ 1·737 apple green, indicating a composition $Mg_{40}Fe_{60}$ (Hess, 1952). Inclusions are apparent in thin section and X-ray single-crystal study shows the presence of substantial amounts of clinopyroxene oriented with (100) and [001] in common with the orthopyroxene host, together with additional reflections due to clinopyroxene in no special orientation. The latter are similar to those found in inverted pigeonites (Bown, personal communication). An analysis of the orthopyroxene plus the intergrown clinopyroxene is given in table II. Both pyroxenes contain small translucent plates of a brown material that has not been identified.

Fifthly, the alkali feldspar is microperthitic, containing abundant oriented spindles of albite. The host is orthoclase, with $2V_{\alpha}$ 52°, α 1·520, γ 1·526 indicating a composition $Or_{75}Ab_{25}$ (Tuttle, 1952). An X-ray single-crystal study of a microperthite from a neighbouring specimen gave a similar result to that for the alkali feldspar of the one-pyroxene dolerite.

The ore mineral in this rock is ilmenite with subsidiary magnetite. Lamellar intergrowth is not found, but the distribution of magnetite in some of the granular aggregates suggests recrystallization of an original lamellar intergrowth.

Garnet–plagioclase amphibolite [84059]. This specimen, collected from a point 3 in. within the dolerite at the northern contact, Creag a' Mhail, is a fine-grained massive unfoliated rock with a patchy appearance in hand specimen due to the irregular distribution of pale garnet. An analysis and mode are given in table I, whence it is apparent that the mineralogical differences are not associated with changes of chemical composition other than an increase in combined water and a rise in Fe_2O_3/FeO relative to both types of dolerite described above.

In thin section the texture is seen to have been derived by alteration of a holocrystalline fine-grained dolerite. The form of plagioclase tablets is preserved, although these are much altered, and encroached on by the aggregates of fine-grained amphibole and quartz that pseudomorph the pyroxene. A few relics of fibrous clinopyroxene similar to that described from the two-pyroxene dolerite are present, but these are commonly recrystallized to a fine granular aggregate of clear pale green clinopyroxene that has β 1·698, $2V_\gamma$ 58° indicating a composition $Ca_{46}Mg_{34}Fe_{20}$ (Hess, 1949) in close agreement with that found by analysis (table II). The clinopyroxene is present in accessory amounts only, and it is associated intimately with quartz, but not directly with amphibole or garnet.

Garnet occurs as large (2 to 3 cm.) clusters of small (0·02 cm.) euhedral grains accompanied by abundant iron ore and quartz and lesser amounts of amphibole. The refractive index is n 1·803, and the cell-size a 11·603 Å. An analysis is given in table II confirming that this is an almandine-rich variety.

The amphibole has α 1·669 yellow-green, β 1·680 olive, γ 1·690 blue-green, γ:[001] 18°. It occurs with quartz, iron ores, and plagioclase throughout the body of the rock. An analysis is given in table II.

A few small anhedral grains of apatite are present, but alkali feldspar is absent. The recrystallized granular plagioclase is untwinned and difficult to distinguish from quartz. A refractive index measurement suggests a composition close to $Ab_{65}An_{35}$. The ore minerals are present only as small grains. An X-ray powder photograph of the separated ore minerals shows the presence of magnetite, ilmenite, and subordinate hematite. No intergrowths are apparent. A little red-brown biotite is present as small flakes.

The grain size of the minerals in this rock is of the order of 0·02 cm., in contrast with the 0·15 cm. grain size of the fine-grained dolerite from which it appears to have been derived. This dolerite was finer grained than the pyroxene-bearing dolerites from the centre of the dyke which have a grain size of 0·2–0·4 cm.

Samples [84039] and [84040] from Poll Eorna, which show the contact with the gneiss, differ from the specimen just described in: scarcity of clinopyroxene; absence of a texture reminiscent of a holocrystalline dolerite; presence of irregular tablets of plagioclase, most of which are oriented parallel to the contact surface; and presence of layering parallel to the contact due to segregation of garnet and amphibole. The amphibole shows no preferred orientation.

The contact itself is sharp and apparently undisturbed by shearing. The gneiss is a coarse-grained granular acid rock whose features have been described in the section on field observations.

Hornblende schist [84218]. This is a foliated and lineated rock, dark green in hand specimen, which was collected from a shear zone in the dolerite at Creag a' Mhail and near the centre of the dyke. An analysis and mode are given in table I. In thin section the rock is seen to be completely reconstructed to a medium-grained hornblende–plagioclase–quartz schist that contains prominent schlieren of iron ore. Accessory apatite is present. None of the minerals exhibit good crystal form, most occurring as lozenge-shaped grains elongated parallel to the plane of foliation.

The amphibole is a pleochroic iron-rich variety (analysis, table II) with the scheme: α 1·665 yellow-green, β 1·680 deep olive-green, γ 1·693 deep blue-green, γ:[001] about 28°. Strong absorption prevented satisfactory determination of 2V. There is pronounced preferred orientation of the amphibole with (100)|| the schistosity and [001] axes in parallel alignment. A parting parallel to (100) is well developed in addition to the good prismatic cleavage. Most grains are elongated parallel to [001].

The plagioclase is andesine, composition $Ab_{64}An_{36}$ as determined by universal stage measurements on the rare twinned grains (method of Turner, 1947) and by refractive index measurements. Zoning and clouding are absent. Owing to the relatively large amount of untwinned feldspar present this mineral has not been distinguished from quartz in the mode. Potash feldspar is absent. The iron ore is largely ilmenite with occasional grains of magnetite. The ilmenite is markedly anisotropic in reflected light and has abundant twin lamellae but no inclusions of magnetite. The magnetite contains three sets of narrow lamellae of ilmenite similar to those ascribed to exsolution when observed in gabbros and dolerites.

Scarce sphene occurs associated with the ilmenite. Garnet is absent from this and all similar hornblende schists that have been examined. Cataclastic effects are similarly lacking, and even the bending of grains noted in the unsheared dolerite is absent from this rock.

Contact facies of Scourie-type dykes.

Further information on the origin of the garnetiferous border facies of the Scourie dyke is provided by an examination of the contacts of other dykes in the same region. Two narrow veins of dolerite 6 to 9 in. wide cut basic pyroxene-granulites on the headland west of Geodh Eanruig (map reference 29/141441). A cave has been eroded through the headland along the line of these dykes, which appear to be composed of a very fine-grained dolerite. Abundant small phenocrysts of plagioclase are visible in hand specimens. In thin section the rock is seen to be composed of numerous tabular phenocrysts of plagioclase and rarer phenocrysts of clinopyroxene, both minerals being extensively clouded by opaque inclusions. Individual phenocrysts are up to 0·2 cm. in length. The groundmass is a very fine-grained unfoliated granular aggregate of amphibole, iron ores, quartz, untwinned plagioclase, and garnet. The small garnets are gathered into clusters of several hundred grains which give rise to pale globular patches in the hand specimen. Near the contact the phenocrysts of plagioclase are aligned parallel to the junction. The contact is sharp and undisturbed, and the country rock is a coarse-grained granular augite–hypersthene–andesine–antiperthite gneiss, which has all the characteristics of the least altered 'charnockitic' gneisses of the early Lewisian metamorphic complex.

This rock is interpreted as a chilled porphyritic dolerite whose groundmass may originally have been glassy, or a very fine grained material in which alignment of phenocrysts had taken place by flow. The state of the groundmass can best be explained on the assumption that the dyke and its country rock were held under conditions of temperature, pressure, and water-vapour pressure such that the chilled dolerite recrystallized to a mineral assemblage characteristic of the almandine–amphibolite mineral facies, while the granulite facies mineralogy of the country rocks persisted metastably. This recrystallization must have preceded the period of the late Lewisian metamorphism because in this narrow dyke, as in the Scourie dyke, the garnetiferous dolerite is converted to hornblende schist within narrow shear belts.

The results of examination of the contacts of dykes similar to the Scourie dyke throughout the Scourie–Lochinver region are presented in table III and fig. 1. The extent to which the textural evidence of original chilling has been obscured in the dyke contacts increases with the width of the dyke concerned, but is independent of the position of the dyke relative to the areas affected by the late regional metamorphism. Even in the broadest dykes the presence in contact specimens of aligned but corroded plagioclase phenocrysts in a matrix of unfoliated amphibolite or garnet amphibolite still affords evidence of original chilling. The occurrence of garnet in the border facies of the dykes is most frequent near Scourie, and decreases in a south-easterly direction, i.e. roughly perpendicular to the strike of the foliation in the early complex gneisses. Irrespective of position, however, the recrystallized assemblages belong to the amphibolite mineral facies.

Superimposed on the recrystallization of the borders of the dykès are three later effects: shearing during the late regional metamorphism;

TABLE III. Contact phenomena of Scourie dykes.

Key to observations

1g	chilled margin identified, with garnet and hornblende.	
1a	chilled margin identified, with hornblende only.	
2	margin sheared to hornblende schist	Laxfordian events.
3	dyke regionally metamorphosed	
4	pseudotachylyte formed in dyke near margin. Pre-Torridonian.	
E	epidote present in margin of dyke.	
5	epidote veining present.	

	Map reference	Locality	Observations
1.	29/241476	½ mile NE. of Laxford Bridge	3
2.	29/230445	1 mile SSE of Badnabay	3
3.	29/207461	½ mile SE. of Loch na Claise Fearna	3+4
4.	29/148464	Coast ⅝ mile N. of Creag a' Mhail	2
5.	29/147463	Coast ½ mile N. of Creag a' Mhail	1a+2
6.	29/166452	Near summit of Creag a' Bhadaidh Dharaich	2+4
7.	29/145458	Creag a' Mhail, Scourie Bay	1g+2
8.	29/150455	Poll Eorna, Scourie Bay	1g+2
9.	29/149448	Near graveyard, Scourie Bay	1g+2+4
10.	29/161435	¼ mile N. of Loch an Daimh Mhor	2
11.	29/141441	Promontory W. of Geodh Eanruig. 9 in. wide dyke	1g+2
12.	29/141441	Promontory W. of Geodh Eanruig. 0 to 10 ft. wide dyke	1g+2
13.	29/146438	½ mile WSW. of school, Scourie	2+4
14.	29/146417	½ mile NW. of Farhead point, Badcall	1a+2
15.	29/197392	W. shore of Loch Crocach	2
16.	29/195388	S. end of Loch Crocach	1a+4
17.	29/194385	½ mile S. by W. of Loch Crocach	2
18.	29/194384	,, ,, ,, ,,	1g+2
19.	29/196380	½ mile S. of Loch Crocach	1g+2
20.	29/245342	½ mile W. of mouth of Maldie Burn	2
21.	29/261358	Near S. end of Loch na Leathaid Bhuain	1g
22.	29/272367	Allt Beallach a' Phollaidh	3+4
23.	29/255338	½ mile E. of Maldie Burn	1a+2+4+E
24.	29/263337	¾ mile E. of Maldie Burn	1a+2+E
25.	29/268338	1 mile E. of Maldie Burn	1a+E
26.	29/274339	½ mile W. of Glendhu house	2+E
27.	29/074211	Badanaban	2+4+E
28.	29/081207	,,	1a
29	29/075212	,,	1a+2+E
30.	29/096233	NE. of Lochinver bridge	1a+2+E
31.	29/113239	Lochinver-Inchnadamph road	1a+E
32.	29/123240	N. of large ultrabasic dyke at Brackloch	2
33.	29/198262	1 mile ESE. of Tumore, Loch Assynt	1a+2+E
34.	29/285234	½ mile SW. of Loch nan Ouaran	1a+2+5
35.	29/285235	,, ,, ,, ,,	1a+2+5
36.	29/285223	¼ mile W. of Lagan Mhuirich	1a+2+5
37.	29/285226	,, ,, ,, ,,	1a+2+5
38.	29/274303	Glencoul Lodge	3+5
39.	29/303224	½ mile W. of Garbh Allt	1a+5
40.	29/126158	Near W. end of Loch Veyatie, Assynt	1a+2
41.	29/133159	,, ,, ,, ,, ,, ,, ,,	1a+2+4
42.	29/138159	,, ,, ,, ,, ,, ,,	1a+2
43.	29/142156	,, ,, ,, ,, ,, ,, ,,	1a+2
44.	29/143157	,, ,, ,, ,, ,, ,, ,,	1a+2
45.	29/145157	,, ,, ,, ,, ,, ,, ,,	1a+2

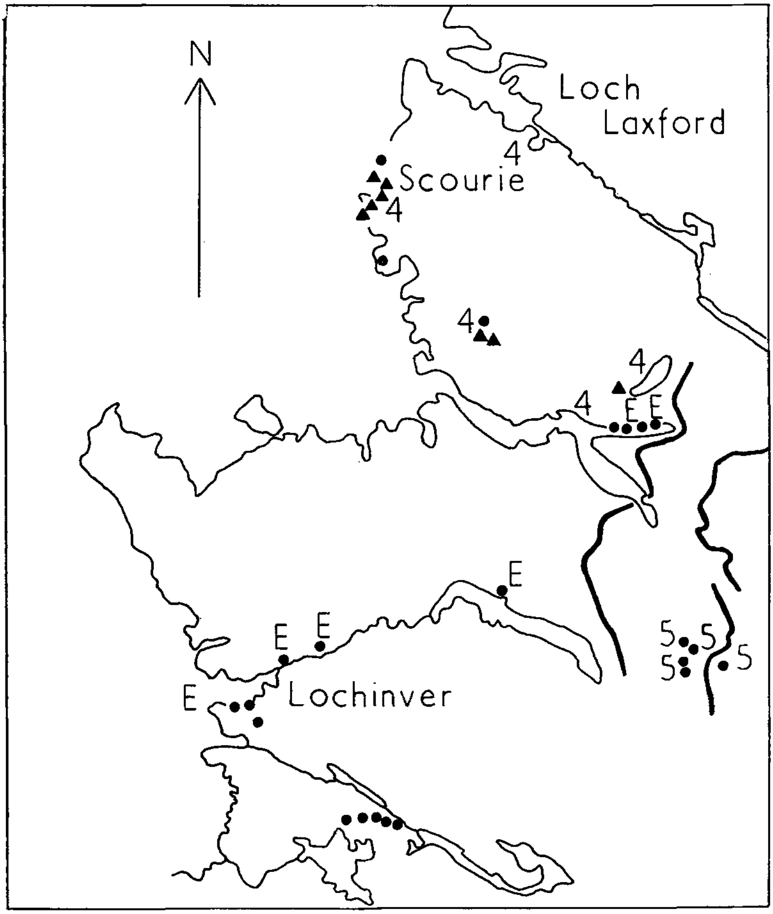


FIG. 1. Sketch-map of the Scourie–Assynt district showing the location of recognizable chilled contacts to Scourie dykes. Those containing garnet as well as amphibole are shown by triangles, those with amphibole only by circles. The situations of pseudotachylyte (4), epidote (E), and epidote vein (5) occurrences are also shown relative to the outcrops of the principal post-Cambrian thrust planes which are shown by heavy lines.

crushing with the formation of pseudotachylyte; and crushing and low-grade metamorphism, with the formation of chlorite and epidote, which is associated with proximity to the post-Cambrian thrust planes.

The varying extent of recrystallization of the chilled margin can only be accounted for if it is supposed that the factor producing the recrystallization of the contacts is dependent upon the dyke width. The heat capacity of the magma is the most obvious factor that would vary in this manner. Accordingly it is proposed that the recrystallization took place immediately after intrusion and because the dykes were intruded into the gneiss at a time when the rocks were still deeply buried and relatively hot. (A temperature of 300–500° C. would be consistent both with chilling of the magma and with the generation of amphibolite facies assemblages.) Recrystallization is more advanced in the border zones both because these chilled assemblages were further from equilibrium under the imposed conditions, and because the border zones were subject to an auto-thermal metamorphism by the heat-flow from the cooling interior.

The petrology of the Scourie dyke is consistent with the crystallization of a one-pyroxene amphibole-free dolerite as the primary product, this material being modified towards a mineral assemblage stable under the external pressure and temperature conditions by an amount dependent upon the distribution of volatiles and the subsequent heat flow. The extent of modification is thus loosely correlated with distance from the centre of the dyke.

Mineralogical changes during metamorphism of the Scourie dyke.

The pyroxenes of the Scourie dyke samples are considered in relation to other igneous and metamorphic pyroxenes in fig. 2. The modification of the primary high-temperature phase by exsolution is complicated by the accompanying incorporation of some of the pyroxene into the amphibole. The amphibole has a higher Fe:Mg ratio (fig. 3) than the associated pyroxene and preferentially takes up the calcium-poor component of the pyroxene. The sequence of events leading towards the attainment of a stable amphibolite facies mineralogy is: first, crystallization of a zoned subcalcic ferroaugite.

Secondly, exsolution of ferropigeonite and consequent increase in the calcium content of the subcalcic ferroaugite. This is accompanied by the appearance of an iron-rich amphibole by reaction between pyroxene and plagioclase, with resulting decrease in the Fe:Mg ratio of the bulk pyroxene assemblage.

Thirdly, inversion of the ferropigeonite to ferrohypersthene, accompanied by further exsolution of ferroaugite from the ferrohypersthene and of ferrohypersthene from the ferroaugite, which has now attained a relatively high calcium content. An accompanying increase in the volume of amphibole leads to a further decrease in the Fe:Mg ratio in the pyroxenes, further reduction in the total volume of pyroxene, and

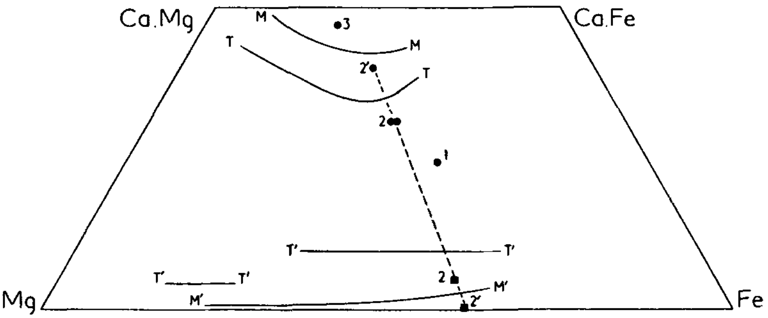


FIG. 2. Part of the Ca–Mg–(Fe+Mn) diagram. T, T′ are curves representing the compositions of coexisting calcium-rich and calcium-poor pyroxenes from tholeiitic gabbros (Brown, 1957; Muir, 1954). M, M′ are similar curves for coexisting pyroxenes from the Madras charnockite series (Howie, 1955). The numbered points represent data from the Scourie dyke: 1, bulk composition of the primary zoned pyroxene of the fresh dolerite; 2, bulk compositions of two portions of clinopyroxene and of the coexisting orthopyroxene from the altered dolerite; each phase contains lamellae of the other and 2′ represents the composition of the host phases (derived from the optical properties). 3 is the composition of the accessory augite from the garnet-plagioclase amphibolite at the margin of the dyke.

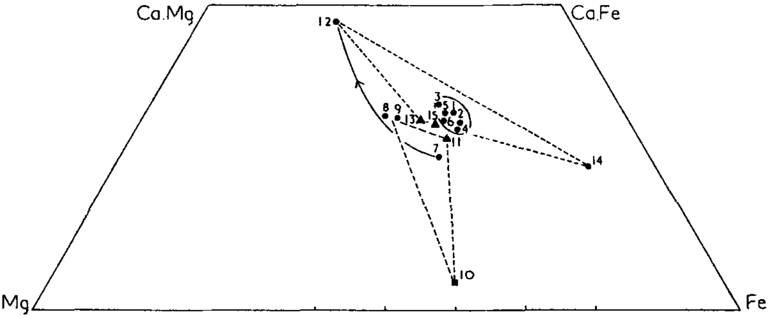


FIG. 3. Compositions of analysed Scourie dyke samples compared in the diagram Ca–Mg–(Fe+Mn). 1 to 6 are the rock compositions numbered to correspond with the analyses in table I. A field for the composition of samples from this dyke is suggested. Other points are numbered to correspond with the mineral analyses of table II: 7, primary pyroxene of fresh dolerite; 8, 9, clinopyroxenes, 10, orthopyroxene, and 11, amphibole of the altered dolerite; 12, clinopyroxene, 13, amphibole, and 14, garnet of the marginal garnet–plagioclase amphibolite. 15, amphibole from the hornblende schist. Broken lines link coexisting minerals (not necessarily in equilibrium), and a curved line with arrow indicates the inferred trend of the bulk pyroxene composition during amphibolization.

selective reduction in the volume of ferrohypersthene relative to ferroaugite.

Finally, further increase in the amount of amphibole leads to the modification of the residual pyroxene, now exclusively clinopyroxene, to a calcium-rich augite of relatively low Fe:Mg ratio. Garnet appears in abundance.

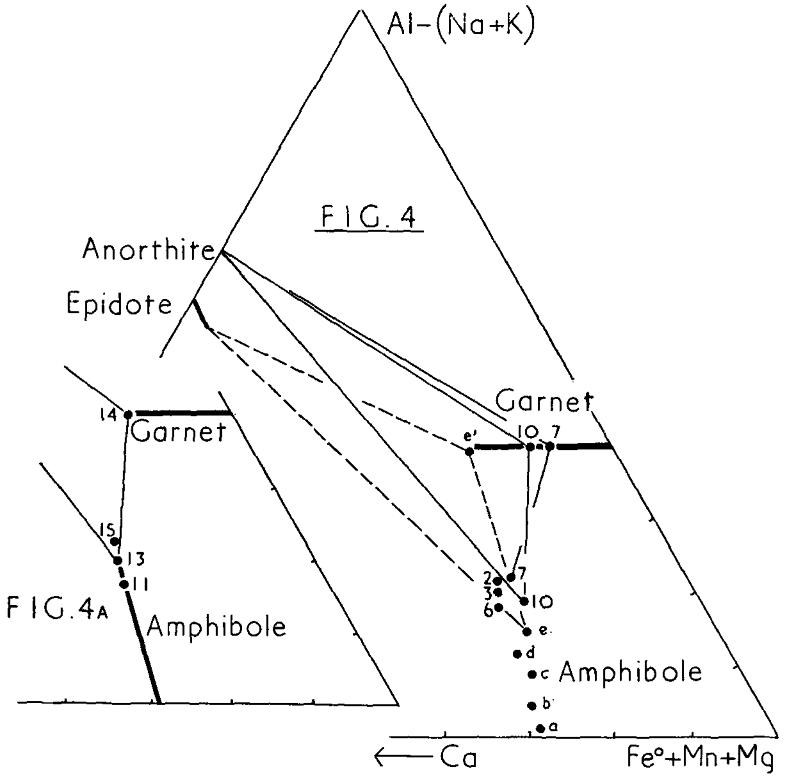
A parallel series of changes is exhibited by the alkali feldspar, which undergoes exsolution followed by incorporation of the potassium in the amphibole.

The submicroscopic exsolution and clouding in the pyroxene and feldspars of the one-pyroxene dolerite need not belong to the immediate post-intrusion period, and may have occurred during the period of the late regional metamorphism. However, clouding of the plagioclase appears to vary with the other aspects of the mineralogy and it is at least possible that the clouding is the result of the rocks being held at a comparatively high temperature for a period immediately following their intrusion as has been suggested in some other cases (Poldervaart and Gilkey, 1953). This does not invalidate Macgregor's (1931) conclusion that the clouding is due to subsequent thermal metamorphism.

Amphibole- and garnet-bearing parageneses are considered in fig. 4, where a case is made for considering the aluminium content (as represented by $Al-[Na+K]$) of amphibole as a function of metamorphic grade, and for considering the appearance of garnet within the amphibolite facies as an indication that the amphibole possesses the maximum aluminium substitution under the particular conditions. The role of garnet is to contain any further aluminium over that which can be accommodated by feldspar+amphibole. On this basis the appearance of garnet within a regional sequence of amphibolite facies metadolerites is an indication either of decreasing metamorphic grade or of a regional variation in bulk composition of the rocks concerned (increase of normative hypersthene relative to diopside). Reference to fig. 1 leads to the conclusion that either the physical conditions within the early complex varied from north-west to south-east at the time of intrusion of the dykes similar to the Scourie dyke, with the higher grade conditions to the south-east, or there is a regional variation in bulk composition in the same direction.

In fig. 4A the analysed amphiboles and garnet from the Scourie dyke are compared. The low aluminium content of the amphibole from the two-pyroxene dolerite is consistent with the absence of garnet from this rock. The aluminium content of the amphibole from the hornblende schist formed during the late regional metamorphism is appreciably greater than that of the unsheared border facies of the dyke.

This might be taken as evidence of conditions of higher temperature or pressure or both in the shear zones during the later metamorphism



FIGS. 4, 4A: FIG. 4. Ternary plot (Ca; Al-(Na+K); total iron+Mn+Mg) of amphibole and garnet analyses from metadolerites. The points *a*, *b*, *c* represent amphiboles coexisting with aluminous chlorite in three greenschist facies rocks (Tilley, 1938). *d*, *e* represent amphiboles from epidote-amphibolite facies epidiorites at Achahoish (Wiseman, 1934). The amphibole *e* is accompanied by epidote and a garnet *e'*. 2, 3, 6 represent amphiboles from garnet-free plagioclase amphibolites of the Adirondack region (upper amphibolite facies) and 7, 10 are coexisting amphiboles and garnets from garnet–plagioclase amphibolites of the same region; numbers refer to analysed assemblages in Buddington, 1952. The lines link amphibole, garnet, and the appropriate calcium aluminosilicate. FIG. 4A. Part of a ternary plot, as in fig. 4, of amphiboles and garnets from the Scourie dyke. 11, amphibole of altered dolerite; 13, amphibole, 14, garnet from marginal garnet–plagioclase amphibolite, and 15, amphibole from hornblende-schist. Tie lines for feldspar–amphibole–garnet of the marginal garnet–plagioclase amphibolite are shown. Numbers refer to analyses in table II.

than were prevalent at the intrusion of the dykes, and might indicate development of the pressure and temperature conditions of the amphibolite facies throughout the Lewisian complex at the time of the later metamorphism, with reconstruction to amphibolite-facies mineral assemblages taking place only in zones affected by local or regional shearing and metasomatism.

Within the shear zones in the early complex both gneisses and dykes were converted directly to an amphibolite facies mineralogy and transition from the early complex into the late metamorphic complex also involves the replacement of the existing mineral assemblages by those of the amphibolite facies (Sutton and Watson, 1951 *a*, *b*) without intervening zones of lower grade rocks.

Noë Nygaard (1948) in a closely comparable instance from Greenland has recorded the development of a zone of low-grade rocks between an early and a late metamorphic complex. The dykes that cut and chill against the early complex in Greenland and are metamorphosed in the late complex, have normal contact features (Sørensen, personal communication).

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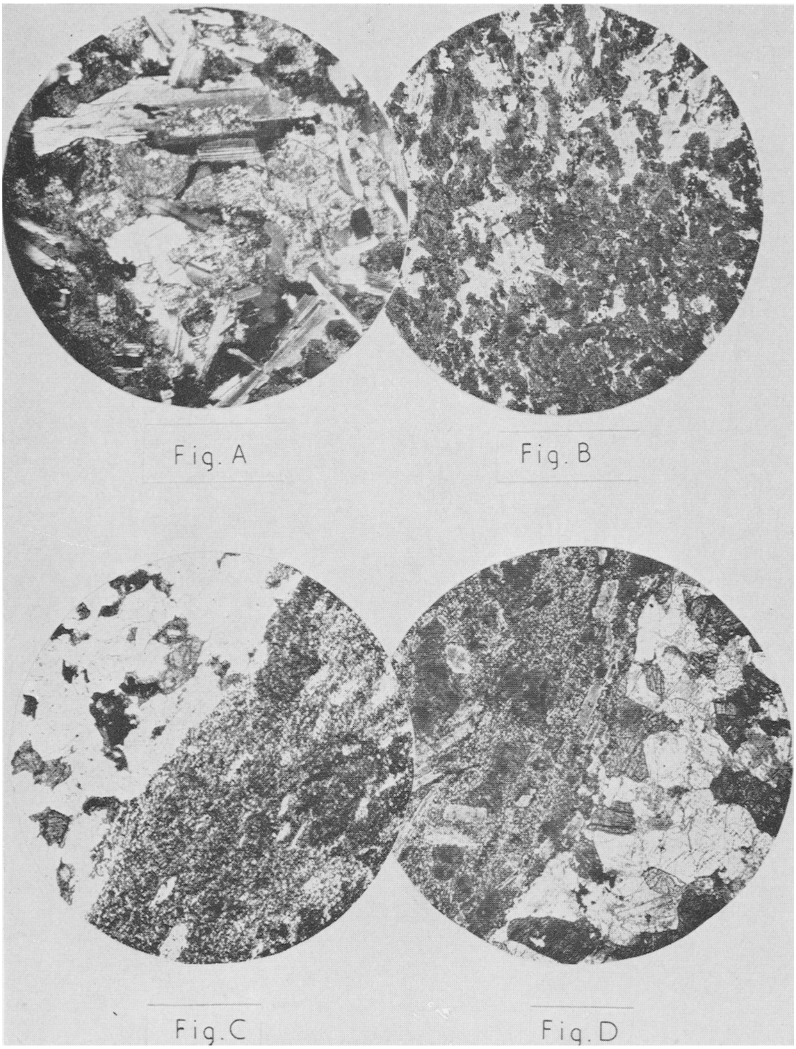
EXPLANATION OF PLATE XVIII.

FIG. A. Altered dolerite (84084) from the Scourie dyke at Poll Eorna. At the centre of the field is a composite grain, partly mantled by iron ore, which consists of ferrohypersthene (grey), forming an independent-looking grain at the left but intergrown as blebs with ferroaugite (pale) at the right. The intergrowth is parallel to (100) of both pyroxenes. Crossed nicols, ×8.

FIG. B. Medium-grained chilled dolerite (84219) 4 in. from the northern contact of the Scourie dyke at Poll Eorna. Amphibole and areas rich in small garnets have developed between plagioclase and pyroxene. One nicol, ×8.

FIG. C. Northern contact of the Scourie dyke and acid gneiss from Poll Eorna. Specimen (84040). The coarse-grained gneiss is unsheared but shows partial amphibolization of pyroxenes. The dolerite contains modified tabular phenocrysts of plagioclase oriented parallel to the contact. A garnet-rich area in the plagioclase amphibolite groundmass is apparent at top right. One nicol, ×8.

FIG. D. Contact of 9-in. vein of chilled dolerite and basic pyroxene gneiss from Geodh' Eanruig, Scourie More. Specimen (84055). Tabular phenocrysts of plagioclase are oriented parallel to the contact. Scarcer phenocrysts of clinopyroxene appear dark due to inclusions of iron ore. The groundmass is composed of amphibole, plagioclase, and iron ore with conspicuous clusters of small granules of garnet. One nicol, ×8.



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