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*The zoned contact-skarns of the Broadford area, Skye:
a study of boron-fluorine metasomatism in dolomites.*

(With Plates XVIII–XXIV.)

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1. REVIEW OF THE PROGRESSIVE METAMORPHISM IN THE AUREOLE OF THE BEINN AN DUBHAICH GRANITE.

IN a preliminary note on the dolomite contact-skarns of the Broadford area, Skye (Tilley, 1948, *a*), a brief account was given of the constitution and environment of these multizoned assemblages at the contact of the Durness limestone succession with the Tertiary Beinn an Dubhaich granite.¹ No detailed survey of the numerous parageneses was then attempted, and it is the purpose of the present paper to fill this gap and to discuss the genetic problems of these skarn assemblages.

¹ The history of the discovery of these skarns and the exploratory work carried out during the 1939–45 war on some of the magnetite ore prospects has been indicated in the paper to which reference is now made.

Meantime, however, three short papers have been presented dealing with specific items of petrogenesis of the granite and its aureole: one on the earlier stages in the metamorphism of the dolomites (Tilley, 1948, *b*), on iron-wollastonite in the skarns (1948, *c*), and on the development of an alkali facies of the granite at the skarn contacts (Tilley, 1949).

The general character of the metamorphism induced in the Cambrian dolomites has been given in some detail in the Skye memoir (Harker, 1904). Three divisions of the Durness limestone succession were recognized by Harker and Clough in the mapping of this part of Skye, and these were given the local names of Beinn an Dubhaich, Strath Suardal, and Ben Suardal groups. The first two of these are commonly dolomitized while the third is normally a limestone. The Beinn an Dubhaich horizon is seen only in a highly metamorphosed state and normally underlies the other two horizons. It is not infrequently referred to as the Ring Limestone, from the occurrence of rings of forsterite (serpentine) and calcite of *Eozoon canadense* type near the granite contact.

The Strath Suardal zone is characterized by chert nodules simulating 'sponge forms', which, when not replaced, weather white, while the Ben Suardal group of limestones carries black cherts and worm casts and represents the fossiliferous horizon. Whether there are sure grounds for the separation of the Beinn an Dubhaich and Strath Suardal horizons has been debated, and for our purpose it is perhaps of no great moment since both are dolomitized. It is clear, for example, that the ring structures of the former represent the metamorphic product of a 'sponge form' which has acquired this concentric layering by metamorphic diffusion in which the 'sponge form' has disappeared or is represented only as a vestigial nucleus to the halo of rings around it.

The accompanying map (plate XXIV) reproduces with minor changes the features of the six-inch mapping of the granite and its aureole carried out by Harker. The two lower dolomite horizons have not been separately distinguished and are included together under the symbol, Strath Suardal. Upon this map have been inserted the chief localities of the skarn developments which will be discussed in detail in the sequel.

The earliest stages of metamorphism of the Strath Suardal dolomite appear on the north-east slopes of Ben Suardal and are there seen in the haloes of talc, eventually tremolite, surrounding the 'sponge forms'. These stages have been previously described (Tilley, 1948, *b*). In the inner parts of the aureole these 'sponge forms' may be completely replaced by tremolite or finally diopside, as, for example, in the strip of Strath Suardal dolomite seen at Loch Kilchrist, immediately west of the

churchyard and near the loch outlet 350 yards north of this position. In the old marble quarries enveloped by the granite magnificent specimens of ring structures surrounding 'sponge forms' now converted to diopside have long been known.

Study makes clear that the progression in metamorphism is expressed mineralogically by the successive development of talc, tremolite, forsterite, and diopside. The highest stages are represented in the structures which have their cores partially or wholly replaced by diopside, this mineral characteristically giving place to a thin forsterite zone followed by rings of calcite and forsterite in repetition.

Though this ring structure has previously been regarded as 'an original peculiarity further developed and accentuated by metamorphism', there can be little doubt that it is a diffusion phenomenon comparable with the Liesegang effect.

Already in the earliest stages of metamorphism the 'sponge forms' become encircled with haloes of talc and calcite due to diffusion, and the more striking ring structures of the inner aureole may be interpreted as a similar phenomenon developed on a more extensive scale, with the heightened amplitude of diffusion consequent upon the more elevated temperature. The eventual complete replacement of the 'sponge form' by diopside is sufficiently indicative of migration of material, and, as the form of the 'sponge' is effectively preserved, the incoming of lime and magnesia is balanced by an outward migration of silica. In the skarn zones to be described subsequently the production of analogous layered structures testifies to the efficacy of diffusion processes in these metamorphic phenomena.

Only rarely in the main body of the aureole has wollastonite been recorded, though this mineral is common at the skarn contacts. Wollastonite has so been noted in association with diopside in the dolomite of the old marble quarries, 500 yards SW. of the old Manse, Kilchrist.

The scarcity of wollastonite in the aureole of the dolomite horizons is not unexpected, as in general their bulk composition would not be such as to provide, without metasomatism, wollastonite parageneses. The dolomites have long been famous for their development of brucite-marbles in the aureole. The more detailed study of the aureole that has now been possible shows that periclase itself may be developed in force. Periclase-bearing marbles are now recorded from Kilbride and Camas Malag, particularly at the former locality. A typical example is figured in pl. XVIII, figs. 1 and 2.

Some of the brucite-marbles are characterized by a veined texture in

which a white marble carrying clear brucite is crossed by narrow veins of darker colour built of calcite and brucite, the latter turbid brown in section or spotted black. This turbidity is due to the separation of fine iron oxide from an original periclase containing ferrous oxide replacing magnesia. In the Kilbride periclase occurrences, this mineral still preserved is not infrequently light brownish in colour and gives place to a halo of brucite in which a similar turbidity and spotting is developed. The restriction of the turbid brucite to the veins of the marbles noted above suggests that the veined texture may have developed prior to or during the metamorphism and that solutions carrying iron circulated in the veins giving rise to a ferriferous dolomite subsequently to be dedolomitized. Some of these veins may carry forsterite in greater concentration than is met with in the body of the marble.

The effects of metamorphism on the Ben Suardal limestone are not so readily studied. The marbles of the skarn localities are dolomitic, and though this horizon has been originally mapped at Kilbride as contacting the granite, the innermost portion of the aureole is there dolomitic as indicated by the mineral assemblages of forsterite, diopside, and brucite, and the nature of the associated skarn minerals. Elsewhere metamorphic effects in the Ben Suardal horizon are indicated by the occurrence of grossular, idocrase, and diopside. No wollastonite has yet been recorded from this horizon. Farther north, within the mass of the Beinn na Caillich granite, an enclosure of Ben Suardal limestone has developed grossular, idocrase, and diopside. The early production of grossular garnet in this horizon in the Beinn an Dubhaich aureole is seen in the exposures of the quarry at the bend of the road 300 yards west of the west end of Loch Kilchrist.

2. THE SKARN ZONES.

The complex skarn zones now to be described occur at or close to the contact of the granite with the dolomite horizons. They are therefore essentially the metasomatic products of original dolomites. Not only do they show a layered structure against the granite, but the 'sponge forms' which are incorporated within the metasomatic zone develop also a layered structure around the 'sponge' nucleus.

The chief localities where these multizoned skarns are developed and have been studied are as follows (pl. XXIV):

1. No. 1 Prospect, Kilchrist (loc. A, sub-locs. *a-g*, fig. 15).
2. At the contact of a dolomite island in the granite, 300 yards SE. of the old Manse, Kilchrist (loc. B).
3. In the quarries lying 350 yards ESE. of no. 1 Prospect, Kilchrist.

4. No 2 Prospect, Kilchrist, with the quarries adjacent (loc. C).
5. Kilbride (loc. D and loc. E).
6. Camas Malag (Loch Slapin), 1730 yards S. 13° W. of Kilbride (loc. G, and loc. F adjacent thereto).
7. South margin of the granite, on the west bank of the burn, tributary to the Allt Leth Slighe, 2030 yards S. 3° E. of Kilbride (loc. H).
8. South margin of the granite, N. of Allt Leth Slighe, 2100 yards S. 7° E. of Kilbride (loc. J).
9. South margin of the granite, small isolated lens of granite in limestone of embayment, 2380 yards S. 27° E. of Kilbride (loc. K).

In the preliminary note on the development of these dolomite skarns, a tabulation of their mineral content was given and the broad zonal distribution of these minerals indicated. An earlier paper (Tilley, 1947) had presented the characteristics of the mineral cuspidine, a prominent constituent, while in 1949 a typical zoned skarn from Kilchrist had been figured (Tilley, 1949).

The skarn zones are in general multiple, but of varying complexity. Broadly a twofold division can be recognized: (a) the primary zones, (b) the secondary zones, each in themselves multiple. The simplest skarn development is that unaccompanied by iron ores or a boron-fluorine pneumatolysis, illustrated in the contact skarns of the quarries near no. 2 Prospect, Kilchrist (loc. C), in the quarries SE. of no. 1 Prospect, Kilchrist, and on the south margin of the granite (loc. K). The succession seen in a skarn zone of the quarries 350 yards SE. of no. 1 Prospect, Kilchrist, illustrates this simpler development (fig. 1*a*).

At the contact with the granite a succession built of hedenbergite-plagioclase-wollastonite solid solution¹ is followed by a zone of white diopside (with accessory spinel and xanthophyllite), a thin band of forsterite which then gives place to the country-rock, a forsterite-bearing marble. Close to the contact the normal hornblende-biotite-granite gives place to a clinopyroxene-bearing granite usually enriched in plagioclase.

When, as exemplified in this section, wollastonite occurs in association with hedenbergite, the mineral is an iron-wollastonite. An analysed example from another skarn has been described (Tilley, 1948, *c*). In the development of this multizoned skarn there is evidence that both silica and alumina have been transferred from the granite; the migration of the latter is, however, largely restricted to the inner zones, those bearing plagioclase. Iron has also diffused outwards in the formation of the pyroxene and wollastonite.

¹ In place of this zone a grossular-wollastonite assemblage may be developed, as in the skarns of the quarries near no. 2 Prospect, Kilchrist.

The central zone of clinopyroxene is doubtless silicated dolomite. The forsterite zone resembles in its position the shell of forsterite which follows on diopside at the periphery of the 'sponge forms' in the main

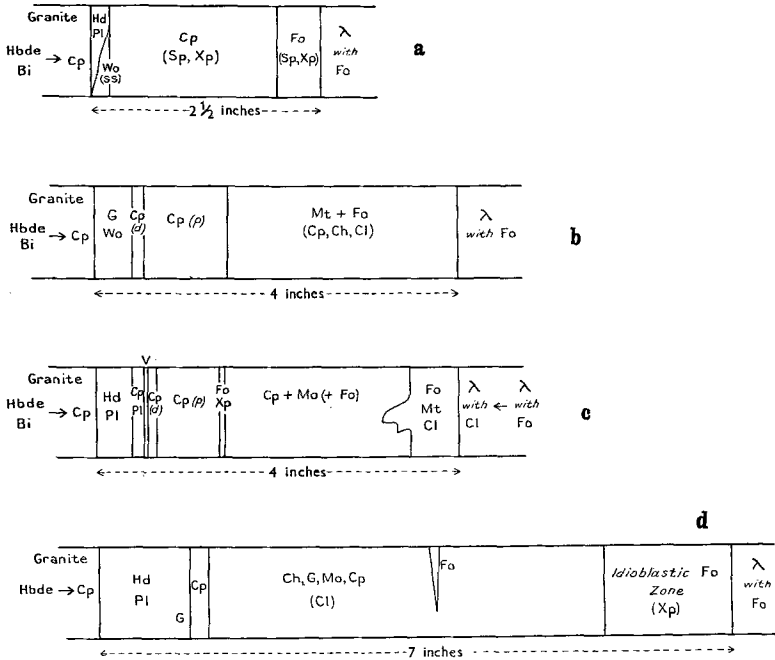


FIG. 1. Sections across zoned skarns, granite contacts.

(a) Quarries 350 yards SE. of no. 1 Prospect, Kilechrist. (b) No. 1 Prospect, Kilechrist, loc. A. (c) Island of dolomite in granite, 300 yards ESE. of the old Manse, Kilechrist, loc. B. (d) Kilbride, loc. E.

Hbde hornblende, Bi biotite, Cp clinopyroxene, Pl plagioclase, G grossular, Hd hedenbergite, Wo (Wo_{88}) wollastonite and solid solutions, Ch chondrodite, Cl clinohumite, Mo monticellite, Fo forsterite, Xp xanthophyllite, Sp spinel, Mt magnetite, V idocrase, λ limestone (dolomite).

aureole. At locality K, as already noted (Tilley, 1949), the inner zone is built of grossular and wollastonite and the contiguous granite is of alkali type. Unlike the former example there has been no reciprocal transfer of material from the dolomite to the granite.

A more complicated zonal development is that characteristic of Kilbride (loc. E, fig. 1 d), where an inner hedenbergite-plagioclase assemblage (sometimes associated with iron-wollastonite) is followed by a narrow zone of clinopyroxene and then by a much wider zone built of

chondrodite, grossular, monticellite, and diopside±clinohumite, in which typically the monticellite occurs as large crystals enveloping diopside and the humite group minerals (pl. XX, fig. 6). Some parts of this particular zone are built essentially of chondrodite and grossular. This wide zone is followed by a remarkable zone built essentially of idioblastic forsterite, often with a minimum of interstitial calcite and some associated xanthophyllite. This zone gives place to the normal forsterite-marble.

Skarn zones which include layers containing both fluosilicates and magnetite are, however, the commonest met with. Those of no. 1 Prospect, Kilchrist, are typical, an example having been figured in an earlier paper (Tilley, 1949). Very characteristic here and at Kilbride is the succession from a magnesia-free grossular-wollastonite zone to two successive clinopyroxene zones, one composed almost wholly of green diopside, usually fine grained and the other, the next outward, of a pale diopside typically coarse grained. As exemplified in a Kilbride example the pyroxenes of both zones contain alumina (analyses 19 and 20 of table XIV). The pale clinopyroxene zone is followed by a zone of variable width forming the essential ore skarn, built of magnetite, and chondrodite, diopside, clinohumite, and forsterite in varying proportion (pl. XX, fig. 5). This zone abuts against the normal forsterite-marble.

A still more complicated multizoned skarn occurs at loc. B, at the contact of the island of dolomite. Here the inner zone is a hedenbergite-plagioclase assemblage, followed by a lighter coloured diopside-plagioclase aggregate.

The usual dark and pale pyroxene zones with an inconstant forsterite layer are succeeded by a zone built of monticellite, clinopyroxene, and forsterite, sometimes with magnetite, and this again by a magnetite-forsterite zone (ore skarn) which shows irregular contacts with it, and which is in part clearly replacing it, as veins of this assemblage penetrate through the monticellite-bearing assemblage (fig. 1 *c*). Both the monticellite and forsterite-magnetite zones may carry subordinate fluosilicates of the humite group. Against the latter the dolomite carries clinohumite, eventually giving way to the normal forsterite type.

The skarn zone of greatest complexity is that met with at Kilbride (loc. D *b*) in a small gully west of the ludwigite locality (loc. D *a*). Here the skarn zones attain a wider dimension. The succession is effectively that portrayed in fig. 2. The distinguishing features of this skarn development are the presence of two monticellite zones separated by a broad zone rich in diopside and cuspidine, but also carrying one or both

of the fluosilicates, clinohumite, and less frequently chondrodite. Each monticellite zone is associated with a narrow clinohumite zone.

The surrounding marble is a periclase-spinel-forsterite type, which in the vicinity of the skarn zones develops clinohumite as idioblastic crystals and as polycrystalline aggregates taking the form of the rounded

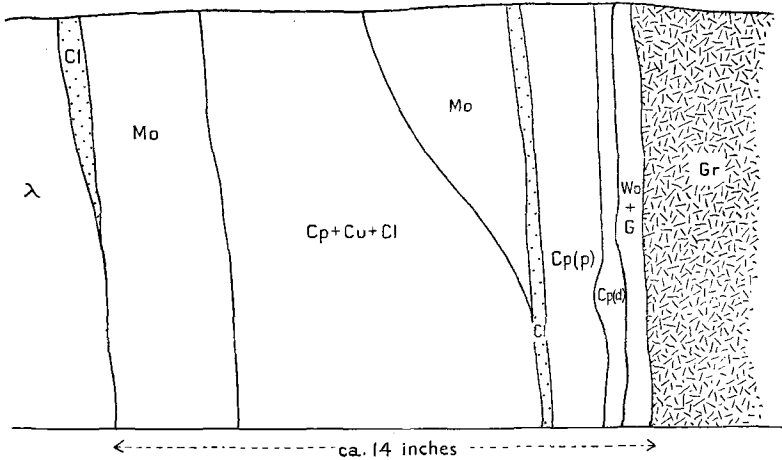


FIG. 2. Section across zoned skarns, Kilbride (loc. D b).

Gr granite with clinopyroxene, Wo+G wollastonite-grossular zone, Cp(d) dark clinopyroxene zone, Cp(p) pale clinopyroxene zone, Cl clinohumite zone, Mo monticellite zone, Cp+Cu+Cl clinopyroxene-cuspidine-clinohumite zone, λ marble with clinohumite.

original, but now transformed, forsterite grains. Periclase disappears close to the contact, and accessory fluoborite and ludwigite, and venules of fluorite may appear in the marble. A photograph of this outer region of the skarn succession and the associated marble is given in fig. 3.

A few yards east of this skarn exposure is the outcrop of the skarn assemblage yielding ludwigite in some abundance. The exposures as now seen occur on the faces of a pit excavated along the granite contact. The limestone horizon appears to be that of the Strath Suardal zone, for ring structures are seen in the outcrops of limestone adjacent and the prevailing type of contact metamorphism is that of forsterite and brucite marbles. The principal skarn from this locality is a ludwigite-chondrodite-magnetite skarn in which fluoborite and szaibelyite may appear as accessories. The granite in contact with the ore skarn in the pit is a porphyritic type of hornblende-granophyre showing phenocrysts

of quartz, microperthite, oligoclase, and brown-green hornblende in a quartz-microperthitic base, partly in micrographic intergrowth.

The ludwigite skarn is dull black on the weathered surface, frequently banded, due to thin impersistent streaks of white or creamy white chondrodite. On the fractured surface the ludwigite appears as radiate clusters of velvet black needles reaching to 1 mm. in length. Magnetite

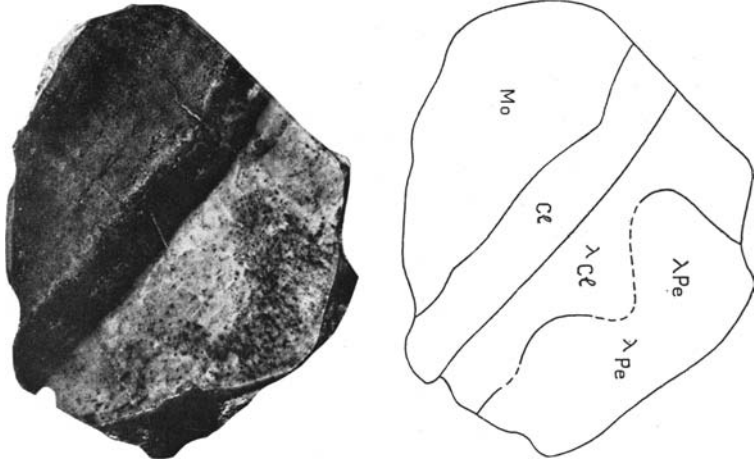


FIG. 3. Zoned skarn at granite contact, Kilbride (loc. D). $\times \frac{1}{2}$.

Edge against marble: marble with periclase λ Pe, forsterite, and spinel, passing inwards into periclase-free marble with forsterite, clinohumite, spinel, some ludwigite λ Cl; contact against clinohumite zone (Cl) and broad monticellite zone (Mo). The marble at the contact against the clinohumite zone is rich in idioblastic clinohumite and has forsterite grains in large part replaced by a polycrystalline aggregate of clinohumite; there are minute sprays of ludwigite fibres. The photograph shows the clearer zones of the marble against the clinohumite zone, freed from dark periclase. In the outer zone of the marble periclase, brown, is mantled by brucite bearing minute iron-ore grains, the ferropericlase yielding brucite with separation of iron oxide. In the parts of the marble bearing both clinohumite and forsterite the former, if as single grains, is idioblastic, forsterite as rounded grains, then often replaced by aggregates of clinohumite.

is usually present, though in variable amount, and some of the skarns contain sporadic patches of basic copper carbonates along joints. Less commonly a skarn composed of diopside and magnetite with accessory grossular and idocrase is found.

Two other skarn localities along the granite edge occur, one to the east and the other to the west at the angle of the contact where a protrusion of the granite is directed northward. It is probably this latter

locality to which A. Geikie refers in his comment on magnetite at Kilbride (Ancient volcanoes, 1897, vol. 2, p. 384). Magnetite is here accompanied by amphibole (altered in part to talc) and clinocllore, and the associated marbles carry idocrase and grossular. Fluorite and blende are also present. The important skarn occurrence on the west contact of the protrusion of granite at Kilbride (loc. E) has already been mentioned and will be discussed in more detail in the sequel.

At the western end of the granite the most important development of skarns is that at Camas Malag on Loch Slapin. Here within an embayment of dolomite three localities are concerned (loc. F, loc. G a, and loc.

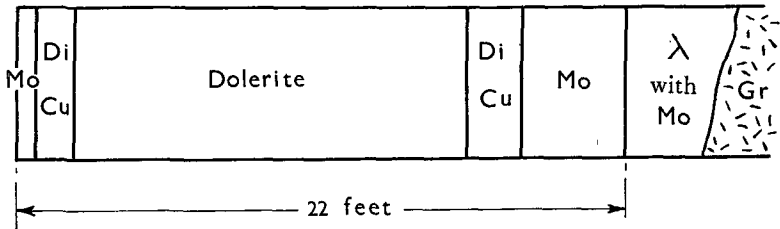


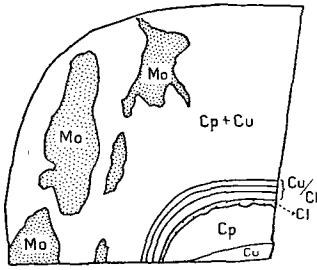
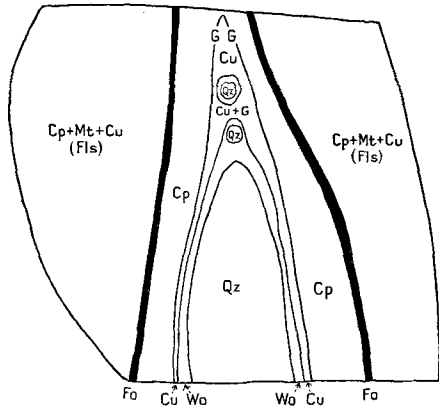
FIG. 4. Skarn development at edges of a pre-granitic dolerite dike at Camas Malag (loc. G a): a diopside(Di)-cuspidine(Cu)-magnetite skarn zone is followed outwards by a monticellite(Mo)-magnetite skarn, λ limestone, Gr granite.

G b). It is these skarns which have provided the most extensive development of monticellite and cuspidine in the region, and have provided at loc. G b the special mineral assemblage carrying the new boron mineral, harkerite. The position of these skarn localities is indicated on the map (pl. XXIV), and in the accompanying section (fig. 4) the zonal arrangement at loc. G a is set out.

A prominent dolerite dike (15 feet wide) seen in the burn section Allt na Garbhlain is sheathed by skarns built of diopside-cuspidine-magnetite \pm chondrodite and monticellite \pm magnetite, while there is a strong development of monticellite-marbles near the adjacent granite contact (fig. 4). In the diopside-cuspidine-magnetite zone occur 'sponge forms' with their own suite of skarn successions. It is clear that the contact surfaces of this pre-granitic dolerite in the marble have provided channel-ways for the introduction of the skarn producing solutions.

At locality F at the end of the embayment an important group of skarns carrying idioblastic cuspidine, forsterite, and clinohumite is developed, and the associated marble carries small idioblastic crystals of clinohumite. Here occurs the clinopyroxene-fluorite skarn, of which an analysis is given in table XIII, no. 15.

The locality of the harkerite-bearing skarns (loc. G b) is at the granite contact about 50 yards SE. of the chief skarn locality in the burn section. The harkerite occurs in a band a foot or two in length and 6–8 inches in thickness in the dolomite associated with monticellite to form a harkerite-monticellite skarn. While monticellite is its commonest associate, other minerals found with it include diopside, calcite, and the ores magnetite, bornite, chalcosine, and blende.

FIG. 5 ($\times \frac{3}{8}$).FIG. 6 ($\times \frac{3}{4}$).

Zoned skarns around 'sponge forms' near granite contact, Camas Malag, Loch Slapin.

The complicated zonal succession is well displayed. In fig. 5 the 'sponge form' itself is wholly replaced by cuspidine and clinopyroxene and is succeeded by alternating narrow bands of cuspidine and clinohumite (Cu/Cl). In fig. 6 the zones show bilateral symmetry across a chert core.

Cp clinopyroxene, Mo monticellite, Qz quartz, Wo wollastonite, Fo forsterite, G grossular, Fls chondrodite-clinohumite, Mt magnetite.

The humite minerals, clinohumite and chondrodite, are found in the associated dolomite, and clinohumite may appear as a thin band in direct contact with the harkerite skarn. Further data on the harkerite paragenesis are given in the section on the mineralogy of the skarns (p. 640).

Three other localities of skarns on the south edge of the granite are marked on the map. They are localities H, J, and K, the first the occurrence of a garnetized dolerite dike carrying idocrase, the second a magnetite skarn, and the last surrounding the lens of alkali-granite previously described.

3. SKARN SUCCESSIONS ASSOCIATED WITH CHERT NODULES ('SPONGE FORMS').

The 'sponge forms' of the Strath Suardal dolomite when involved in the skarn zones exhibit their own succession of zones and have suffered fundamental metasomatic change. The best examples come from Kilchrist (loc. A) and Camas Malag (loc. G *a*). In the aureole we have noted that in the highest grades of metamorphism the core of the nodules may be

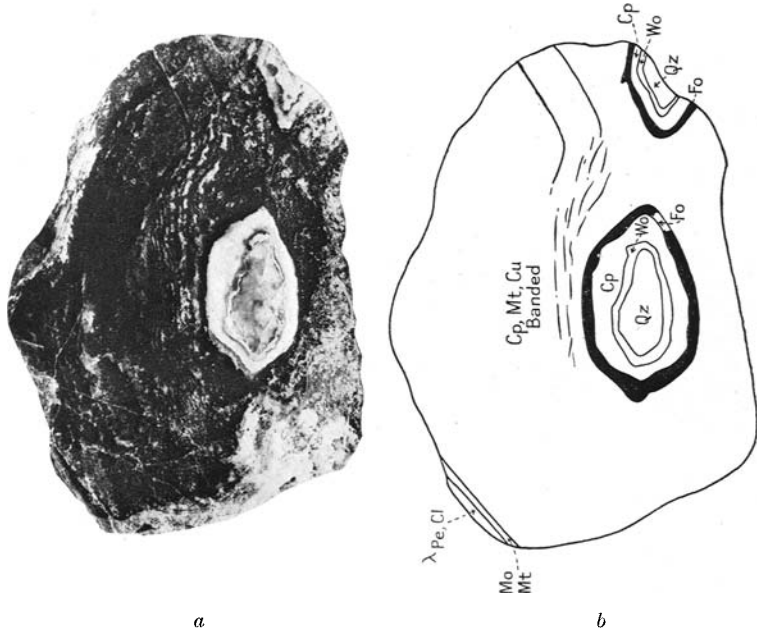


FIG. 7. Zoned skarn around 'sponge form', Camas Malag (loc. G), Loch Slapin. $\times \frac{2}{3}$.

The chert core is surrounded successively by a zone of wollastonite, clinopyroxene, fine-grained forsterite, with some chondrodite. The dark groundmass beyond is ore skarn built of clinopyroxene, magnetite, cuspidine, and subordinate fluosilicate (chondrodite series), often banded with layers rich in magnetite. At the periphery (bottom left) the ore skarn is followed by a zone of magnetite-monticellite with some calcite passing to marble with periclase, spinel, and some clinohumite.

replaced partly or wholly by diopside. In the skarn zones where the core is transformed by metasomatism the ultimate replacement is by wollastonite, cuspidine, or sometimes even by apophyllite. In the larger nodules a core of recrystallized quartz is preserved, but it may be traversed by venules of wollastonite, diopside, pectolite, or xonotlite.

A typical succession at Kilechrist outward from the quartz core is wollastonite as radiating pencils at right angles to the core surface, followed by diopside or diopside and cuspidine with grossular or idocrase, eventually giving place to a magnetite-cuspidine skarn. In some examples the core of quartz is partially or wholly replaced by apophyllite, optically positive, and showing anomalous brown interference tints.

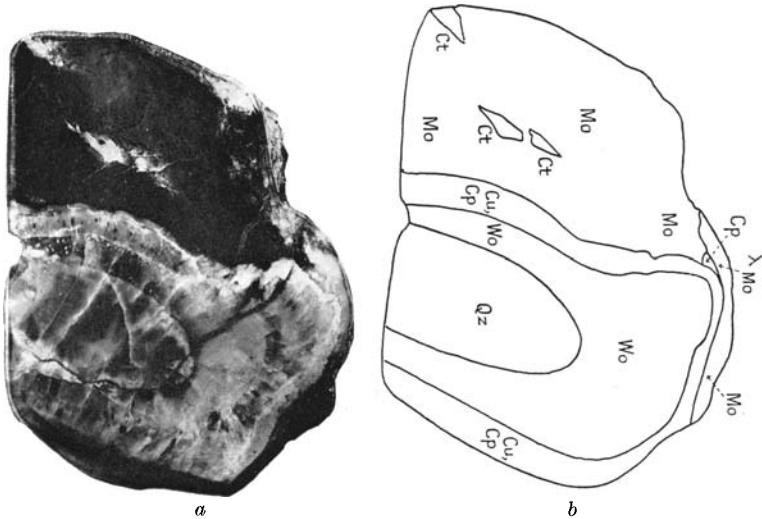


FIG. 8. Zoned skarn around 'sponge form' close to granite, Camas Malag (loc. G), Loch Slapin. $\times \frac{1}{4}$.

A recrystallized quartz core (with some diopside, wollastonite, and pectolite) is surrounded by a broad wollastonite zone (pencils at right angles to contact). Then follows a narrow zone of cuspidine which contains some intergrown clinopyroxene and calcite. This zone borders a marble with monticellite (right) and at the top a broad zone of monticellite skarn containing patches of calcite.

Both at Kilechrist and at Camas Malag the border between the quartz core and the radiate wollastonite zone may be occupied by a very narrow band less than $\frac{3}{4}$ mm. in thickness of a colourless mineral in the form of fibres of parallel orientation set parallel to the wollastonite pencils. This mineral has a refraction, α 1.620, γ 1.628, a little less than that of the wollastonite, elongation positive, sensibly uniaxial, optically positive. It appears to be a hydrated calcium silicate, though its properties do not accord with any of the described species of that type of composition. When a slice is strongly heated, the band containing this mineral becomes turbid and eventually appears to be converted to wollastonite, losing

then something of its parallel orientation. The exact nature of this material, owing to the scarcity of it, has not yet been established.

The 'sponge forms' in the skarn zones of Camas Malag show more fundamental changes and a more complicated zonal succession outward from the core. These transformations are illustrated in figs. 5-8. A wollastonite sheath may be followed by a zone of diopside, a zone built of forsterite with which chondrodite or clinohumite may be associated, that zone being succeeded by an ore skarn often in a banded succession, Eozoon-like, of diopside, cuspidine, and clinohumite with magnetite (fig. 7). An important variant of this succession is seen in the examples of figs. 6 and 8, where the wollastonite zone is succeeded by a zone of cuspidine with granules of diopside and calcite, in which the cuspidine has a similar radiate texture as the wollastonite but so oriented that the lath-like sections show negative elongation, suggesting that the cuspidine is developed flattened parallel to (001). This cuspidine zone may be followed by a zone of brown monticellite (fig. 8) or a diopside zone (fig. 6). In the smaller 'sponge forms' the core may be replaced at its centre by wollastonite or by cuspidine (fig. 5).

TABLE I. Minerals present in aureole and skarn zones.

Aureole beyond the skarn zones.	Skarn zones.	
	Group I, Primary skarns.	Group II, Boron-fluorine ore skarns.
Talc	Grossular-andradite*	Magnetite*
Tremolite	Wollastonite* solid solutions	Tremolite
Forsterite	Diopside-heden- bergite*	Forsterite*
Diopside	Spinel	Diopside*
Periclase	Plagioclase*	Monticellite*
Wollastonite (rare)	Idocrase	Cuspidine*
Spinel	Xanthophyllite	Fluorite
Idocrase	Phlogopite	Chondrodite*
Grossular	Orthite	Humite
Phlogopite	Clinozoisite-epidote	Clinohumite*
Bruceite	Prehnite	Ludwigite
Serpentine	Apophyllite	Fluoborite
Chlorite	Pectolite	Szaibelyite
Hydromagnesite	Xonotlite	Datolite
		Harkerite

* Most abundant skarn minerals.

4. MINERALOGY OF THE SKARN ZONES.

The mineral development in the aureole and in the skarn zones of the granite is set out in table I, the columns separating the minerals

characteristic of (a) the aureole beyond the skarn zones, (b) the primary skarns (group I), and (c) the secondary (group II) skarns.

Clinopyroxenes.

Clinopyroxenes play a prominent role both in the skarns of groups I and II. Analyses of the clinopyroxenes of the twin zones of group I at Kilbride (loc. D b) are given in table II together with their optical properties. Comment on the character of these zones will be made in the sequel (p. 646). An analysis of a skarn zone from Camas Malag, built of clinopyroxene and fluorite enables us to calculate the composition of a more ferrous diopside in a skarn zone. The analysis is given in table III.

Hedenbergite is not an uncommon constituent of the zone which takes the place of the grossular-wollastonite assemblages at some of the granite contacts. A typical example is provided in the hedenbergite-plagioclase skarn of Kilbride (loc. E). Here the hedenbergite is practically free of magnesia (analysis 11 of table XIII). It is with the more

TABLE II. Analyses of diopside.

	1.	Metal atoms to 6 oxygens.	2.	Metal atoms to 6 oxygens.
SiO ₂	50.74	1.876	49.81	1.828
Al ₂ O ₃	3.67	0.159	6.42	0.277
Fe ₂ O ₃	0.96	0.026	1.25	0.035
FeO	0.79	0.024	1.03	0.030
MnO	0.08	—	0.06	—
MgO	16.92	0.938	15.22	0.837
CaO	25.78	1.009	25.92	1.011
TiO ₂	0.11	—	0.14	—
H ₂ O—	0.11	—	0.06	—
H ₂ O+	0.54	α 1.669	0.13	α 1.680
CO ₂	0.24	γ 1.695	0.15	γ 1.704
	99.94		100.19	

1. Diopside of pale clinopyroxene zone } Skarn, Kilbride, loc. D b.
 2. Diopside of dark clinopyroxene zone }

hedenbergite pyroxenes that wollastonites, having the properties of iron-wollastonite, occur. An example from Camas Malag has already been described (Tilley, 1948, c). At Kilbride (loc. E) pockets of an iron-wollastonite are associated with the hedenbergite-plagioclase skarn

TABLE III. Analysis of clinopyroxene-fluorite skarn.

			1.	2.	Metal atoms to 6 oxygens.	
SiO ₂	...	...	38.48	51.08	1.921	} 2.00
Al ₂ O ₃	...	...	1.99	2.64	0.110	
Fe ₂ O ₃	...	...	0.44	0.58	0.02	} 1.029
FeO	...	...	5.78	7.67	0.248	
MnO	...	...	0.15	0.20		
MgO	...	...	9.77	12.97	0.731	
CaO	...	...	35.59	24.37	0.982	
Na ₂ O	...	...	0.05	0.07		} 2.01
K ₂ O	...	...	0.02	0.03		
H ₂ O—	...	...	0.16	0.21		
H ₂ O+	...	...	nil	—		
TiO ₂	...	...	0.08	0.10		
P ₂ O ₅	...	...	0.05	0.07		
SO ₃	...	...	0.38			α 1.682, γ 1.710, $\gamma:c=40^\circ$,
F	...	...	11.52	—		$2V_\gamma$ 60°
			<hr/>	<hr/>		
			104.46	99.99		
Less O=F	...	...	4.85			
			99.61			

1. Clinopyroxene-fluorite skarn, Camas Malag (loc. F). Diopside 75.5, fluorite 23.6, calcium sulphate 0.6 %.

2. Clinopyroxene, after deducting fluorite, and SO₃ as calcium sulphate.

noted above. It shows γ 1.655, $\alpha':c = 44^\circ$, in sections perpendicular to the zone of cleavages, thus corresponding to a composition CaSiO₃ 80, FeSiO₃ 20 wt. % (Plate XXI, fig. 3).

In association with diopside pyroxene in the skarn zones—for example those occurring as borders to 'sponge forms', or in the grossular-wollastonite assemblages at the granite contacts—the wollastonite shows the normal optic properties of the iron-free mineral.

Fluorine-bearing minerals.

Humite series.—The chief minerals of the humite series developed in the skarns are chondrodite and clinohumite. Humite is much less common, while norbergite has not been recorded. Both chondrodite and clinohumite are developed at the chief localities; humite is present in parallel growth with clinohumite at Kilbride in the clinohumite skarn of loc. D b and with chondrodite at no. 1 Prospect, Kilchrist. Parallel growth of both with forsterite are also recorded. A fine example of a clinohumite-forsterite intergrowth is figured from the ore skarn of

Kilchrist (pl. XX, figs. 1 and 2). Repeated twinning on (001) is characteristic of both fluosilicates; in addition, twinning on (105) or ($\bar{3}05$) occur in chondrodite and on ($\bar{1}03$) in clinohumite (pl. XX, fig. 4).

Both minerals occur as idioblastic crystals in the marbles adjacent to the ore skarns. At Kilbride and Camas Malag both minerals form polycrystalline aggregates replacing the rounded forms of forsterite in zones in the marble adjacent to the skarns (pl. XVIII, fig. 2). In the monticellite bands of Kilbride (loc. D b) the monticellite close to the fluosilicate bands frequently contains clinohumite enclosures. In some cases the relation is found to be that of parallel growths as illustrated in pl. XX, fig. 3. The optical relations of the oriented intergrowths found among the olivine and humite-group minerals in the skarns are depicted in text-fig. 9.

An analysis of a clinohumite skarn forming a half-inch band at the outer edge of the multizoned skarn of loc. D b Kilbride is given in table XIII, no. 12. It contains some intergrown humite and has as accessories, calcite, clinochlore, xanthophyllite, fluorite, and a little magnetite.

Cuspidine.—The characteristic properties of this important mineral of the skarns have already been described (Tilley, 1947). Magnificent specimens of idioblastic cuspidine are recorded from Camas Malag, especially at locality F and illustrated in pl. XIX, figs. 1 and 2.

Fluoborite is richly present in a number of the ludwigite skarns, but also appears as an accessory in some of the magnetite-chondrodite assemblages. It is intimately associated with chondrodite in the form of hexagonal prisms. Examples studied show ω 1.550, ϵ 1.522, corresponding approximately to a composition of 50 % of the hydroxyl end-member of the series $3\text{MgO} \cdot \text{B}_2\text{O}_3 \cdot 3\text{Mg}(\text{OH}, \text{F})_2$ (Schaller, 1942). A specimen from a ludwigite skarn gave ω 1.556, ϵ 1.528. A section of a fluoborite-bearing skarn is figured in pl. XIX, fig. 5.

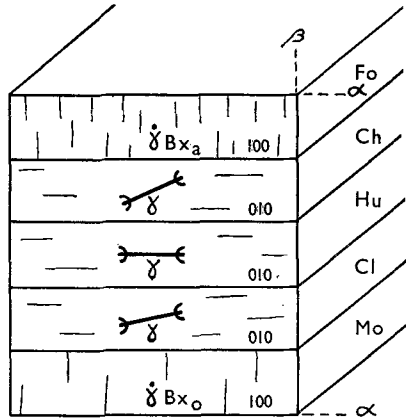


FIG. 9. Relations of parallel growths of the humite-group minerals (Ch, Hu, Cl), forsterite (Fo), and monticellite (Mo) in the skarns of the contact zone of the Beinn an Dubhaich granite.

Boron-bearing minerals.

In addition to fluoborite, szaibelyite, datolite, ludwigite, and the new boron mineral harkerite call for some notice.

Szaibelyite ($2\text{MgO} \cdot \text{B}_2\text{O}_3 \cdot \text{H}_2\text{O}$) occurs in magnetite skarns at no. 1 Prospect, Kilchrist, and at Kilbride. At the former locality the rock is a magnetite-ludwigite-chondrodite-carbonate assemblage. Set in the carbonate is fine-granular magnetite and coarser chondrodite, but there are knots built of an intergrowth of magnetite and lath-like ludwigite in part converted to haematite. At the periphery of these knots is szaibelyite as a mica-like development of matted fibres or plates with high birefringence, negative elongation, pseudo-uniaxial, negative sign, α 1.575, γ 1.650. In its occurrence the Skye szaibelyite resembles that of Tallgruvan of the Norberg district, Sweden, described by Geijer (1927, 1939).

Datolite is recorded at no. 1 Prospect, Kilchrist, at the contact of the grossular-wollastonite skarn with the alkali type of granite there produced. It appears replacing quartz of the granite at the immediate contact and is usually accompanied by prehnite which may similarly replace the adjacent orthoclase. As spherulitic botryolite it occurs in a similar environment in venules at the contact. A secondary mineral entirely, it derives its boron from solutions which have given rise to the associated ore skarns.

Ludwigite.—A description of the chief occurrence of ludwigite has already been given (p. 628). Besides its development at Kilbride, it is found as an accessory in the skarns of Kilchrist and in the marbles of Kilbride and Camas Malag. In its chief occurrence it is a ferroludwigite, transparent only in the thinnest fibres; then pleochroic, γ brown, α and β green, absorption $\gamma > \alpha = \beta$. Straight extinction, γ parallel to the fibre length. The mineral is magnetic. An analysis of the Kilbride ludwigite is given in table IV. After minor amounts of chondrodite and magnetite have been removed, this analysis shows close agreement with that of the end-member ferroludwigite (col. 2).

An analysis of a typical ludwigite assemblage at Kilbride, a ludwigite-chondrodite-magnetite skarn, is given in the list of analyses (table XIII, no. 14). It is quoted below (table V).

The ludwigite paragenesis with chondrodite (or clinohumite) and fluoborite characterizes other ludwigite occurrences such as those of the Norberg district (Geijer, 1927, 1939), Rézbánya (Watanabe, 1939), and the Suian district of Korea (Watanabe, 1939, 1943). This type of paragenesis may be conveniently illustrated graphically as in the tetrahedron

TABLE IV. Analysis of ludwigite.

	1.	2.	Mol. ratios.	Chondro- dite.	Magne- tite.	Re- mainder.
SiO ₂ ...	1.28	—	21	21	—	
Al ₂ O ₃ ...	2.25	—	22	—	—	} 226 1.0
Fe ₂ O ₃ ...	35.31	37.95	221	—	17	
TiO ₂ ...	0.30	—	4	—	—	} 218 0.97
FeO ...	16.36	17.08	227	—	17	
MnO ...	0.29	—	4	—	—	
MgO ...	28.33	28.46	708	52	—	656 2.90
CaO ...	0.07	—	—	—	—	
B ₂ O ₃ ...	15.74	16.51	226	—	—	226 1.0
H ₂ O— ...	0.19	—	—	—	—	
H ₂ O+ ...	0.44	—	—	—	—	
	100.56	100.00				

1. Ludwigite, loc. D a, Kilbride, from a ludwigite-chondrodite skarn with magnetite.

2. Ferroludwigite (theoretical, 3MgO.B₂O₃.FeO.Fe₂O₃).

TABLE V. Analysis of ludwigite-chondrodite-magnetite skarn.

		Mol. ratios.	Chondro- dite.	Magne- tite.	Remainder.
SiO ₂ ...	5.47	91	91	—	
Al ₂ O ₃ ...	2.62	25	—	—	} 166 1.0
Fe ₂ O ₃ ...	33.29	208	—	67	
TiO ₂ ...	0.11	1	—	—	} 129 0.77
FeO ...	13.78	191	—	67	
MnO ...	0.30	4	—	—	} 0.99
MgO ...	30.20	755	227	—	
CaO ...	0.36	6	—	—	} 534 { 0.22 3.00
P ₂ O ₅ ...	0.01	—	—	—	
B ₂ O ₃ ...	11.53	166	—	—	166 1.0
H ₂ O— ...	0.09	—	—	—	
H ₂ O+ ...	2.47	—	—	—	
F ...	0.34	—	—	—	

100.57 less 0.14 O=F, 100.43

The composition of this rock (sp. gr. 3.515) is estimated as ludwigite 67.1, chondrodite 15.5, magnetite 15.5 wt. %. This type of skarn is figured in pl. XIX, fig. 6.

figure (fig. 10) where the apices of the tetrahedron are represented by MgF₂, forsterite, kotoite (3MgO.B₂O₃), and magnetite. The compositions of fluorborite, the humite minerals (represented by chondrodite or clinohumite), and ludwigite are represented on the tetrahedron edges.

The four-phase assemblage of the Skye boron-fluorine minerals is represented by the field ludwigite-chondrodite-magnetite-fluorite. Other possible four-phase assemblages are also indicated.

Kotoite has not been recorded in the Skye skarns, nor should it be expected in ferroludwigite associations with magnetite, for we may write kotoite + magnetite = ludwigite, and further forsterite + fluoborite = chondrodite (clinohumite) + kotoite, so that forsterite-fluoborite associations are further unlikely. The four-phase assemblages carrying kotoite have been recorded from the type locality for kotoite in Korea.

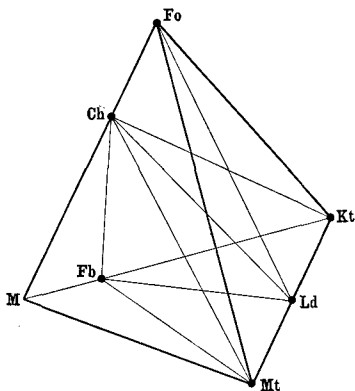


FIG. 10. Four-phase assemblages in the system Mg_2SiO_4 (Fo)- MgF_2 (M)- Fe_3O_4 (Mt)- $3MgO.B_2O_3$ (Kt kotoite). Ch chondrodite, Fb fluoborite, Ld ludwigite.

Harkerite.—This mineral is developed at one locality only, that of Camas Malag (G b). It occurs typically in the form of simple octahedra (pl. XXI, fig. 2). When fresh it is colourless with a vitreous lustre, but its ready alteration to fine calcite leads to its appearance as white masses in which, however, the octahedral outlines can still be observed on fractured surfaces. Bands of the harkerite-monticellite skarn may pass into zones of almost pure harkerite-rock in which, however, incipient alteration to calcite is seldom absent. This alteration of the mineral may affect the core of the mineral or be confined to narrow zones within the crystal following the outline of the idiomorphs. The zoned character of the crystals as seen under a hand-lens is due to this characteristic feature of the mineral.

In section harkerite is colourless with a refractive index of 1.653. It is

thus closely similar in refraction to its chief associate, monticellite. In this environment the mineral is distinguished in ordinary light by its idioblastic development in contrast to the granular character of the mosaic of monticellite, irregular crystals of which may also be enclosed within the harkerite. The mineral shows no signs of a significant cleavage and has a density of 2.959 at 20° C. Many of its sections behave as a cubic mineral, being isotropic, but frequently an anomalous birefringence is met with resembling in this regard the grossular garnet of contact zones.

The optical structure corresponds closely to that of the Elba type of garnet in which the octahedral crystal behaves as if built of pyramidal units with their bases in the octahedron face. Thus in sections parallel to (100) the squarish sections extinguish in the parallel position and separate into four fields with weak birefringence in the diagonal position giving a low first-order grey interference tint with each of the fields optically negative, the fast ray being normal to the edge length. Sections cut parallel to the octahedron face show an isotropic, triangular core with the peripheral sectors weakly birefringent and fast ray across their long edges. This structure, however, does not always involve the whole crystal, for it may be intercepted by, or alternate with, narrow zones following the outline which remain isotropic, a feature recognized in some grossulars.

The mineral has been isolated from a skarn containing accessory ore minerals, bornite, chalcosine, and magnetite, together with a little diopside. From these minerals it is readily separated by heavy liquids, but the removal of the intimately associated fine-grained calcite occurring in zones of the harkerite and in minute cracks has proved a more difficult operation. The uncontaminated mineral dissolves with effervescence in acetic or hydrochloric acid and gives a good flame reaction for boron. Heated to 850° C. for long periods, harkerite breaks down to a turbid brown sheaf-like product spreading through it in spherulitic fashion. After 30 hours' heating some of the original harkerite is still preserved as islands in this transformation product. After ten days' heating at 850° C., followed by five days at 950° C., this sheaf-like product had itself broken down to yield in slice a dense grained material almost isotropic.

An analysis of harkerite carried out by Mr. H. C. G. Vincent is set down in table VI. This analysis shows that harkerite is of complex composition and may be described as essentially a carbonate-borosilicate of calcium and magnesium containing chlorine.

TABLE VI. Analysis of harkerite.

	1.	2.	3.	4.	5.	6.	7.
	wt. %	Mol. ratios.	Metals.	O,OH, Cl.	Metals to 156 (O,OH, Cl).	Calc. wt. %	Metals to 156 (O,OH, Cl).
SiO ₂ ...	14.17	0.2359	0.2359	0.4718	13.35	13.67	13
B ₂ O ₃ ...	7.77	0.1116	0.2232	0.3348	12.63	6.71	11
Al ₂ O ₃ ...	2.84	0.0279	0.0558	0.0837	3.16	3.12	3.5
Fe ₂ O ₃ ...	0.85	0.0053	0.0106	0.0159	0.60	0.70	0.5
FeO ...	0.46	0.0064	0.0064	0.0064	0.36	0.63	0.5
MnO ...	0.02	—	—	—	—	—	—
MgO ...	11.15	0.2765	0.2765	0.2765	15.65	10.87	15.5
CaO ...	46.23	0.8243	0.8243	0.8243	46.65	47.12	48
CO ₂ ...	14.94	0.3394	0.3394	0.6788	19.21	15.42	20
Cl ...	1.36	0.0383	—	0.0383	2.17	1.25	2
H ₂ O+ ...	0.81	0.0450	0.0900	0.0450	5.09	0.79	5
H ₂ O- ...	0.11	—	—	—	—	—	—
	100.71			2.7755		100.28	
Less							
O = Cl ...	0.31			0.0191		0.28	
	100.40			2.7564		100.00	

For the following X-ray data on the mineral I am indebted to Dr. N. F. M. Henry. Oscillation, Laue, and powder photographs, the last with both iron and copper radiation, were taken. The cell side was found to be 29.53 Å. to an accuracy of 1 part in 3000. The odd-layer lines in the oscillation photographs were very weak, thus showing the existence of a pseudo-repeat distance of 14.76, i.e. half the true repeat distance. The Laue group was found to be $m\bar{3}m$, and the results of tests for pyro- and piezo-electricity were both negative. Consequently it is very probable that the crystal class is $m\bar{3}m$ (cubic holosymmetric). The large cell size makes the assignment of indices to the powder lines rather difficult. Even with a 19-cm. diameter camera and iron radiation it was not found possible to do this completely. With iron radiation seventy-three lines could be measured, while the use of copper radiation allows another nineteen to appear. The spacings and estimated relative intensities are given below, the four strongest lines being marked (table VII).

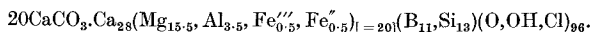
Taking a pseudo-cell as half $29.53 = 14.76$ Å. the molecular weight is 5731, and from this value the chemical analysis gives 157 as the number of anions in this pseudo-cell. In table VI the analysis on a basis of 156(O,OH,Cl) gives the figures set out in column 5, but these results manifestly do not provide the answer to the formula of this mineral.

TABLE VII. X-ray powder data for harkerite in Å.

No. of line.	<i>d.</i>	<i>I.</i>	No. of line.	<i>d.</i>	<i>I.</i>	No. of line.	<i>d.</i>	<i>I.</i>
1	5.22	s	26	2.22	vw	51	1.33	vw
2	4.45	w	27	2.16	vw	52	1.30	m
3	4.17	vw	28	2.13	s (3)	53	1.28	w
4	3.84	vw	29	2.07	m	54	1.26	w
5	3.69	vw	30	2.03	vw	55	1.25	w
6	3.61	vw	31	2.00	vw	56	1.22	w
7	3.58	vw	32	1.97	m	57	1.20	vw
8	3.39	m	33	1.92	w	58	1.18	vw
9	3.30	vw	34	1.84	s (2)	59	1.17	m
10	3.24	w	35	1.82	vw	60	1.15	vw
11	3.15	vw	36	1.80	vw	61	1.14	vw
12	3.01	m	37	1.74	m	62	1.13	vw
13	2.97	vw	38	1.70	m	63	1.11	w
14	2.95	vw	39	1.65	m	64	1.10	vw
15	2.84	m	40	1.61	w	65	1.08	vw
16	2.81	vw	41	1.60	vw	66	1.07	vw
17	2.66	w	42	1.57	w	67	1.06	w
18	2.61	vs (1)	43	1.55	vw	68	1.05	vw
19	2.53	vw	44	1.51	s (4)	69	1.0	w
20	2.50	vw	45	1.48	vw	70	1.03	vw
21	2.46	w	46	1.44	w	71	1.00	vw
22	2.39	vw	47	1.42	w	72	0.997	vw
23	2.37	vw	48	1.39	vw	73	0.986	m
24	2.33	w	49	1.38	vw			
25	2.25	vw	50	1.34	vw			

vs very strong, s strong, m medium, w weak, vw very weak. The four strongest lines are marked (1)-(4).

In columns 6 and 7 (table VI) are set down a calculated composition based on a pseudo-cell containing 156 anions with boron and silicon grouped together as a $(B, Si)O_4$ unit. The corresponding formula for this composition (columns 6 and 7) may be written as follows:



Comparison of columns 1 and 6 show greatest departure for CaO and B_2O_3 . It is clear that harkerite calls for a detailed X-ray structural analysis, and a further chemical analysis of selected material is much to be desired. It is hoped that this further study may shortly be continued. Meantime the presentation of optical, chemical, and X-ray powder data may at this stage provide the means of ready recognition of the mineral, should it appear in other contact zones subject to boron metasomatism.

Monticellite.—This mineral is one of the more important silicates both of the ore-free and ore-bearing skarns of group II. In the marbles immediately adjacent to these skarns, brown idioblastic monticellite

with ϵ (111), m (110), h (011) prominent, may appear. The best examples of such monticellite-marbles occur at Camas Malag (loc. G a), where they are developed in association with ore skarns built essentially of monticellite and magnetite. The analysis of monticellite isolated from such a marble is quoted below. This monticellite shows close agreement in composition and properties with a Crestmore monticellite (col. 2) described by Moehlman and Gonyer (1934).

TABLE VIII. Analyses of monticellite. 1, Skye; 2, California.

	1.*	2.	Mol. ratios (1).	Magne- tite.	Metals to 4 oxygens.
SiO ₂	36.55	37.46	609	—	0.990
Al ₂ O ₃	0.18	—	—	—	—
Fe ₂ O ₃	0.59	—	4	4	—
FeO	4.71	3.98	65	4	0.099
MnO	—	0.52	—	—	—
MgO	22.11	22.78	553	—	0.899
CaO	35.21	35.20	628	—	1.021
H ₂ O+	0.84	0.15			
H ₂ O-	0.56				
CO ₂	nil				
	100.75	100.09			
Sp. gr.	3.09	3.083			
α	1.645	1.646			
β	1.654	1.653			
γ	1.660	1.660			
2V _{α}	80°	78°			

* Corresponding to
CaMgSiO₄ 88,
CaFeSiO₄ 12 wt. %.

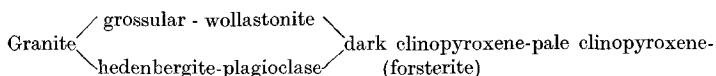
In the monticellite-magnetite skarns, while the monticellite is usually light brown in colour, there are areas of this mineral which are grey-white, and these tend to be free from magnetite—a clear indication that the skarn-forming solutions varied in their iron content yielding a more magnesian monticellite where magnetite was not precipitated in the immediate environment of the grey-white crystals. The monticellite of the skarns shows usually a poor cleavage and is usually in the form of simple crystals. In some of the skarns, however, a twinning on (031) has been recognized. Idioblastic crystals set in a matrix of chalcocine-bornite intergrowth are figured in plate XXI, figs. 5 and 6.

5. PARAGENESIS OF THE SKARN ZONES.

The skarn zones have been divided broadly into 2 groups, each characterized by a distinctive set of minerals. Skarns of group I are found immediately in contact with the granite and typically carry no fluorine- or boron-bearing minerals. Those of group II occupy a zone

on the dolomite side of the skarns of group I and are the home, not only of the fluorine-boron-bearing assemblages, but of monticellite and of the chief ore mineral magnetite.

The development of the skarns of group I may be unaccompanied by those of group II (loc. K, quarries near no. 2 Prospect, Kilchrist). They are to be attributed to a local silication of the dolomite, the effects of which can often be related to endomorphic changes in the contact facies of the granite itself. Broadly we may include among skarns of group I the successive zones arranged as follows:



As has already been described, the association of the grossular-wollastonite zone at Kilchrist and at loc. K on the south side of the granite is with an endomorphic facies of granite notably potassic and carrying an alkali-clinopyroxene. The hedenbergite-plagioclase skarn development is associated with a contact facies of granite enriched in plagioclase giving clear evidence that lime has been incorporated in the granite (pl. XXI, fig. 4). At Kilbride (loc. E) the contact phase of the granite assumes against a broad zone of hedenbergite-plagioclase skarn, locally the character of a quartz-monzonite (table XII, no. 5).

Confining our attention to the metasomatic phenomena of the skarn zones at the contact itself, the contrasting compositions of the alternative first skarn layers may be illustrated by the analysed zones of (1) grossular-wollastonite at Kilchrist, (2) hedenbergite-plagioclase at Kilbride (table IX).

Assuming equality of volume of skarn zone and dolomite from which it is formed it is seen that in both cases, besides the main addition of silica and alumina, there has been almost a complete elimination of magnesia. In the second example, however, there has been notable introduction of ferrous oxide. Some lime has been eliminated, but in the first example the reciprocal changes have involved the introduction of lime which must have come from the dolomite beyond. The magnesia eliminated presumably moved out into the dolomite in the first example where there is evidence of one way transfer only from the granite (Tilley, 1949).

In the case of the hedenbergite-plagioclase skarn some of the eliminated lime may have moved into the granite as this has suffered an endomorphic change involving the production of plagioclase. But it is

TABLE IX. Analyses of skarns of group I.

		Gain or loss in grams per 100 c.c.			
	1.	2.	3.	3 → 1.	3 → 2.
SiO ₂ ...	46.48	46.62	—	+147.34	+156.27
Al ₂ O ₃ ...	8.04	7.83	—	+25.48	+26.25
Fe ₂ O ₃ ...	0.92	0.25	—	+2.91	+0.83
FeO ...	0.36	19.60	—	+1.14	+65.70
MnO ...	0.19	0.81	—	+0.60	+2.71
MgO ...	0.39	0.81	21.74	-61.16	-59.68
CaO ...	43.24	21.58	30.43	+49.74	-15.00
Na ₂ O ...	nil	0.66	—	—	+2.22
K ₂ O ...	0.04	0.54	—	—	+1.81
H ₂ O— ...	0.02	0.03	—	—	—
H ₂ O+ ...	0.51	0.86	—	—	—
TiO ₂ ...	0.05	0.07	—	—	—
F ...	—	0.98	—	—	+3.28
CO ₂ ...	—	—	47.82	-137.24	-137.24
	100.24	100.64, less 0.4 O=F	100.23		
Sp. gr. ...	3.170	3.352	2.87		

1. Grossular-wollastonite skarn (first zone against granite), no. 1 Prospect, Kilchrist.
2. Hedenbergite-plagioclase skarn (first zone against granite), loc. E, Kilbride.
3. Dolomite (theoretical).

not easy to assess the balance of the transfer of lime to the granite as it seems probable that the skarn development completed itself before the final consolidation of the granite and some of the skarn itself may have been bodily incorporated in the contact facies. Whether any part of the magnesia moved out into the dolomite as in the first type of skarn cannot be determined.

These first-zone skarns are succeeded by a broader zone of clinopyroxene very characteristically divisible into a narrower zone green in colour and finer grained, and a wider pale clinopyroxene zone coarser in grain-size (cf. fig. 11, p. 650). Examples of the pyroxenes of these two zones at Kilbride (loc. D) contain respectively Fe oxides 2.28, 1.75 %, and alumina 6.42, 3.67% (nos. 20 and 19, table XIV). In this zonal arrangement we see a gradual decrease in the amounts of iron and aluminium fixed as the solutions moved out into the dolomite from the granite. Apart from that feature these clinopyroxenes derive from the straight silication of dolomite. These zones are usually, but not invariably, followed by a zone of varying width composed of forsterite with which some xanthophyllite may be associated.

By analogy with the succession seen around 'sponge forms' in the main aureole we may attribute this zone to processes operating during the formation of the group I skarns, and this zone therefore forms a component of the group, and the external one. The formation of this forsterite zone involves the continued outward movement of silica into the zone, addition of magnesia, and removal of lime. This addition of magnesia must be regarded as a process not necessarily conditioned by the availability of magnesia released from the first zone we have already remarked, for the zone is, as we have seen, typical of the halo around the 'sponge forms' in the main aureole. Reference to this particular problem will be made in the following section where the parageneses of the skarns of group II are considered.

Skarns of group II including the ore skarns.

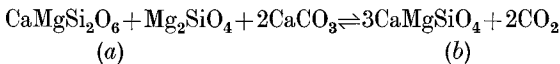
Here we include the skarn zones found on the dolomite side of those just discussed. Besides magnetite they carry the group of boron and fluorine minerals of the mineral table I (p. 634) summarizing the minerals of the skarns.

Perhaps the simplest development of these skarns is seen at Kilchrist where the clinopyroxene zones of group I are succeeded by an ore skarn built of magnetite, forsterite, chondrodite or clinohumite, and diopside, together with, in places, accessory grossular and secondary clinocllore (fig. 1 *b*). The analysis of such a magnetite-diopside-chondrodite skarn is given in table XIII, no. 8, the composition of the magnetite concentrate from it under no. 9 in the same table. The analysed skarn itself contains approximately magnetite 78, diopside 11, and chondrodite 8%. The analysis of the magnetite fraction shows that the ore mineral contains MnO 4% and holds also some magnesia.

The occurrence of manganese and magnesia in skarn magnetites has previously been recorded, for example in the Quebec occurrence analysed by Harrington (1907). The ore skarn gives way sharply to the normal metamorphosed dolomite with forsterite and calcite. The development of the ore skarn of Kilchrist must be attributed to ore-bearing solutions, not directly local in origin, probably ascending from below and attacking preferentially the dolomite which has acted as an absorption apparatus.

The more complex skarn development of group II type at Kilchrist (loc. B) calls for some consideration. Here a zone rich in monticellite intervenes between the clinopyroxene zone with its forsterite edge and

the typical ore-skarn zone (fig. 1 *c*). The zone is built of monticellite, diopside, forsterite, and accessory clinohumite. Magnetite is variable in amount. Both the occurrence of this mineral and clinohumite point to this zone as a group II assemblage. Monticellite frequently invests both diopside and forsterite and may form large poikiloblasts with these minerals as enclosures. An analysis of a typical member of the skarn zone is given in table XIII, no. 10. The mineralogical composition is computed as follows: monticellite 50, diopside 13, forsterite 15, clinohumite 4, magnetite 16, calcite 1 %. This zone is clearly derived by the silication of a dolomite with the introduction of iron and probable removal of some lime.¹ Compared to the assemblages in the main aureole the zone shows the development of the normally higher index mineral of the decarbonation series, monticellite, as represented in the stage (*b*) of the equation



This question is further discussed in the sequel under the heading—role of monticellite.

The monticellite-bearing zone is followed outward by a magnetite-forsterite zone (with accessory clinohumite). In this skarn locality there is very clear evidence that the ore zone bears an invasive replacement relation to the monticellite zone, for in the sections the ore skarn zone can be seen veining it (cf. fig. 1 *c*) and the skarns shown in figs. 12 and 13.

The magnetite-forsterite zone is thus the latest member of the skarn group. Beyond this zone appears marble with clinohumite passing out into the normal forsterite-marble. A variant of the monticellite-type skarn zone of this locality appears in the skarn succession at Kilbride (loc. E) fig. 1 *d*. There an intermediate zone reaching up to 4½ inches in width is built of chondrodite (locally clinohumite), diopside, monticellite (variable in amount), and grossular. Here again the monticellite may appear in large poikiloblasts investing chondrodite and diopside. Grossular appears both as large grains and as an investing skin to grains of the other silicates as if developed late in the succession. Sections of this zone are figured in pl. XIX, figs. 3 and 4, showing the relations of grossular, and in pl. XX, figs. 3, 4, and 6. This zone is followed outwards by the idioblastic forsterite zone carrying xanthophyllite, often in process of replacement by magnetite (pl. XVIII, fig. 5).

¹ After removal of magnetite, the composition plotted in the diagram of fig. 14 falls at B in the appropriate triangle.

In the neighbouring skarn section of loc. D *b*, Kilbride, the skarn zones are succeeded by an inconstant monticellite zone and a wide zone built essentially of diopside, cuspidine, and clinohumite; this is followed by a second monticellite zone, an inconstant clinohumite zone, and finally the dolomite. An analysis of the main diopside-cuspidine-clinohumite zone is given in table XIII, no. 13. Its computed composition is cuspidine 50, clinohumite 35, diopside 15 %. The ratio $\text{CaO}:\text{MgO} = 1.12:1$ is that of a dolomite and the ratios $\text{CaO}:(\text{Mg},\text{Fe})\text{O}:\text{SiO}_2$ have been plotted at A, in fig. 14, falling within the triangle cuspidine-diopside-clinohumite.

A somewhat similar zone occurs in the skarn succession at Camas Malag (loc. G *a*). There the ore-bearing solutions have used the contact surfaces of a dolerite dike in the marble as channel ways and converted the marble into a diopside-cuspidine-magnetite skarn reaching a thickness of two feet (fig. 4). This zone is followed outwards by a broad monticellite zone carrying magnetite.

The role of monticellite in the aureole.

Monticellite is unknown in the aureole beyond the immediate vicinity of the skarn zones. Monticellite-bearing marbles appear immediately adjacent to the monticellite zone of Camas Malag, and at Kilbride a similar assemblage is met with in like association, and as narrow brown stringers through a diopside-forsterite-marble (loc. E). These stringers form vein-like masses through the marble investing forsterite grains or cutting diopside hornfels (pl. XVIII, fig. 6). It may be accompanied by accessory cuspidine.

That the development of monticellite in this environment is late and due to solutions connected with the formation of the skarns is clear from these relationships. In the aureole proper the highest grade of metamorphism is revealed in the development of periclase and in the rare presence of wollastonite.

The widespread development of monticellite in the skarn zones is, however, not necessarily to be attributed to higher temperatures, for in the skarn environment metamorphism and metasomatism is accomplished by moving solutions and the entry of this normally higher stage in the decarbonation series may quite reasonably be attributed to reduction of pressure of CO_2 due to its escape in such solutions.

There remains some discussion of the time relations of the development of the monticellite-rich zones to those by which they are bounded. At Kilchrist (loc. B) the monticellite-diopside-forsterite zone was probably

formed at an early stage among the assemblages of group II skarns. It is followed outward by the forsterite-magnetite zone carrying in places clinohumite. This zone shows a distinct transgressive relation to the monticellite zone and has in part been formed by metasomatism of this zone (figs. 12 and 13).

At Kilbride (loc. D *b*) there are two prominent monticellite zones, the inner adjacent to a narrow clinohumite zone (fig. 2). This fluosilicate

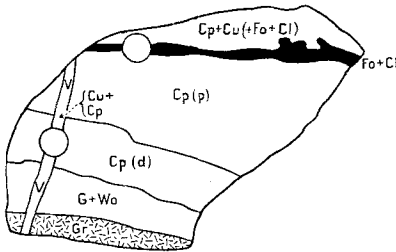


FIG. 11.

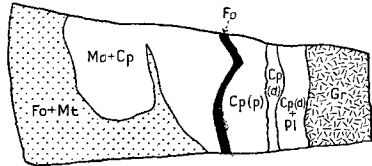


FIG. 12.

FIG. 11. Zoned skarn at granite contact, Kilbride (loc. D *b*). $\times \frac{1}{2}$.

Clinopyroxene granite (Gr), grossular-wollastonite zone (G + Wo), dark and pale clinopyroxene zones (Cp(d) and Cp(p)), forsterite-clinohumite zone (Fo + Cl).

A later vein cross-cutting the skarn zones consists in part of idocrase (V) and clinopyroxene (Cp), in part of cuspidine (Cu) and clinopyroxene.

The ringed areas are figured in pl. XVIII, fig. 3 (upper ring), fig. 4 (lower ring).

FIG. 12. Zoned skarn, loc. B, Kilchrist. $\times \frac{1}{2}$.

A zone built of hedenbergite and plagioclase (Cp(d) + Pl) borders the pyroxene-bearing granite: there follow two clinopyroxene zones, a forsterite zone, clinopyroxene-monticellite zone (Mo + Cp), and finally, a transgressive ore skarn built of magnetite and forsterite with scattered grains of bornite and chalcosine.

zone appears to have been formed by transformation of the forsterite zone which normally succeeds the two clinopyroxene zones of group I assemblages (pl. XVIII, fig. 3). The inner monticellite zone can be traced in a transgressive band through the broader diopside-cuspidine zone, appearing as a narrow monticellite band carrying cuspidine with a fine-grained monticellite edge corroding the large diopside crystals of the diopside-cuspidine zone (pl. XXI, fig. 1). On the marble side of this zone the second or outer monticellite zone is developed. This may make direct contact with the marble carrying clinohumite or chondrodite and spinel, but the section also reveals that a second clinohumite zone ($\frac{1}{2}$ inch thick) may intervene in places between the marble and the monticellite zone.

sought, none has been found, and the lack of such evidence is consonant with a relative late development of monticellite.

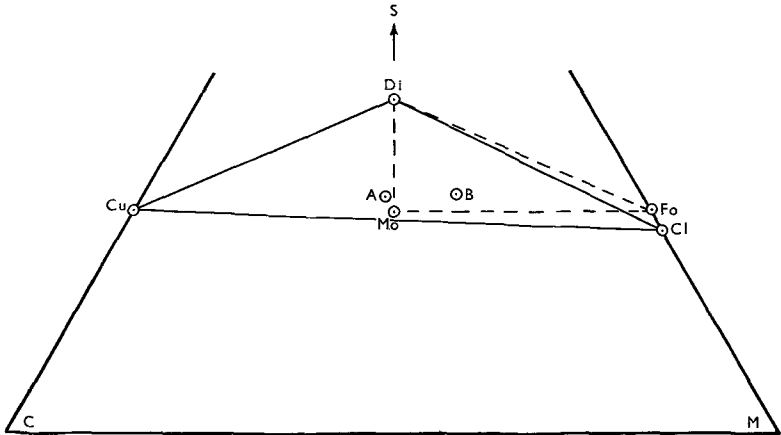


FIG. 14. Plot showing the compositions of the skarn zones diopside-cuspidine-clinohumite (A) and diopside-monticellite-forsterite (B) in the system $\text{CaO}-(\text{Mg,Fe})\text{O}-\text{SiO}_2$ (CMS). Cu cuspidine, Cl clinohumite, Mo monticellite, Fo forsterite.

6. PRODUCTS OF LIME METASOMATISM.

(a) *Metasomatism of pre-granitic dolerite dikes.*

Dolerite dikes invading the Durness dolomite horizons are cut off abruptly at the contact of the granite and are contact-altered. The petrography of these pre-granitic dolerites has been described by Harker in the Skye memoir (1904, pp. 318, 320), and he has discussed the changes they experience in the granite aureole. Further changes of a fundamental kind affect these rocks where they are associated with the ore skarns. Probably the best development of this metasomatism is to be found at no. 1 Prospect, Kilchrist, at Camas Malag, and at locality H on the south side of the granite.

The dolerites are ophitic to subophitic types, ordinarily containing no olivine. They consist of augite, labradorite, and subordinate iron ores. In the aureole they suffer amphibolization usually without their doleritic textures being effaced. In an example from no. 1 Prospect, Kilchrist, a 15-inch dike striking towards the granite contact (sketch-map, fig. 15), the augite is partially or wholly replaced by a brown pleochroic amphibole. It may become mottled with this new hornblende, be wholly replaced by it, or be reduced to a granoblastic aggregate consisting of interlocking grains of pyroxene and amphibole. The plagioclase remains

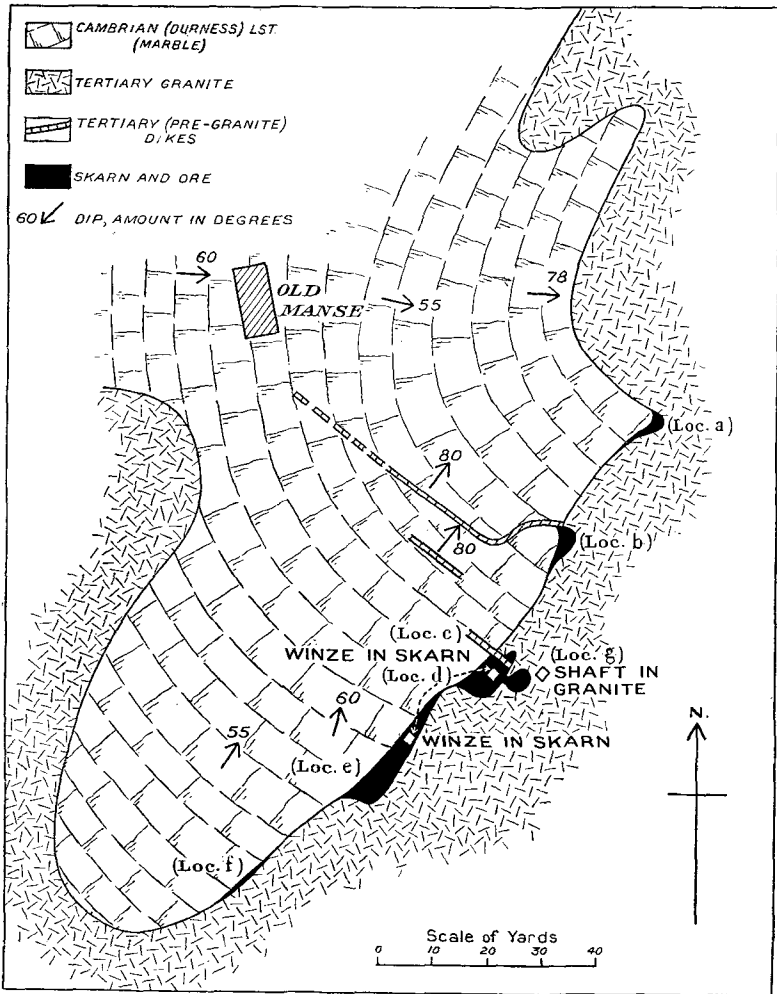


FIG. 15. Sketch-map of no. 1 Prospect (locality A, sub-localities a-g), Kilchrist, Skye.

unchanged, of composition $Ab_{40}An_{60}$. This amphibolized dolerite has been analysed (table X, no. 1). It may be compared with an analysis of an unaltered olivine-free dolerite of an inclined sheet intersecting the Cuillin gabbro (Harker, 1904, p. 370).

The radical change in chemical composition and mineralogy suffered by these dolerites when they become involved in the ore skarn environment is shown in a specimen of an adjacent dolerite at Kilchrist associated with the magnetite ore skarn ('c' section, loc. A). A specimen of this rock showing the effects of metasomatism in hand-specimens is described below. The specimen comes from a dike entangled in the ore skarn at the granite contact, and microscopic study shows that it has suffered strong metasomatism. It is crossed by narrow venules bearing diopside and idocrase, and against these venules the transition to amphibolized dolerite can be traced. The venule is built at its core of diopside (2 mm.) and has a margin of idocrase on both sides (1.5 mm.). In this part of the dolerite all original texture has been destroyed.

Beyond the idocrase bands metasomatism has not completely effaced original textures. The assemblage is then built of idocrase and diopside, the plagioclase laths being replaced pseudomorphously by idocrase of the same type as in the marginal vein. Traced outward this idocrase replacement is succeeded by that of grossular, the rock then being built of clinopyroxene aggregates with labradorite laths completely converted to garnet (pl. XXII, figs. 1-4). More remote from the venule brown hornblende is found among the clinopyroxene, and eventually labradorite laths remain unchanged or are partially replaced by sericite in aggregates of flakes. Biotite may be sporadically developed.

The transformation stages can thus be followed in their entirety from the amphibolized dolerite to the venule where all structures are lost and the rock consists of diopside and idocrase. Similar transformations can be followed from the ore skarn contacts. Elsewhere the dolerite may be completely replaced by diopside in microgranulitic aggregates \pm grossular, and in some examples this aggregate may be crossed by thin venules of xanthophyllite carrying sporadic green spinel which may also appear dispersed in the clinopyroxene groundmass.

An analysis of the metasomatized dolerite in the ore skarn at 'c' section Kilchrist (loc. A) is set out in table X, no. 2. The material analysed is a garnetized dolerite showing conspicuous laths of plagioclase in all stages of conversion to grossular, the ferromagnesium minerals being both augite and hornblende. Some relatively unaltered areas in which labradorite is partially replaced by sericite are also included in the material analysed. The analysis is to be compared with that of the adjacent 15-inch dike described (table X, no. 1). The preservation of the doleritic texture in the metasomatism allows us to set out the changes

involved, by comparing equal volumes of the two rocks, the gains and losses being shown in column 3 (table X).

TABLE X. Analyses of dolerite and dolerite skarn, Kilchrist.

	1.	2.	3. Gain or loss in grams per 100 c.c. 1 → 2.
SiO ₂	45.90	43.86	+5.60
Al ₂ O ₃	15.68	14.49	+0.29
Fe ₂ O ₃	2.29	2.34	+0.78
FeO	7.89	6.39	-2.82
MnO	0.12	0.37	+0.86
MgO	8.11	7.41	-0.13
CaO	12.61	18.75	+23.62
Na ₂ O	2.96	1.03	-5.56
K ₂ O	0.45	1.25	+2.76
TiO ₂	1.89	1.74	+0.01
CO ₂	0.58	0.23	-1.00
H ₂ O—	0.25	0.19	
H ₂ O+	0.85	1.49	
S	0.92	0.71	
	100.50	100.25	
Less O=S... ..	0.46	0.35	
	100.04	99.90	
Sp. gr.	3.026	3.295	

1. Amphibolized dolerite, 15-inch dike close to granite, no. 1 Prospect, Kilchrist (loc. A).
2. Dolerite skarn (garnetized dolerite hornfels), associated with ore skarns, no. 1 Prospect, Kilchrist.

The principal changes there noted are the introduction of lime, silica, and potash, and removal of soda and ferrous oxide. These changes find adequate expression in the grossular development from labradorite, the presence of subordinate biotite, and the sericite replacing plagioclase.

(b) *Metasomatism of the granite.*

Endomorphic skarn formation in the granite is found at the contact at no. 1 Prospect, Kilchrist. It is local in its development, being associated with late vein formation in the vicinity of the ore skarns. Examples are recognized from two points at Kilchrist, one close to the 'b' section (fig. 15) where it occurs close to the granite-skarn junction at the ledge and in specimens from the trial pit in the granite close to 'c' section.

The granite is traversed by dark zones or veins which prove to be lanes along which solutions have penetrated and caused fundamental

changes in the mineralogy (fig. 16). The width of these bands varies, ranging from five inches down to a fraction of a millimetre. In hand-specimens the metasomatic band appears often sharply, if irregularly, separated from the lighter coloured granite.

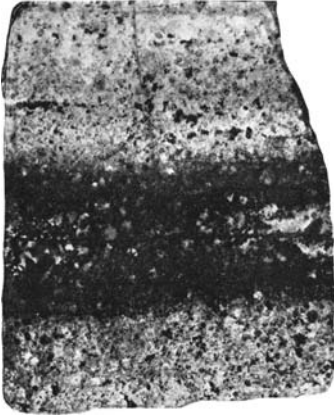


FIG. 16. Metasomatic vein in granite, no. 1 Prospect, Kilchrist. $\times \frac{2}{3}$.

Hornblende-biotite-granite rich in potash-felspar veined by solutions giving rise to a clinopyroxene-oligoclase metasomatic product with accessory fluorite and with areas rich in grossular-andradite and fibrous idocrase. The granite and vein product have been analysed and figured.

blende, also as accessories, magnetite, sphene, and grains of orthite. This is veined for a width of $1\frac{1}{2}$ inches. The onset of the metasomatized state is rather sudden. Potash-felspar and quartz disappear and a clinopyroxene (hedenbergite) is developed surrounding the plagioclase, oligoclase or oligoclase-andesine, often speckled with fine calcite.

The composition of the plagioclase is not uniform throughout the vein; in areas where garnet is developed a striated albite may appear. Idocrase is abundantly developed in some sections in the form of a mat of light green, optically negative, fibres which appear to be developing at the expense of the felspar. Orthite is sporadic, in part intergrown with yellow epidote, often strongly zoned and otherwise patchy.

The constituent minerals of the veins are clinopyroxene (diopside to hedenbergite), plagioclase (oligoclase to andesine), fluorite, grossular-andradite, idocrase, and accessorially epidote and orthite. In the narrowest veins the simplest expression of the metasomatism is the appearance of a narrow band of green clinopyroxene (near hedenbergite) with which a little fluorite is frequently associated. The commonest skarn assemblage is, however, in the form of medium-grained aggregates of clinopyroxene with twinned andesine or oligoclase, again usually with some fluorite. These are seen to end sharply against the granite. More complex veins carry grossular-andradite and idocrase, while locally orthite may be prominent.

Analyses have been carried out on the normal granite and an associated metasomatic vein. The granite (table XI, column 1) bears oligoclase, microperthite, quartz, biotite, and horn-

This orthite is an optically negative type with dispersion $r < v$, pleochroism variable, but β and γ are brown, while α is yellow or brownish-green. Absorption $\gamma > \beta \gg \alpha$.

In the final stages of metasomatism the centre of the vein is composed of an idocrase-clinopyroxene skarn where idocrase has completely replaced the plagioclase. The successive stages in the replacement process are depicted in the plate of photomicrographs (pl. XXIII, figs. 1-6).

The analysis of the vein material, essentially clinopyroxene, andesine, fluorite, some grossular, and a little idocrase, is set down in column 2 (table XI). Assuming no change of volume in the transformation we see

TABLE XI. Analyses of granite and associated metasomatic vein, no. 1 Prospect, Kilchrist, Skye.

	1.	2.	3. Gain or loss in grams per 100 c.c.
SiO ₂	74.88	47.65	-57.66
Al ₂ O ₃	12.73	11.02	-1.29
Fe ₂ O ₃	0.53	5.88	+15.75
FeO	1.33	6.72	+16.10
MnO	0.02	0.85	+2.40
MgO	0.25	0.29	+0.19
CaO	1.12	19.33	+53.40
Na ₂ O	3.33	2.44	-1.63
K ₂ O	4.99	0.87	-10.57
TiO ₂	0.18	0.09	
P ₂ O ₅	0.05	—	
H ₂ O—	0.16	0.38	
H ₂ O+	0.79	1.30	
F	—	0.95	+2.77
CO ₂	—	2.69	+7.84
	100.36	100.46, less O for F 100.06	
Sp. gr.	2.625	2.915	
<i>Norm:</i>			
Quartz	32.94	6.42	
Orthoclase	29.47	5.56	
Albite	28.30	20.44	
Anorthite	5.00	16.40	
Diopside	0.71	18.36	
Hypersthene... ..	1.82	Wo 14.50	
Magnetite	0.70	8.58	
Ilmenite	0.46	—	
Fluorite	—	1.95	
Calcite	—	6.11	

1. Biotite-hornblende-granite.

2. Clinopyroxene-plagioclase vein with fluorite, grossular, and little idocrase.

that the significant chemical changes are removal of silica and potash and the accession of ferric and ferrous iron, and lime. Mineralogically we observe that quartz and potash-felspar disappear, potash being removed, but the alumina of the orthoclase building up with lime new plagioclase, while the lime and ferrous iron give the new-formed hedenbergite. The introduced ferric oxide appears principally in grossular-andradite.

The analysis of column 2 represents an intermediate stage of transformation. The clinopyroxene-idocrase assemblage—equivalent to the mineralogical combination ultimately found too in the skarned dolerite—denotes of course the final stage of lime metasomatism with the building up of idocrase (and garnet) at the expense of the plagioclase. Good examples of replacement of plagioclase by idocrase are figured in pl. XXIII, figs. 5 and 6.

7. CONTRASTS OF LIME AND IRON-MAGNESIA METASOMATISM IN THE SKARN SUCCESSIONS.

The time relations of the primary (group I) and secondary (group II) skarn assemblages are manifest from their relationships. The first group may be unaccompanied by ore skarns, and the ore skarns themselves are not necessarily restricted to the environment of the first group which are spatially bound to the granite. Furthermore, the ore skarns are seen to traverse *not only parts of their own succession, but also, though less commonly, the primary group I zones*, as in the venules of magnetite skarn which cross-cut the diopside zones of this group. It seems evident that we may conclude that the skarns of group II result from solutions which have moved into their present position mainly through the dolomite bounding the primary skarns. The iron-bearing solutions found the carbonate-rocks more easily replaceable than the silicated group I assemblages.

In the primary zones the inner grossular-wollastonite assemblage represents a silicated dolomite to which alumina has been contributed from the granite and to which lime also has been added. It provides an example of lime metasomatism, even if *only on a small scale*. Lime metasomatism is prominent in the inner zones of 'sponge forms' in the skarns of group II. In nature they contrast with those of the 'sponge forms' in the main aureole. The latter are tremolitic and diopsidic, but in the former calcium minerals, wollastonite and cuspidine, are prominent, these eventually giving place externally to diopside. Lime metaso-

matism of the chert material or of the dolomite has, in the case of cuspidine, been accompanied by introduction of fluorine.

These zones differ from those of the granite contact by the absence or rarity of grossular. The silica of the cherts has contributed essentially to the inner zones around them, whereas with the granite, alumina as well as silica has been available.

The zones of the 'sponge forms' beyond have, however, clearly derived their silica from the solutions which are responsible for the ore skarns. It seems probable that the original size of these 'sponge forms' includes not only the quartz core which itself may be wholly replaced, but also the zones extending out to the limits of the diopside zone.

In the skarns of the second group, those rich in humite minerals, forsterite, and magnetite, the striking metasomatism is associated with the introduction of iron and magnesia and a notable loss in lime. The iron solutions are doubtless derived from residual solutions from the granite, but the source of magnesia may most likely be sought in the dolomite country-rock, ultimately to be precipitated, along with or separately from magnetite, in the humite minerals and forsterite.

The evidence for lime removal in the development of these ore skarns being thus clear, it may be inquired if there is evidence of the fate of these lime-bearing solutions. At Kilchrist it is apparent that these released solutions have themselves been responsible for late metasomatism.

As already described, the granite itself at the contact and the dolerite dikes entangled in the ore skarns have suffered locally a thoroughgoing lime replacement, and we may confidently attribute this process to the lime solutions set free in the ore skarn development. It has clearly operated subsequent to the consolidation of the border zone of the granite.¹

8. COMPARISON WITH THE SKARN ZONES OF OTHER REGIONS.

Examples of boron-fluorine metasomatism associated with banded skarns have not frequently been described. Perhaps the closest analogue to the Skye skarn development is that described by Watanabe (1943) from the Suian district of Korea as exemplified in the Hol Kol area, where dolomites have in places been converted at the contacts of the

¹ Umpleby (1914, 1917) has described the garnetization of granite-porphry of the Mackay region, Idaho, around included blocks of limestone, and he associates the lime metasomatism of the granite-porphry with the release of lime during the garnetization of the adjacent limestone inclusions (1914, p. 350; 1917, p. 62).

Suian granite into banded skarns bearing chondrodite minerals, and the boron minerals kotoite, fluoborite, and ludwigite.

In the Norberg district of Sweden, Geijer (1927, 1939) has described a somewhat similar boron-fluorine metasomatism with the production of humite minerals, ludwigite, and fluoborite in association with magnetite ore skarns in dolomite.

Apart from the occurrence of boron minerals, the Skye skarns in their multizoned character show resemblance to the ore skarns of Pitkäranta described by Trüstedt (1907) and to the more recently described banded skarns ('ribbon rock') of Iron Mountain, New Mexico (Jahns, 1944, *a, b*). While Trüstedt expressed the opinion that some of his skarns were due to replacement, he conceived for some of them deposition in open channels (by crustification). Such a mode of occurrence would require solutions of repeatedly changing composition, and the evidence that Trüstedt supplies for the operation of such a process is not entirely convincing. At Iron Mountain, New Mexico, Jahns has set out the evidence for a replacement origin of his rhythmically layered 'ribbon rock', and he remarks that this layering is probably best interpreted as a diffusion effect as in the Liesegang phenomenon. Moreover, the 'ribbon rock' occurs on the limestone side of the contact zone, i.e. between the limestone and the massive tactite which is nearest the intrusion. These conditions, as we have attempted to show, are reproduced in the development of the Broadford skarns.

Acknowledgements.—The map of plate XXIV is reproduced, with a few minor emendations, from the six-inch Geological Survey sheet (one-inch 71, six-inch 46, Scotland) mapped by Dr. A. Harker and Mr. C. T. Clough. For permission to make this reproduction the author is indebted to the Director of the Geological Survey.

Professor W. Q. Kennedy has kindly supplied the sketch-map of figure 15, and thanks are especially due to him for the opportunity of co-operating in the study of those skarn localities first discovered by him and for the fruitful discussion of genetic problems in the early stages of the work.

For the execution of the twenty-six chemical analyses the author is indebted to Geochemical Laboratories, Mr. H. C. G. Vincent, M.A., and Mr. J. H. Scoon, B.Sc. Part of the cost of this chemical work has been defrayed from a grant provided by the Royal Society, financial assistance now gratefully acknowledged.

TABLE XII. Analyses of the Beinn an Dubhaich granite and its modifications.

	1.	2.	3.	4.	5.	6.
SiO ₂	74.88	73.99	75.33	74.69	70.72	47.65
Al ₂ O ₃	12.73	13.02	11.88	12.00	12.64	11.02
Fe ₂ O ₃	0.53	0.76	0.43	0.44	0.21	5.88
FeO	1.33	1.60	0.95	0.71	2.79	6.72
MnO	0.02	0.02	0.01	0.03	0.06	0.85
MgO	0.25	0.31	0.08	0.12	1.10	0.29
CaO	1.12	1.22	0.92	1.66	4.18	19.33
Na ₂ O	3.33	3.43	2.55	2.02	3.24	2.44
K ₂ O	4.99	4.74	7.18	7.78	3.40	0.87
TiO ₂	0.18	0.32	0.06	0.14	0.36	0.09
P ₂ O ₅	0.05	0.05	0.08	trace	0.10	—
H ₂ O—	0.16	0.14	0.06	0.20	0.22	0.38
H ₂ O+	0.79	0.22	0.23	0.17	0.55	1.30
CO ₂	—	—	—	nil	0.44	2.69
F	—	—	—	—	—	0.95
	100.36	99.82	99.76	99.96	100.01	100.46
					less O for F	100.06

1. Biotite-hornblende-granite, no. 1 Prospect, Kilchrist (loc. A). (Tilley, 1949, p. 84).
2. Biotite-hornblende-granite, trial pit, no. 1 Prospect, Kilchrist (loc. A). (Tilley, 1949, p. 84.)
3. Aegirine-hedenbergite-granite, at contact with skarn, south side of Beinn an Dubhaich granite mass, ESE. of Camas Malag, Loch Slapin (loc. K). (Tilley, 1949, p. 84.)
4. Potash-rich granite, contact with skarn, no. 1 Prospect, Kilchrist (loc. A). (Tilley, 1949, p. 92.)
5. Clinopyroxene-hornblende-granite, bulk composition of band immediately adjacent to hedenbergite-plagioclase skarn, Kilbride (loc. E). Anal. J. H. Scoon.
6. Metasomatic vein (with clinopyroxene, plagioclase, idocrase, &c.) in granite (no. 1 of this table), no. 1 Prospect, Kilchrist (loc. A). Anal. Geochemical Laboratories.

TABLE XIII. Analyses of skarns of the Beinn an Dubhach granite contact zone.

	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.
SiO ₂	46.48	8.96	1.76	33.23	46.62	30.53	37.53	5.47	38.48	12.94	43.86	45.90
Al ₂ O ₃	...	3.61	2.64	1.16	7.83	2.63	1.55	2.62	1.99	2.61	14.49	15.68
Fe ₂ O ₃	...	52.27	64.07	11.07	0.25	0.90	1.58	33.29	0.44	0.89	2.34	2.29
FeO	...	0.36	17.54	21.39	19.60	1.40	1.49	13.78	5.78	0.65	6.89	7.89
MnO	...	0.19	3.83	0.79	0.81	0.39	0.39	0.30	0.15	0.07	0.37	0.12
MgO	...	0.39	8.22	23.35	0.81	46.01	20.79	30.20	9.77	11.48	7.41	8.11
CaO	...	43.24	4.02	21.40	21.58	7.55	32.54	0.36	35.59	41.15	18.75	12.61
Na ₂ O	...	nil	—	—	0.66	—	nil	—	0.05	—	1.03	2.96
K ₂ O	...	0.94	—	...	0.54	—	—	—	0.02	—	1.25	0.45
TiO ₂	...	0.05	—	—	0.07	—	—	—	0.08	0.06	1.74	1.89
P ₂ O ₅	...	—	0.18	—	—	0.11	—	—	0.05	—	—	—
H ₂ O-	...	0.02	—	—	0.03	—	—	—	0.16	—	—	—
H ₂ O+	...	0.51	—	—	0.86	—	—	—	0.09	2.64	0.19	0.25
F	...	—	—	—	1.33	—	—	—	1.19	3.23	1.49	0.85
CO ₂	...	—	—	—	0.10	—	—	—	2.47	0.10	—	—
B ₂ O ₃	...	—	—	—	0.98	—	—	—	11.52	16.48	0.23	0.58
SO ₃	...	—	—	—	0.44	—	—	—	—	6.08	—	—
S	...	—	—	—	—	—	—	—	0.38	—	—	—
Less O = F, S	...	100.24	100.31	100.03	100.53	101.03	101.95	100.57	104.46	100.30	100.25	100.50
		—	—	—	0.07	0.41	1.93	0.14	4.85	0.32	0.35	0.46
		—	—	—	100.46	100.23	99.80	100.02	99.61	99.98	99.90	100.04

- 7. Grossular-wollastonite skarn, no. 1 Prospect, Kilchrist (loc. A). (Tilley 1949, p. 88.)
- 8. Magnetite-chondrodite skarn with diopside, no. 1 Prospect, Kilchrist (loc. A). Anal. J. H. Scoon.
- 9. Magnetite concentrate from (8), same locality. Anal. J. H. Scoon.
- 10. Monticellite-diopside-forsterite skarn with magnetite and some clinohumite, contact of island of dolomite in granite, 300 yards ESE. of old Manse, Kilchrist (loc. B). Anal. J. H. Scoon.
- 11. Hedenbergite-plagioclase skarn, granite contact, Kilbride (loc. E). Anal. H. C. G. Vincent.
- 12. Clinohumite skarn (with some calcite, chlorite, xanthophyllite, and fluorite), Kilbride (loc. D b). Anal. Geochemical Laboratories.
- 13. Diopside-cuspidine-clinohumite skarn, Kilbride (loc. D b). Anal. J. H. Scoon.
- 14. Ludwigite-chondrodite skarn with magnetite, Kilbride (loc. D e). Anal. Geochemical Laboratories.
- 15. Clinopyroxene-fluorite skarn, Camas Malag (loc. F). Anal. Geochemical Laboratories.
- 16. Harkerite skarn, Camas Malag (loc. G b), with 1.31 CuO. Anal. Geochemical Laboratories.
- 17. Dolerite skarn (garnetized dolerite-hornfels) associated with ore skarns, no. 1 Prospect, Kilchrist (loc. A). Anal. J. H. Scoon.
- 18. Amphibolized dolerite, 15-inch dike, contact zone, no. 1 Prospect, Kilchrist (loc. A). Anal. J. H. Scoon.

TABLE XIV. Analyses of minerals from contact zones of the Beinn an Dubhaich granite.

	19.	20.	21.	22.	23.	24.	25.	26.
SiO ₂ ...	50.74	49.81	49.69	36.55	50.00	31.31	1.28	14.17
Al ₂ O ₃ ...	3.67	6.42	0.48	0.18	—	1.64	2.25	2.84
Fe ₂ O ₃ ...	0.96	1.25	8.79	0.59	nil		35.31	0.85
FeO ...	0.79	1.03	18.23	4.71	9.29	—	16.36	0.46
MnO ...	0.08	0.06	0.25	—	1.22	—	0.29	0.02
MgO ...	16.92	15.22	1.98	22.11	nil	0.11	28.33	11.15
CaO ...	25.78	25.92	16.87	35.21	38.86	59.05	0.07	46.23
Na ₂ O ...	—	—	3.79	—	—	0.15	—	—
K ₂ O ...	—	—	nil	—	—		—	—
TiO ₂ ...	0.11	0.14	0.45	nil	trace	—	0.30	—
P ₂ O ₅ ...	—	—	—	—	—	—	—	—
H ₂ O ⁻ ...	0.11	0.06	nil	0.56	—	0.33	0.19	0.11
H ₂ O ⁺ ...	0.54	0.13		0.84	—	0.41	0.44	0.81
F ...	—	—	—	—	—	9.80	—	—
CO ₂ ...	0.24	0.15	—	nil	—	0.75	—	14.94
B ₂ O ₃ ...	—	—	—	—	—	—	15.74	7.77
Cl ...	—	—	—	—	—	0.10	—	1.36
insol. ...	—	—	—	—	0.45	—	—	—
	99.94	100.19	100.53	100.75	99.82	103.65	100.56	100.71
Less								
O = F, Cl	—	—	—	—	—	4.13	—	0.31
						99.52		100.40

19. Pale green clinopyroxene of zoned skarn, Kilbride (loc. D b); pale clinopyroxene zone. Anal. J. H. Scoon.
20. Green clinopyroxene of zoned skarn, Kilbride (loc. D b); dark clinopyroxene zone. Anal. J. H. Scoon.
21. Aegirine-hedenbergite, pyroxene of alkali-granite, ESE. of Camas Malag (loc. K); in granite (analysis 3 of table XII). (Tilley, 1949, p. 85.)
22. Monticellite of monticellite marble, Camas Malag (loc. G). Anal. Geochemical Laboratories.
23. Iron-wollastonite, in contact skarn, Camas Malag (loc. G). (Tilley, 1948 (c), p. 737.)
24. Cuspidine in cuspidine-clinopyroxene skarn, Camas Malag (loc. G). (Tilley, 1947, p. 93.)
25. Ludwigite in chondrodite-ludwigite-magnetite skarn, Kilbride (loc. D a). Anal. Geochemical Laboratories.
26. Harkerite in harkerite skarn with diopside, Camas Malag (loc. G). Anal. H. C. G. Vincent.

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EXPLANATION OF PLATES XVIII-XXIV.

PLATE XVIII. Kilbride marbles and skarns.

- FIG. 1. Marble close to the granite contact, showing periclase with brucite haloes, spinel, and rounded grains of forsterite. (Loc. D b.) $\times 22$.
(Harker slide collection, 51881.)
- FIG. 2. Marble with ludwigite (left centre), spinel, periclase with brownish haloes of brucite, rounded forsterite grains largely replaced by sheaves of clinohumite, and idioblastic clinohumite. (Loc. D b.) $\times 22$. (51882.)
- FIG. 3. Zoned skarn at contact. A zone of forsterite with intergrown clinohumite separates a diopside zone (right) from a broad diopside-cuspidine zone (left). Clear areas on the right edge of the central zone are secondary chlorite. (Loc. D b.) $\times 22$. (52343/3.)
- FIG. 4. Diopside-cuspidine vein cross-cutting the fine diopside zone of a zoned skarn. The positions of sections of figs. 3-4 are indicated by circles in the drawing of the zoned skarn of text-fig. 11. (Loc. D b.) $\times 22$. (52343/4.)
- FIG. 5. Idioblastic forsterite zone of zoned skarn. Closely packed forsterite crystals with a little interstitial calcite. Kilbride (Loc. E.) $\times 17$. (55768/1.)
- FIG. 6. Monticellite border to diopside-rock at marble edge of zoned skarn. Fine diopside below, above coarser monticellite. (Loc. D b.) $\times 17$. (55809.)

PLATE XIX. Camas Malag and Kilbride skarns.

- FIG. 1. Cuspidine-clinohumite-forsterite-calcite skarn. Spear-shaped crystals of cuspidine set in calcite and associated with clinohumite and forsterite. Camas Malag (loc. F.) $\times 17$. (55889/5.)
- FIG. 2. Cuspidine-clinohumite-forsterite-calcite skarn. Another section of the same skarn: centre, large vertical section of cuspidine showing repeated twinning, surrounded by calcite (also twinned). The rest of the section shows clear cuspidine and grains of both clinohumite and forsterite. Camas Malag (loc. F.) + nicols. $\times 17$. (55889/4.)
- FIG. 3. Chondrodite-grossular skarn. Idioblastic chondrodite wrapped round by grossular. Diopside is seen left of centre: some calcite. Kilbride (loc. E.) $\times 17$. (55748.)
- FIG. 4. Chondrodite-grossular skarn. Shows the interstitial development of grossular (dark) in chondrodite-rock. Kilbride (loc. E.) $\times 17$. (55780/3.)

- FIG. 5. Ludwigite-fluoborite skarn with magnetite. The clear areas are formed of fluoborite; dark, rich in acicular ludwigite; below some turbid areas of carbonate replacing chondrodite. Kilbride (loc. D *a*). $\times 17$. (52303.)
- FIG. 6. Ludwigite-chondrodite skarn with magnetite. Clear areas, chondrodite; dark, mostly acicular ludwigite with some intergrown magnetite. Kilbride (loc. D *a*). $\times 17$. (52322/2.)

PLATE XX. Kilchrist and Kilbride skarns.

- FIG. 1. Clinohumite-diopside-forsterite-magnetite skarn. The section shows large clinohumite crystals enwrapped by magnetite. The rectangular section in the centre has a peripheral zone of more highly refringent forsterite in parallel growth. Kilchrist, no. 1 Prospect (loc. A). $\times 25$. (50101.)
- FIG. 2. Another section of the same skarn showing clinohumite cores to a forsterite grain. Both minerals are cut perpendicular to the acute bisectrix, one set of clinohumite lamellae being in the extinction position. Traces of the (010) cleavage of olivine at right angles to the twin lamellae of clinohumite are indicated. + nicols, $\times 66$. (50104.)
- FIG. 3. Outer monticellite zone of the banded skarn of Kilbride (loc. D *b*). The section shows a parallel orientated enclosure of clinohumite in a large crystal of monticellite. Clinohumite cut perpendicular to $\gamma(Bx_a)$, monticellite cut perpendicular to $\gamma(Bx_o)$. + nicols. $\times 70$. (51869.)
- FIG. 4. Twinned crystal of clinohumite in a clinohumite-monticellite-grossular skarn. The large crystal of clinohumite shown is cut perpendicular to the acute bisectrix and shows repeated twinning on (001) and a simple twin on (103) repeated in a set of fine lamellae on the right. Kilbride (loc. E), + nicols, $\times 15$. (55749/1.)
- FIG. 5. Chondrodite-magnetite-skarn with diopside, Kilchrist (loc. A). + nicols, $\times 23$. (49629.)
- FIG. 6. Clinohumite-monticellite skarn. The upper half of the section represents a single crystal of monticellite at extinction, enclosing grains of clinohumite (poikiloblast); the lower half is made of clinohumite in diversely orientated grains. Kilbride (loc. E). + nicols, $\times 17$. (55749/3.)

PLATE XXI. Kilchrist, Kilbride, and Camas Malag skarns.

- FIG. 1. Diopside-cuspidine-clinohumite skarn (right) bordered by a replacing skarn of monticellite with cuspidine (left). A fine edge of monticellite forms a sinuous border to coarse-grained clinopyroxene at the junction of the two skarns. Kilbride (loc. D *b*). $\times 17$. (51883/3.)
- FIG. 2. Harkerite-monticellite skarn. Idioblastic harkerite (with zones of secondary calcite), set in granular monticellite, opaque ore is an intergrowth of chalcosine and bornite. Camas Malag (loc. G *b*). $\times 22$ (52190/2.)
- FIG. 3. Hedenbergite-iron-wollastonite skarn. Showing the junction of a zone rich in iron-wollastonite solid solution (left) with a hedenbergite-granulitic plagioclase skarn. Kilbride (loc. E). $\times 17$. (55752/2.)
- FIG. 4. Contact of clinopyroxene-granite with hedenbergite skarn with granulitic plagioclase. Kilchrist (loc. B). $\times 17$. (52354/3.)
- FIG. 5. Monticellite-chalcosine-bornite skarn. Idioblastic monticellite set in copper ore, an intergrowth of chalcosine and bornite. Camas Malag (loc. G *b*). $\times 22$. (50809.)

FIG. 6. A similar skarn, but here the ore enclosing monticellite consists of blende (centre) and chalcosine-bornite intergrowths. Camas Malag (loc. G b). $\times 22$.
(52181/1.)

PLATE XXII. Amphibolized dolerite and dolerite skarn, no. 1 Prospect, Kilchrist.

FIG. 1. Amphibolized dolerite, 15-inch dike in marble. Clinopyroxene areas replaced by aggregates of brown hornblende. $\times 20$. (52116.)

FIG. 2. Dolerite skarn entangled in ore skarn, 'c' section. Section from core of venule through dolerite, in succession from above: (1) clinopyroxene zone (Cp), (2) band of idocrase (V), (3) assemblage of grossular replacing plagioclase laths (G), and aggregates of turbid clinopyroxene. $\times 15$. (52167.)

FIG. 3. The same. Below amphibolized dolerite passing upwards into dolerite skarn with plagioclase replaced by grossular (G) and hornblende aggregates by new clinopyroxene. $\times 15$.

FIG. 4. The same. Dolerite completely converted to a skarn composed of grossular after plagioclase (G) and clinopyroxene. $\times 15$.

PLATE XXIII. Endomorphic skarns of Beinn an Dubhaich granite, no. 1 Prospect, Kilchrist (loc. A), Skye.

FIG. 1. Biotite-hornblende-granite, near metasomatic vein. The central dark grain is hornblende, associated with biotite, magnetite, and orthite; clear, quartz; turbid, perthitic orthoclase. Oligoclase appears below. $\times 17$.
(52134/8.)

FIG. 2. Clinopyroxene-plagioclase skarn, developed from rock of fig. 1 at the edge of a metasomatic vein. Aggregates of clinopyroxene with twinned andesine. Carbonate (calcite) is present in the clinopyroxene aggregates and epidote appears elsewhere in the section. $\times 17$. (52134/3.)

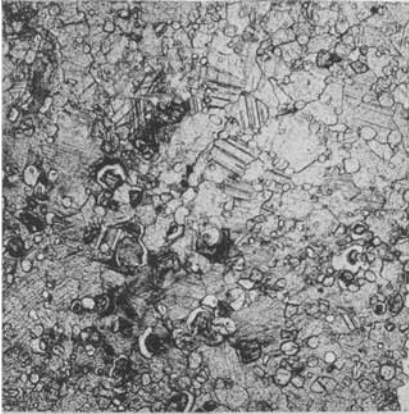
FIG. 3. Clinopyroxene-plagioclase skarn, developed from rock of fig. 1 in a metasomatic vein. In addition to pyroxene and andesine, clear fluorite is present. This rock has been analysed (table XII, no. 6). $\times 17$. (52134/7.)

FIG. 4. Metasomatic vein in granite, showing zoned, twinned orthite associated with epidote and set in a matrix of clinopyroxene, oligoclase, and fluorite. Fibres of idocrase are developing in the plagioclase. $\times 23$. (49678.)

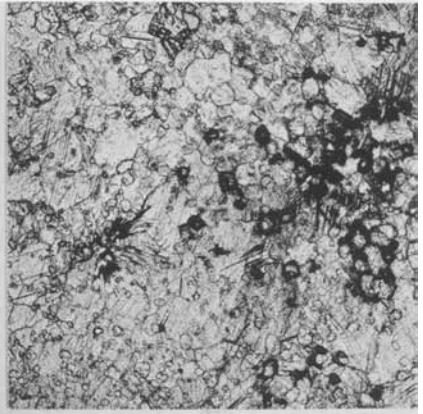
FIG. 5. Idocrase-rich skarn. A further stage of metasomatism seen in the same rock as that of fig. 4. Fibres of idocrase replacing plagioclase are seen in the central portion of the photograph. $\times 23$. (49684.)

FIG. 6. Idocrase-clinopyroxene skarn with orthite. A still further advanced stage, in which replacement of plagioclase by fibrous idocrase is complete. Centre and below orthite with some clinopyroxene. $\times 23$. (49675.)

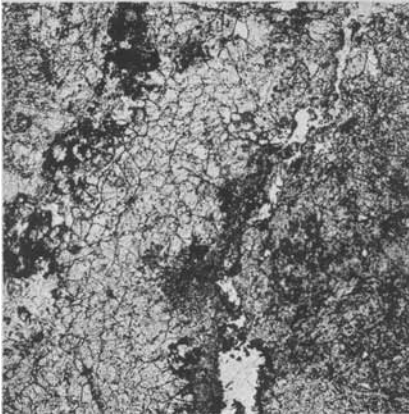
PLATE XXIV. Geological and locality map of dolomite contact zones around the Beinn an Dubhaich granite, Skye.



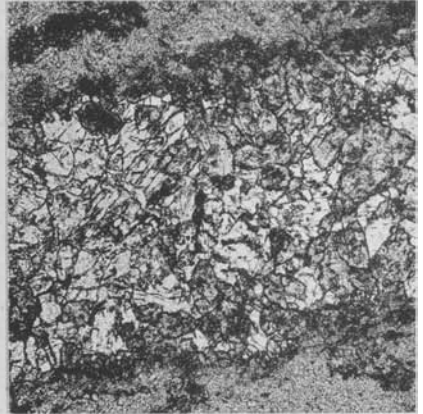
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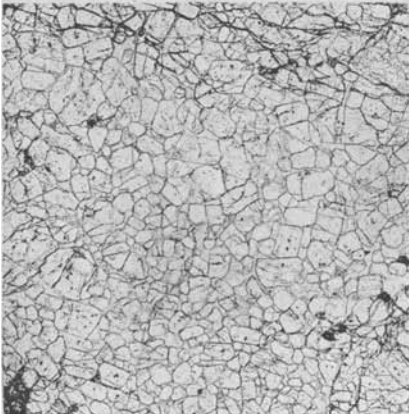
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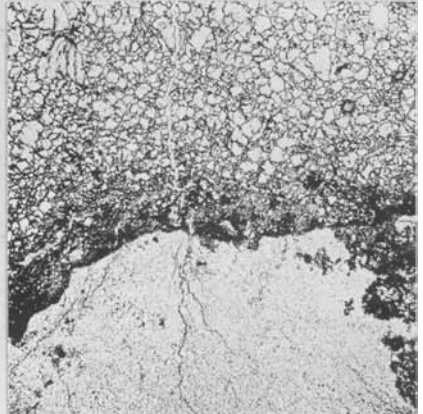
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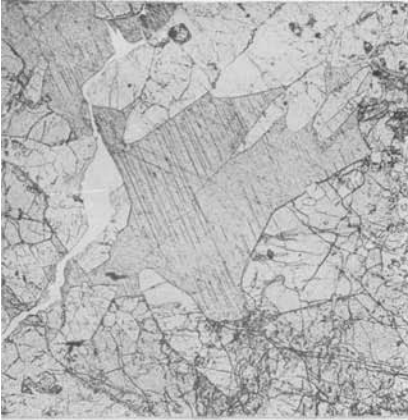


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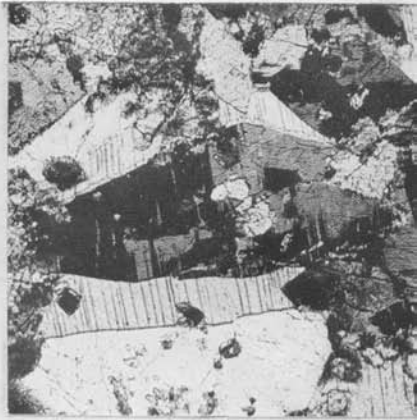


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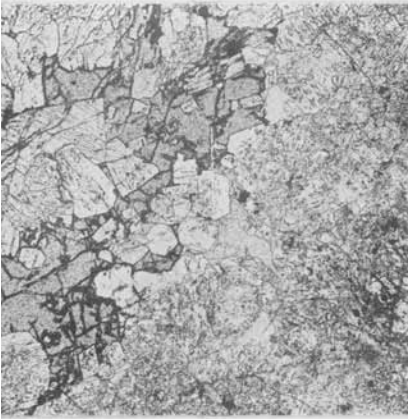
C. E. TILLEY: MARBLES AND SKARNS, KILBRIDE, SKYE



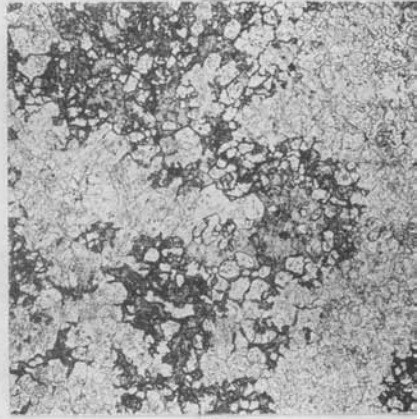
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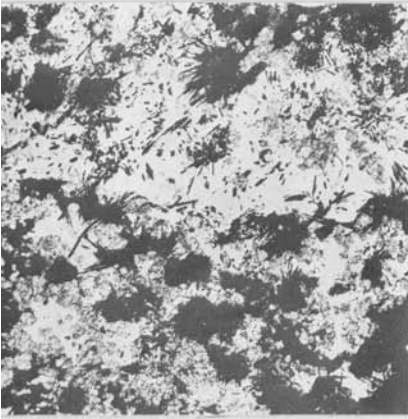
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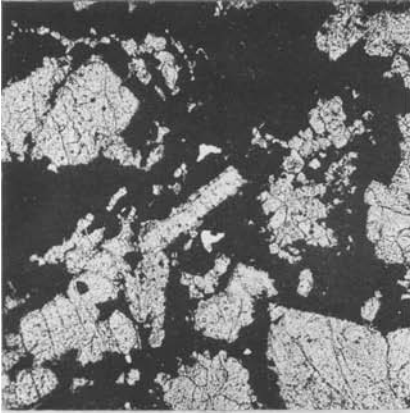


5



6

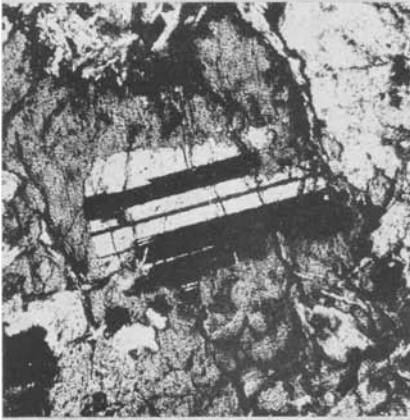
C. E. TILLEY: SKARNS, CAMAS MALAG AND KILBRIDE, SKYE



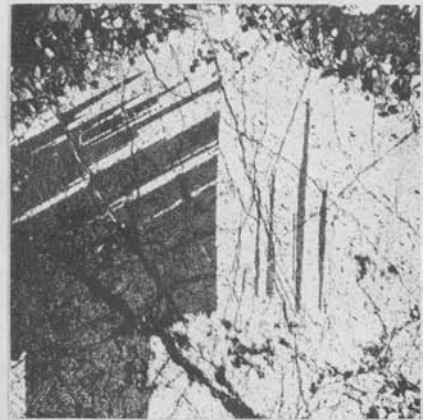
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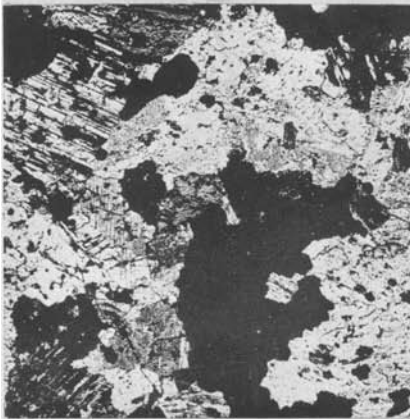
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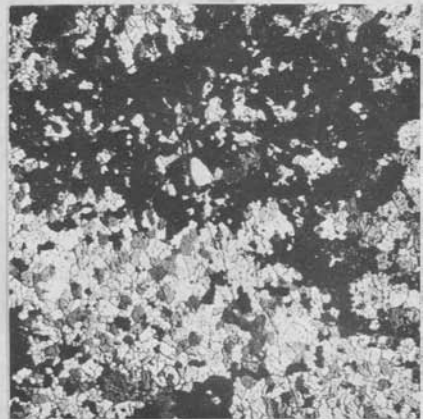
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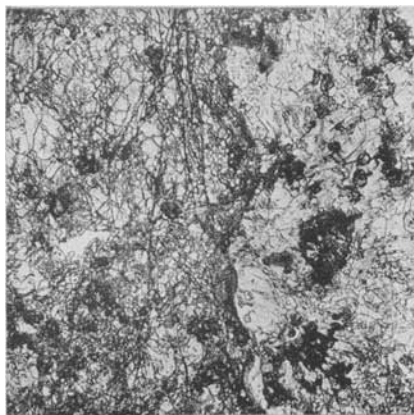


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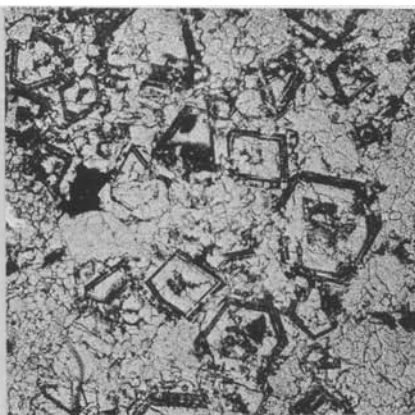


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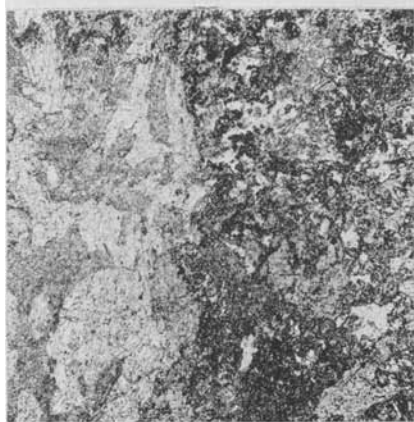
C. E. TILLEY: SKARNS, KILCHRIST AND KILBRIDE, SKYE



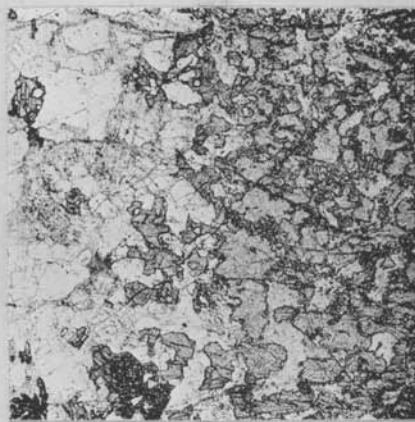
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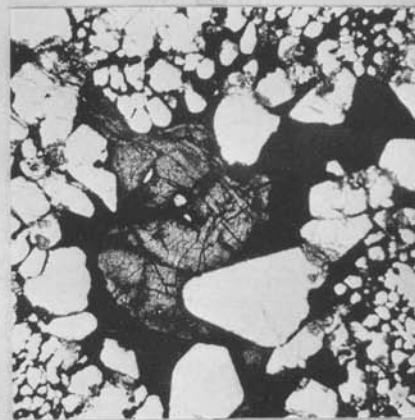
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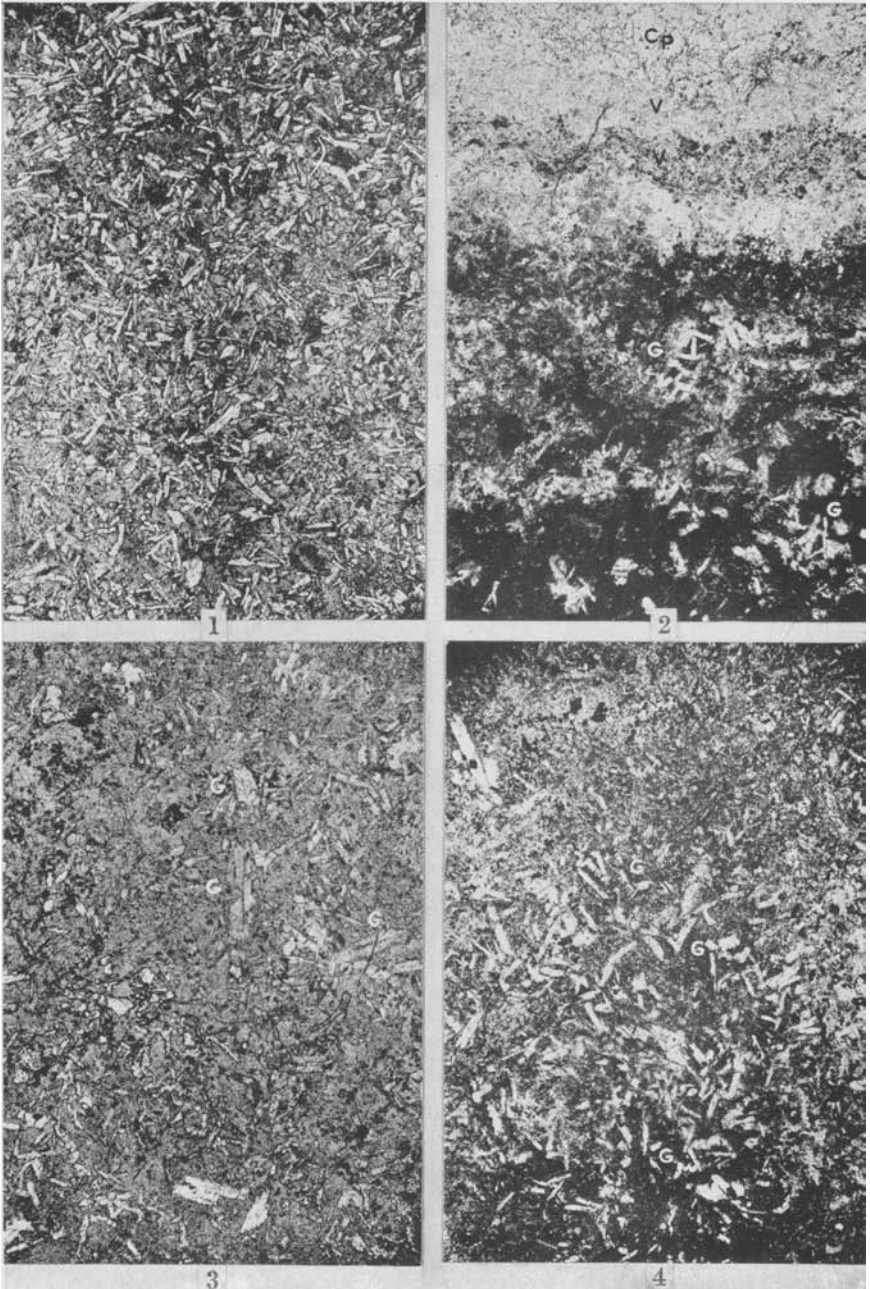


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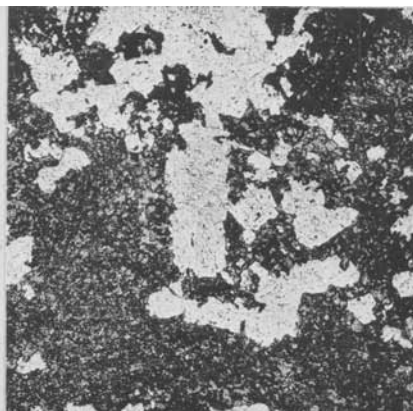
C. E. TILLEY: SKARNS, KILCHRIST, KILBRIDE, AND CAMAS MALAG, SKYE



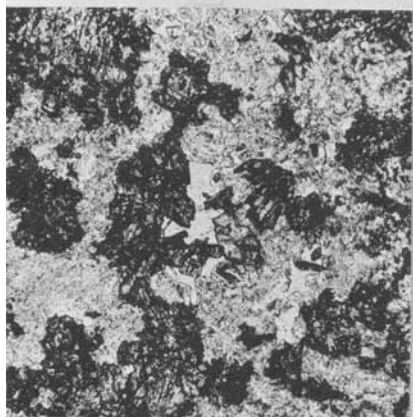
C. E. TILLEY: DOLERITE AND DOLERITE SKARN, KILCHRIST, SKYE



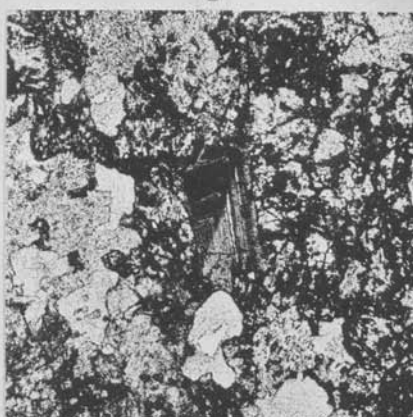
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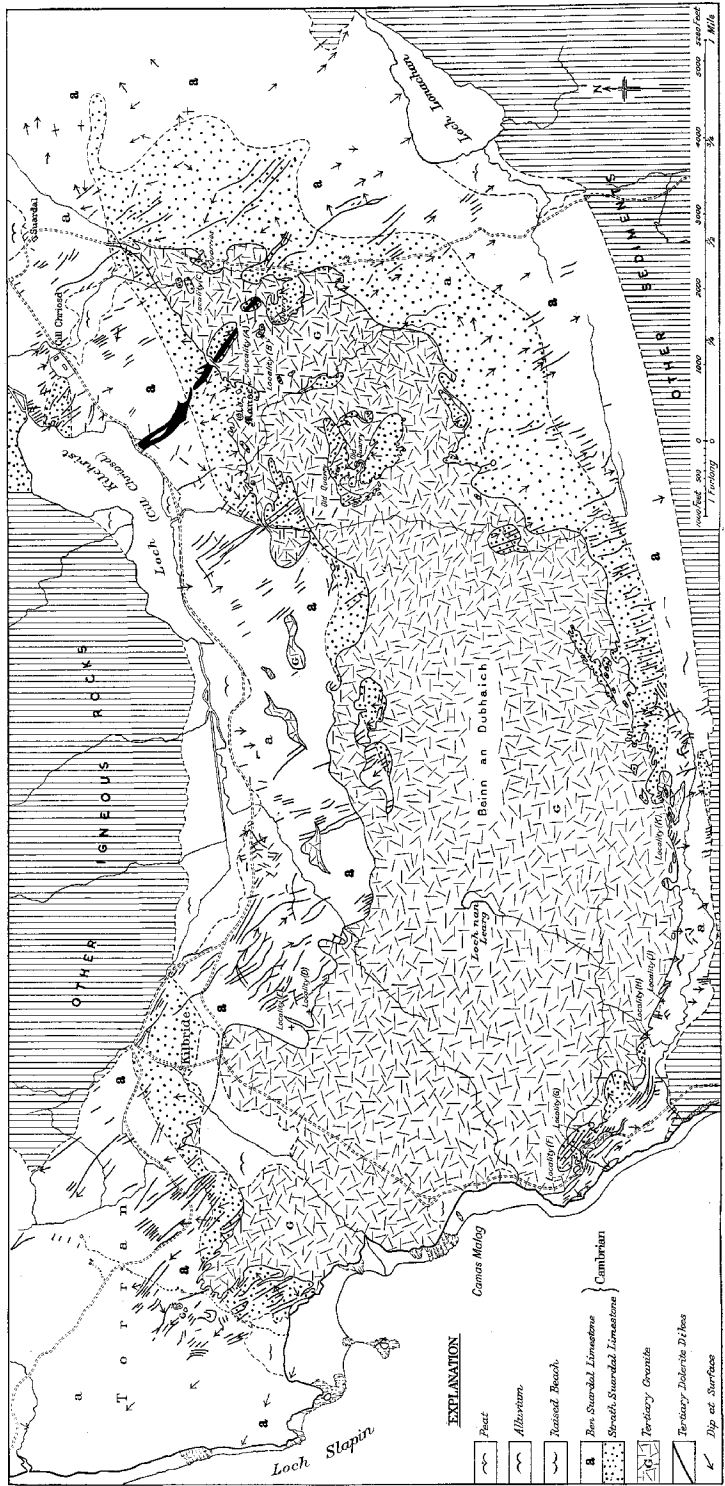


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6

C. E. TILLEY: ENDOMORPHIC SKARNS IN GRANITE, KILCHRIST, SKYE



EXPLANATION

- Peat
- Alluvium
- Tertiary Beach
- Ben Shuardal Limestone
- Strath Shuardal Limestone
- Cambrian
- Tertiary Granite
- Tertiary Diorite Dykes
- Dip at Surface

C. E. TULLY: GEOLOGICAL AND LOCALITY MAP OF DOLOMITE CONTACT ZONES AROUND THE BEINN AN DUBHAICH GRANITE, SKYE