Chapter 18 Rocks of Lower Old Red Sandstone age contact-alteration due to plutons

Contact-altered schists south-east of Loch Linnhe

Introduction including regional metamorphism

The various "granites" of the district were intruded into the schists after the latter had attained a low to medium grade of regional metamorphism. The "granites" have locally effected an easily recognisable alteration of a different type; new minerals and new textures have been produced, and the final result is a complete transformation. In the field the alteration reveals itself in such matters as loss of fissility, increased hardness, change of colour, and, in many cases, in the production of spots and sometimes of definite recognisable crystals. The features enumerated above are restricted to well-marked aureoles round about the "granites", and admit of fairly accurate mapping (Figure 39).

The "granites" are surrounded by a heterogeneous assemblage of schists, and the range of their influence is correspondingly varied. It is found, for instance, that impure limestones have been particularly susceptible, and have been converted into calc-silicate-hornfelses at distances ranging up to 1¾ miles from the margins of the various intrusions. Phyllites have been more stable, and are seldom noticeably hardened more than three-quarters of a mile from the "granites". On the other hand pyrites is more susceptible than even calcareous material (p. 251).

Introduction of magmatic felspar seems to have occurred to an important extent in the aureole of the Fault-Intrusion of Glen Coe (pp. 157, 219); and pronounced reactions with xenoliths have been carefully studied. Still, most of the changes which have taken place in the schists during contact-metamorphism appear to have depended upon simple reconstruction of the material already present, and upon a certain amount of expulsion of the volatile constituents, mainly carbon dioxide and water. It is an open question how much of these volatiles passed outward through country-rock, and how much inwards to be dissolved in magma. If much was taken into solution, it is probable that a considerable proportion was eventually discharged in volcanic explosions.

In its more important features the contact-metamorphism in the present district is identical with that of the Pass of Brander [NN 060 275] country to the south, already described by Teall (*in* Sum. Prog. 1899, pp. 83–8) and Kynaston (*in* Sum. Prog. 1898, pp. 88–90; Kynaston, Hill and others, 1908, chapter 10). Its phenomena are also closely similar to those recorded from other West Highland districts, such as Kilmelfort [NM 850 130] (Kynaston 1909, pp. 71–2), Glen Fyne [NN 200 140]–Garabal Hill [NN 305 175] (Clough 1897, pp. 98–101) and the Ross of Mull (Bosworth 1910).

Macculloch's account (1817, p. 126) of the marginal relations of the Ballachulish "Granite" affords the first reference to the phenomena of contact-alteration in Sheet 53. Professor Judd's short description (1874, p. 292) of the metamorphism produced in the schists by the Ben Nevis "Granite" is also worthy of note. Later, during the Geological Survey's work in the district, the subject has been frequently dealt with by the various members of the staff. Brief references and more detailed descriptions have thus from time to time appeared dealing with the contact-alterations of the schists due to the Ben Nevis (Ann. Rep. 1896; Sum. Prog. 1898, 1899, 1901), Mullach nan Coirean [NN 123 663] (or Meall a' Chaoruinn [NN 113 660]) (Sum. Prog. 1899), Ballachulish (Ann. Rep. 1897; Sum. Prog. 1903, 1904, 1905), ',Glen Coe (Sum. Prog. 1905; Clough, Maufe and Bailey 1909, pp. 636–8) and Cruachan (Sum. Prog. 1899, 1905) "Granites", and to the neighbouring smaller masses of diorite and kentallenite (Sum. Prog. 1905). The upshot is that Grant Wilson, in particular, clearly established the existence of definite contact-aureoles around the various plutonic masses, and that, in specimens from these aureoles, Teall, in the first instance, recognised actinolite, tremolite, malacolite, andalusite, and cordierite. All who have mapped in the district are agreed as to the distinctive characters assumed by the schists within these aureoles; in fact, it takes much experience of the district to correlate individual groups of the schists within and without the contact-aureoles.

In preparing the corresponding chapter in the 1916 edition of this memoir the writer received much assistance from Flett. What follows is very little altered, save that the rest of this introduction is devoted to a short summary regarding pre-contact regional metamorphism. Also advantage has been taken of three important papers, one by Neumann (1950, *see* Ballachulish Slates below), and two by Muir (1953a,b, *see* Appin Limestone and Quartz Xenoliths).

The main facts of distribution of regional metamorphism in Sheet 53 have been established by a number of workers, and, since the 1916 edition, have been made the subject of a couple of papers (Bailey 1923a; Elles and Tilley 1930). It is agreed by all that an ill-defined curving metamorphic boundary can be traced southwards from Fort William right across Sheet 53. West of this boundary grey pelitic sediments do not carry garnet, while to the east they very often do. Such a boundary is now termed an isograd.

The garnet isograd, starting from Fort William, reaches the north shore of Loch Leven a little west of the Glen Coe Quartzite outcrop, one mile east of Ballachulish Ferry [NN 053 598]. It then crosses the Loch to include on its garnet-bearing side a considerable proportion of the Leven Schist outcrop at the roadside east of the Ballachulish Pluton. From here it must swerve eastwards for about three miles, very probably with a bulge to the north-east somewhat as shown by Elles and Tilley in their coloured map. At any rate, turning south again it crosses Allt Socach a little upstream from the outcrop of the Sgòrr a' Choise Slide, and next, three miles to the south-west, the River Creran [NN 060 510] above the Salachail [NN 056 512] diorite. Then two miles farther still it passes close to Glenure House [NN 043 481].

The garnetiferous belt to the east generally begins with a wide stretch of country in which garnet is merely an inconspicuous accessory. Eventually, however, the mineral becomes very prominent, for instance in the Leven Schist spread south of the An t-Sròn "Granite" and east of the Beinn Fhionnlaidh [NN 100 500] out-outcrop of Glen Coe Quartzite towards Glen Etive. Blades of actinolite commonly accompany abundant garnet.

In Sheet 62 (Geol.), north of Sheet 53, the type outcrop of Leven Schist runs north-east towards Glen Spean [NN 230 817] into a highly garnetiferous region like that of Glen Etive. In Sheet 53 again, the Reservoir Schist passing the Blackwater Reservoir [NN 250 605] is in parts rich in garnet and actinolite.

In the other direction, west of the Fort William — Glenure line, metamorphism wanes, and the garnet zone is separated by a biotite zone from a chlorite zone in which biotite is wanting. The outcrop of the Eilde Flags at Fort William carries garnet, according to Elles and Tilley; but it has reached the chlorite zone before it finally goes out to sea west of Onich. The Appin Phyllites further east at Onich are still in the biotite zone; though rather unexpectedly the westernmost part of the Leven Schist outcrop north of Ballachulish Ferry [NN 053 598] seems to be in the chlorite zone. This alternation from west to east from chlorite to biotite and back again to chlorite may perhaps be due to the interaction of two opposing tendencies: (1) there is a tendency for the regional metamorphism to increase eastwards irrespective of structural position; (2) there is also an independent tendency, as we shall see demonstrated in Glen Coe, for this metamorphism to decrease at structurally higher levels; and it so happens that eastwards, between Onich and Callert, beyond Ballachulish Ferry [NN 053 598], one is dealing with a structurally ascending sequence. On the other hand it is possible that the Appin Phyllites at Onich have proved more susceptible to metamorphism than the Leven Schists north of the Ferry. One cannot be certain.

South of the mouth of Loch Leven Elles and Tilley have found biotite continuing in the Appin Phyllites south-west as far as Cuil Bay; though they note that it does not occur in the adjoining carbonaceous Cuil Bay Slates. We shall return to this last point presently. Meanwhile we note that the same authors place the south-west continuation of the Appin Phyllite outcrop, beyond Cuil Bay, into the chlorite zone, along with the greater part of the Leven Schist outcrop that lies to the east.

Much the most important phenomenon connected with regional metamorphism in Sheet 53 is the down-throw of slightly metamorphosed Leven Schist within the cauldron-subsidences of Glen Coe and Ben Nevis against much more obviously metamorphosed Leven Schist outside (pp. 71, 179). This long ago convinced Maufe (and now the writer) that the regional metamorphism of the district diminishes upwards. Accordingly we may interpret the garnet zone of the eastern half of Sheet 53 as dipping beneath the biotite and chlorite zones further west. Readers must consult Elles and Tilley (1930) for an alternative interpretation.

As might be expected the maps illustrating the writer's (1923a) and Elles and Tilley's (1930) publications agree fairly closely; but the 1930 map is superior in that it sets out to distinguish biotite and chlorite zones — the 1923a map merely shows where mica is conspicuous or inconspicuous as the case may be. Also Elles and Tilley are probably right in interpreting the eastward swing of the garnet isograd from the Ballachulish pluton to Allt Socach as connected with the pitch-depression that takes the outcrop of the Ballachulish Slide along Lower Glen Coe. On the other hand, it seems that these authors have sometimes been misled by not sufficiently recognising what a contrast of metamorphic response may be expected from rocks of different chemical composition. In the first edition of this memoir the following observation is recorded: — The Ballachulish Slates "have a very fine crystallisation, much finer than that of the Leven Schists on the one side of them or of the Appin Phyllites on the other. This denotes a selective metamorphism which is probably connected with the large amount of finely disseminated carbon present in the group" (Bailey *in* Bailey and Maufe 1916, p.202). Further experience in Scotland has confirmed such delay of metamorphism in carbonaceous rocks; and similar behaviour has been found in other countries. If allowance is made for this phenomenon, there is no reason to follow Elles and Tilley (1930, fig. 7) and admit a mechanically induced "break" in metamorphism associated with the Ballachulish Slide on the west side of the Callert exposure of the Ballachulish Core ((Figure 8), p. 50).

In conclusion one may recall, what is familiar to all Scottish geologists, that the mapping of metamorphic zones with reference to first appearance of certain selected index minerals was initiated long ago by George Barrow working in the East Highlands.

In what follows regarding the contact-metamorphism of the schists, the various formations are taken in order according as they are calcareous, dolomitic, pelitic or psammitic.

Ballachulish Limestone

In its purer portions the Ballachulish Limestone, where not affected by the "granites", is a dark-grey finely crystalline limestone with quartose bands and occasional cubes of pyrites (S15374) [NN 085 564]. The grey tint is due to disseminated black carbonaceous dust. Pale brown phlogopite and muscovite both occur as minor constituents. The following is an analysis by B. Lightfoot from Allt Socach (S15374) [NN 085 564]: SiO_2 12.70; Al_2O_3 4.10; Fe_2O_3 2.44; MgO 1.98; CaO 42.21; H_2O 0.91; CO_2 35.98; total 100.32. Restated in terms of major carbonates this gives: $CaCO_3$ 75.3; $MgCO_3$ 4.1; etc., 20–9.

More impure portions of the limestone (S12367) [NN 1930 5812], (S15375) [NN 100 544] contain much dolomite (determined by rough chemical tests), quartz, mica, and chlorite; the mica is in part muscovite, and in part a phlogopite approaching biotite, but not nearly so dark as the biotite of the pelitic schists of the district; the chlorite is colourless and often polysynthetic, and has a birefringence about equal to that of quartz; it appears to be primary (S12367) [NN 1930 5812], and occurs in the same way as the mica (*cf.* Flett 1902, p. 48). Irregular granules of sphene are also present in small amount. Regional tremolite has been recorded from the north shore of Loch Leven near Callert House [NN 092 604], and across the loch at Bridge of Coe [NN 104 589] (Elles and Tilley 1930, p. 640).

Minute pea-like concretions may occasionally be noted on the surface of the limestone: in some cases these consist of quartz and chlorite (S15429) [NN 094 684], in others of alkali-felspar with poikilitic inclusions (S11050) [NN 116 579]; (S39694) [NN 1171 5794], p. 74); similar spots of alkali-felspar are well-known in the pelitic schists of this and other districts.

Much of the Ballachulish Limestone is very impure (S15429) [NN 094 684]; (S15430) [NN 094 684]; (S15431) [NN 0944 6066], with calcareous matter occupying merely a subordinate position.

Contact-alteration of the purer type of Ballachulish Limestone

Contact-alteration of the purer type of Ballachulish Limestone has been studied in a suite of specimens taken from the western slopes of Glen Nevis (S15432) [NN 1181 7197]; (S15433) [NN 1181 7197]; (S15434) [NN 1235 7122]; (S15437) [NN 1235 7122]; (S15438) [NN 1235 7122] in the neighbourhood of the overlying Ballachulish Slates—here in the condition of hard, black, spotted cordierite-hornfels ((Figure 3), p. 39). The purer bands of the limestone retain their dark colour and the main part of their carbonates; they have, however, lost their disseminated quartz, where this was accompanied by other impurities in the original, and have developed numerous porphyroblastic crystals of tremolite ranging up to about an inch in length, and darkened with included carbon (S15433) [NN 1181 7197]. Similar crystals of tremolite are abundant in the Ballachulish Limestone outside the area of the map in the Spean section (Sheet 62, Geol.), north of Ben Nevis, where they owe their origin to regional metamorphism; but in Glen Nevis their restriction to the aureole of the Ben Nevis "Granite" renders it probable that they are of contact-origin. The dark tremolite-bearing limestone of Glen Nevis alternates with thin seams of calc-silicate-hornfels of the type to be described below. Nothing of the kind is found in the Spean, or for that matter anywhere in this neighbourhood outside the aureoles indicated in (Figure 39). These seams represent more impure laminae in the original limestone; at some distance from the margin of the Ballachulish Slates carbonate in bulk is no longer encountered, and the whole deposit is in the condition of calc-silicate-hornfels.

South of the Ballachulish "Granite" the purer part of the Ballachulish Limestone has suffered an interesting type of alteration which extends for a mile beyond the aureole drawn on the map. It loses much of its dark tint and, when freshly broken, emits a strong foetid odour. This is due to decomposition of pyrites (p. 251).

Dark limestones, or marbles, still rich in carbonates, are found among the representatives of the Ballachulish Limestone in the lower limb of the Ballachulish Fold within the contact-aureole of the Cruachan "Granite", east of Glen Creran. These occurrences are in Sheet 45 (Geol.), but their distribution is stated in Section F, Chapter 6.

Contact-alteration of the impure parts of the Ballachulish Limestone

Contact-alteration of the impure parts of the Ballachulish Limestone has usually resulted in the production of a fine-grained, pale-green or white, banded calc-silicate-hornfels. A small proportion of original calcareous material, after alteration, sets its stamp upon this hornfels, so that the distinction between impure Ballachulish Limestone and adjoining pelitic schist is accentuated, rather than otherwise, within the aureoles (Glen Nevis, (S6238) [NN 112 717]; (S6239) [NN 112 717]; (S8279) [NN 120 715]; (S8280) [NN 1343 7060]; (S15435) [NN 1235 7122]; (S15436) [NN 1235 7122]; (S15439) [NN 1235 7122]; (S15440) [NN 1235 7122]; (S15441) [NN 1235 7122]; (S15442) [NN 1235 7122]; (S15443) [NN 1235 7122]; Aonach Beag, (S13836) [NN 1946 7176]; (S13923) [NN 223 740]; Glen Coe, (S11048) [NN 1246 5702]; (S11049) [NN 1280 5667]; (S15871) [NN 125 567]; (S15872) [NN 125 567]; (S39692) [NN 1352 5663]; (S39693) [NN 1384 5665]; Windows of Etive, (S11485) [NN 1711 5032]; (S11486) [NN 1716 5023]; (S11625) [NN 1504 5208]; Beinn Ceitlein, (S11449) [NN 1818 5005].

Carbonates and quartz are only sparingly represented. The micas and chlorites have also been extensively attacked. Considering the variety of composition of the original limestone it is surprising to find that the contact minerals set up are few in number. Tremolite, malacolite (colourless diopside), and alkali-felspar are met with again and again. Epidote and zoisite are much more rarely found. Basic felspar has only been noted in a single slide (S11486) [NN 1716 5023], while wollastonite, garnet and idocrase have not been identified. As a matter of inference a portion of the calcite present may be regarded as of contact-origin resulting from dedolomitisation during the formation of tremolite. Sphene and rutile have recrystallised as accessory minerals.

Banded structures representing bedding are often prominent in these altered rocks. Some of the bands have a finely crystallised groundmass of tremolite, or closely related pale-coloured amphibole; their fracture tends to be rough, porous, and fibrous, and their colour varies in the hand-specimens from greenish-white (S6239) [NN 112 717] to nearly black. Other bands consist mainly of malacolite in small ragged crystals or finely granular aggregates, often associated with alkali-felspar; their fracture is very compact and flinty, and their colour is almost white (S6238) [NN 112 717]; (S8280) [NN 1343 7060]; (S15442) [NN 1235 7122]. Some thin black seams consist of undecomposed phlogopite (S15443) [NN 1235 7122].

While the calc-silicate-hornfelses are generally fine-grained, Peach and Maufe found a coarsely crystalline variety in the low, rocky ground south of the Glen Coe road, 400 yards W.N.W. of Clachaig Hotel. In the hand-specimen this variety is very beautiful, owing to an abundance of pale-green tremolite in stout prisms. Under the microscope the groundmass is seen to consist of alkali-felspar and malacolite, with undecomposed phlogopite, chlorite, calcite, and quartz (S11048) [NN

1246 5702]. Tremolite also occasionally occurs in large crystals in the calc-silicate-hornfelses of Glen Nevis (S6238) [NN 112 717] in the same porphyroblastic fashion as in the associated calcareous bands; the groundmass in such cases is sometimes rich in tremolite, sometimes in malacolite.

An unusual mode of occurrence for amphibole is represented in a few bands from the transition zone between the Ballachulish Limestone and the Leven Schists in Aonach Beag [NN 197 714] east of Ben Nevis and in the valley to the north. The amphibole in this case is green and pleochroic, and occurs in broad allotriomorphic crystals, building aggregates which appear as small spots in the hand-specimens; it may perhaps be replacing garnet. In the same rock (S13836) [NN 1946 7176]; (S13923) [NN 223 740] epidote is very abundant, occurring in flat prisms disposed along the foliation. Quartz and felspar are also much in evidence, with subordinate flakes of biotite.

The impression is formed, on looking through a large suite of slides of these calc-silicate-hornfelses, that there is an ill-defined tendency for special association of malacolite and alkali-felspar. Sometimes, as in the tremolite rocks of Glen Coe already mentioned, the felspar occurs in fairly large crystals and encloses curious confluent beaded aggregates of malacolite, thus giving rise to a variety of poikilitic structure. In other cases where the foliation is fairly well preserved, the felspar is often granular, and the malacolite occurs in ragged crystals or granules (S6238) [NN 112 717]; (S15436) [NN 1235 7122]; (S15442) [NN 1235 7122]. In all the calc-silicates, lenticular eyes of alkali-felspar and malacolite are met with in which the malacolite occurs in larger individuals with fair crystal boundaries. Occasionally a flinty band is found consisting almost wholly of granular malacolite (S8280) [NN 1343 7060].

An exceptional variety of the metamorphosed Ballachulish Limestone was collected by Maufe, near Clachaig Hotel, Glen Coe, in association with normal calc-silicate-hornfelses well developed at this point. Zoisite occurs in this rock in abundant stout prisms, a couple of inches long, in a base consisting of abundant quartz, muscovite, and phlogopite (S11049, (S15872) [NN 125 567]. From the prevalence of micas and the absence of the normal contact-minerals, it is obvious that the production of the zoisite here must be due to a very low grade of contact-alteration unless, indeed, it should be referred to an abnormal phase of regional metamorphism.

A limited amount of interaction. between the limestone and the invading "granite" can sometimes be made out with fair probability. A specimen (S15370) [NN 1390 7180] collected by Maufe from the Ben Nevis path has an igneous aspect; it consists in the main of dark greenish-brown hornblende, up to half an inch in length, lying without orientation in a medium-grained allotriomorphic base made up of small crystals of orthoclase, with less abundant oligoclase, malacolite, sphene and a little quartz. The dark hornblende is bordered by pale-green hornblende and malacolite. There can be no question but that this rock is closely linked with the calc-silicate-hornfelses, while the dark colour of the hornblende and the excessively felspathic nature of the groundmass suggest addition of material from the neighbouring "granite".

Turning now to the texture of the calc-silicate-hornfelses, we have noted already that original bedding is retained intact. Foliation has also in many cases been preserved, although less perfectly; tremolite, malacolite, and felspar often show a more or less definite orientation, least marked in the case of the felspar. In such cases it is frequently evident that the foliation now apparent is merely a relict structure, and that it was originally determined by the presence of minerals of micaceous habit, subsequently destroyed (S15440) [NN 1235 7122]. In other instances it is not uncommon to find the foliation more or less obliterated: the felspars may grow in large crystals, enclosing granular aggregates of malacolite in poikilitic fashion, or the tremolite may build radiating felted aggregates (S6239) [NN 112 717].

Chemistry of the changes involved in contact-metamorphism of the Ballachulish Limestone

The chemistry of the changes involved in contact-metamorphism of the Ballachulish Limestone has not been investigated by analysis, but certain main principles can be laid down, as a result of microscopic investigation. In the first place, the reactions have proceeded in such a manner as to eliminate, more or less completely, the volatile constituents, carbon dioxide and water — though Allen and Clement (1908, p. 101) have shown that tremolite and malacolite (diopside) both contain water, apparently in solid solution. Another leading principle is that the magnesia at any point has been satisfied with silica before the lime — Teall's dedolomitisation principle (1903).

In no case investigated has the silica: magnesia ratio of the Ballachulish Limestone fallen beneath that required to give tremolite, for brucite and forsterite are absent. The development of tremolite in place of malacolite seems to have been determined by the following conditions. All the magnesia present at any particular point must be accommodated with silica. If possible it enters the compound malacolite, CaO. MgO. 2 SiO_2. If there is a deficiency, either as regards silica or lime, tremolite, CaO_3 MgO. 4 SiO_2, results instead. Thus it happens that among the altered limestones of Glen Nevis tremolite occurs both in highly calcareous bands, free from quartz (S15437) [NN 1235 7122], and also in highly quartzose bands, free from calcite (S15441) [NN 1235 7122].

The occurrence of tremolite in bands free from calcite, or other lime minerals, such as wollastonite, idocrase, or garnet, immediately suggests a problemmalacolite is not here classed as a lime mineral because its molecular ratio of CaO: MgO is only unity. The production of tremolite from dolomite and silica involves the simultaneous formation of calcite-

3(CaO. MgO. 2 CO_2)+4 SiO_2 (Dolomite + Quartz)

= CaO_3 MgO. 4 SiO_2+2(CaO. CO_2)+4 CO_2 (Tremolite + Calcite + Carbon dioxide)

It is true calcite thus produced may elude detection through its power of segregation, or perhaps its lime may be removed in some form in solution; but in many cases the absence of calcite is probably due to its interaction with non-calcareous ferromagnesian minerals. One must remember that much of the Ballachulish Limestone is a pelitic or psammitic sediment with only a subordinate amount of carbonate. Phlogopite and chlorite are rarely preserved in the calc-silicate-hornfelses, and cordierite, which, as we shall see presently, is the characteristic ferromagnesian mineral of the pelitic hornfelses, is entirely absent. It would appear, therefore, that the phlogopite and chlorite have been destroyed, and that their magnesia has gone to build up tremolite or malacolite, as the case may be.

The destruction of phlogopite and chlorite referred to above is of course accompanied by an expulsion of water. The same principle is involved in the decomposition of muscovite. How important the metamorphism of the micas has been is attested by the abundance of alkali-felspar in the calc-silicate-hornfelses. It would be interesting to ascertain the final destination of the excess of alumina liberated as a result of the change of the micas and chlorite. It seems fairly certain that it, and also the iron derived from phlogopite, chlorite, pyrites, etc., must have been taken up by the pyroxenes or amphiboles so abundantly developed, although the latter agree closely in character, and presumably in composition, with the ideal non-aluminous silicates, malacolite and tremolite (*cf.* Flett 1909, p. 100). It has already been stated that the malacolite of these rocks seems particularly prone to be associated with alkali-felspar, and accordingly it would not be surprising to find that it has accommodated the main part of the excess alumina.

Appin Limestone

The most prevalent type of Appin Limestone is a cream, pink, or very pale blue magnesian limestone or dolomite (S15376) [NN 2030 6143]; (S15377) [NM 9853 5915]; (S15378) [NM 9350 4941]. No staining tests have been undertaken, but the analyses of (Table 4) indicate a prevalence of magnesian carbonate not encountered among the purer forms of the Ballachulish Limestone. The texture is fine- to medium-grained.

The Appin Limestone enters the *contact-aureole* of the Ballachulish"Granite" at seeral points. Specimens taken from exposures a little west of the path leading from Ballachulish to Glen Creran are of exceptional interest, for they recall precisely the features described by Teall (1907, chapter 31) as characterising the Durness Dolomite in the aureoles of the Ledbeg Syenite, Sutherland, and of the Skye gabbros and granites.

(Table 4) Analyses of Appin Limestone

	1	2	3	4	5	6	7	8	9	Dolomite
SiO_2	3.4	13.9	1.9	1.3	3.5	3.3	25.9	3.7	—	—
AL_2O_3	1.2	5.3	1.8	—	2.1	—	5.0	—	—	—
Fe_2O_3	-	5.1	1.3	—	3.3	—	1.8	—	—	—
FeO	0.2	—	—	—	—	—	—	—	—	—
MgO	9.0	8.0	18.5	20.0	17.1	21.8	5.4	20.9	18.4	21.8

CaO	42.5	33.7	31.7	30.7	29.7	291	28.9	28.9	26.7	30.4
CO_2	431	34.3	44.6	45.9	44.0	46.8	29.3	45.6	41.1	47.8
Etc.	0.5	0.2	0.9	—	—	0.6	4.1	—	13.1	—
Total	99.9	100.5	100.7	—	100.2	—	100.4	—	—	100.0
$MgCO_3$	18.8	15.2	38.0	41.8	35.7	45.7	11.4	43.8	38.6	45.7
$CaCO_3$	75.6	60.0	56.4	54.8	52.9	52.0	51.6	51.6	47.6	54.3
Surplus MgO	0.0	0.8	0.4		0.0		0.0			0.0
Surplus CO_2	0.0	0.0	0.0		2.1		0.9			0.0

1. Waterfall in stream 50 yd E. of Kentallen railway station (contact-altered). Anal. I. D. Muir.
2. Onich shore, 400 yd W. by S. of church (S15376) [NN 2030 6143]. Anal. B. Lightfoot.
3. Three hundred yards above path S.W. of Sgòrr a' Choise (contact-altered, S 15379, 15380). Anal. B. Lightfoot.
4. Dalnatrat [NM 968 533], near Duror station. Supplied by Stewarts and Lloyds, Ltd.
5. Hillslope, 200 yd N.E. of Portnacroish [NM 926 474] (Appin station). Anal. B. Lightfoot.
6. Dalnatrat [NM 968 533], near Duror station. Supplied by Steetley Lime and Basic Co., Ltd.
7. Marble Quarry [NN 080 574], pathside, River Laroch [NN 080 560], 660 yd S. of Laroch Bridge, Ballachulish. The full analysis by A. Muir and H. G. M. Hardie (1956, p. 20) shows Na_20 1.95, K_20 1–00.
8. Tributary of River Laroch [NN 080 560], 660 yd S. 23°W. of Laroch Bridge, Ballachulish.
9. East of Duror railway station.

Pure dolomite is quoted for comparison.

Analyses of xenolith and of contaminated and normal Ballachulish quartz-diorite

	A	B	C	D	E	F
SiO_2	54.73	59.24	62.51	59.81	59.11	51.61
Al_2O_3	742	20.80	19.10	16.61	17.85	2.18
Fe_2O_3	1.71	0.29	0.65	1.50	1.78	1.04
FeO	5.03	0.99	0.41	2.80	3.24	9.28
MgO	8.11	1.20	0.23	2.49	3.85	11.29
CaO	18.32	7.13	2.01	3.20	5.05	22.86
Na_2O	2.35	7.47	218	3.49	4.10	0.43
K_2O	1.19	0.85	11.47	7.92	3.06	0.07
Etc.	1.05	2.22	1.50	2.05	1.66	1.09
Total	99.91	100.19	100.06	99.87	99.70	99.85

Analyses by I. D. Muir (1953a).

1. Xenolith of Appin Limestone transformed through immersion in Ballachulish quartz-diorite (see E. below). The specimen was taken 50 yd from 1 of previous Table.
2. Plagioclase zone enveloping A, and 1–2 inches thick.
3. Potash syenite zone enveloping B, 3 inches.
4. Augite-syenite zone enveloping C, a few inches.
5. Quartz-diorite of Ballachulish Pluton unmodified by Appin Limestone.
6. Diopside from D.

The contact-metamorphism does not notably increase the coarseness of texture of the altered limestone, but produces a grey tint in it which is often associated with an extremely rough manner of weathering. The grey shade is due to finely disseminated minute black pseudomorphs after forsterite. The rough weathering, as Teall has shown in a cognate case, depends upon the presence of residual dolomite side by side with calcite; brucite is represented on the roughened surface by very small pits occurring indifferently in the dolomitic excrescences and the calcitic hollows. Isolated little rounded crystals of forsterite, Mg_2SiO_4, often more or less altered to chlorite or serpentine giving very low polarisation tints (S13932) [NN 061 532], are easily identified under the microscope. The brucite appears as colourless and transparent spots of slightly larger size, which between crossed nicols break up into aggregates of more or less wavy, parallel scales with a moderate birefringence (S13930) [NN 061 532]. Obviously this scaly mineral is a secondary product, and its recognition as brucite is based upon a comparison with slides described by Teall (S9208) NC 244 138]; no doubt the brucite, $Mg(OH)_2$, replaces periclase, MgO, the crystal form of which is sometimes suggested by the shape of the transparent spots.

Thus the Appin Limestone in this exposure, and also east of Glen Creran (Section F, chapter 6), illustrates the phenomenon of dedolomitisation in a rock in which the silica: magnesia ratio is lower than that required to yield tremolite; and such is often the case with the Appin Limestone. Anal. 3 is of a grey specimen from the contact zone. It shows only slight dedolomitisation, because it contains so little silica that the amount of forsterite formed has been but trivial, while the more advanced change of dolomite to periclase does not seem to have taken place.

Various names have been given to dedolomitised marbles with the characters described above. Marbles consisting of calcite and serpentine, in most cases apparently derived from forsterite, are known as ophicalcites. Marbles, on the other hand, consisting of calcite and brucite are known either as pencatites or predazzites. Harker, in his account of the dedolomitised limestones of Skye (1904, p. 150), states that "it is most in accordance with the original usage to employ the name pencatite for an aggregate of calcite and brucite in equal molecular proportions, i.e. with the percentage composition of 63.3 calcite to 36.7 brucite, reserving the name predazzite for varieties richer in calcite."

A special study has been undertaken by Muir of xenoliths of Appin Limestone immersed in the quartz-diorite of the Ballachulish Pluton (1953a). The locality is in a stream 50 yards south of Kentallen railway station, 10 yards in from the pluton's margin and 150 yards from the coast. The xenoliths are pale green slabs, up to 3 feet in diameter and 3 inches in thickness (Anal. A, (Table 4)). They are bordered externally by successive distinctive zones (Anals. B-D) due to contamination of the surrounding quartz-diorite (Anal. E). Anal. 1, shown above, is from an Appin Limestone outcrop 50 yards downstream. Unfortunately the junction of this band with the quartz-diorite is not exposed.

Muir assumes that the xenoliths (Anal. A) had originally the same composition as the *in situ* limestone (Anal. 1). This seems uncertain since the xenoliths might quite possibly have been derived from some portion of the formation with a different composition, such as, for instance, that shown in Anal. 7 with its Na_2O 1.95 and K_2O 1.00. Be this as it may, Muir's main points seem firmly established. Early crystallisation of diopside and plagioclase within (Anal. A) and about (Anal. B) the xenolith have led to enrichment of the succeeding zones (Anals. C, D) of the quartz-diorite (Anal. E) in potash felspar, some residual, some refugee. We are furnished with a good example of what D. L. Reynolds would call a potash front.

Leven, Binnein, Eilde and Reservoir Schists. — The Leven and older micaschists are sufficiently alike to be taken together in this account. The Leven Schists enter the aureoles of the Ben Nevis, Mullach nan Coirean [NN 123 663], Ballachulish, Fault-Intrusion of Glen Coe, and Cruachan "Granites"; while the Binnein and Eilde Schists are affected by the Fault-Intrusion of Glen Coe; and the Reservoir Schists by the Moor of Rannoch "Granite". All the slices quoted below come from the Leven Schists unless otherwise stated.

The Leven Schists, it will be remembered, are widely developed in the chlorite, biotite and garnet zones of regional metamorphism. A characteristic type is a grey phyllite or mica-schist, carrying small porphyroblasts of brown, highly pleochroic biotite, and much less frequent garnet, in a base of muscovite, quartz, and alkali-felspar, the last-named often in very small amount (Plate 12)A. Irregular grains of iron ore are always present, and epidote is often a conspicuous accessory (S11618) [NN 1126 5486]; tourmaline and zircon occur as very minor constituents. In the banded group, near the margin of the Glen Coe Quartzite, there are fine-grained seams of a dark tint, probably due to disseminated carbon. Similar dark bands occur also at the quartzite margins of the Binnein and Eilde Schists (S12925) [NN 139 620].

Green chlorite has frequently arisen through the weathering both of biotite and of garnet; and sometimes it plays an important role as a primary mineral along with the muscovite of the base (S11619) [NN 1131 5474]. Biotite commonly occurs in the groundmass of the Binnein and Eilde Schists (S12362) [NN 1427 6084]. The alkali-felspar generally forms irregular water-clear grains associated with the quartz, which at times it almost equals in amount. In other cases the felspar has segregated into small round crystals, including quartz in poikilitic fashion (S12361) [NN 1348 6082]. Such crystals sometimes show indications of the microcline type of twinning, in which case they are probably orthoclase, including microcline. The occurrence of alkali-felspar with this habit, as the result of regional metamorphism, is not at all infrequent.

Most of the rocks of the Leven Schists, outside the "granite" aureoles, have a very perfect wavy foliation, owing to the regular orientation of the muscovite and to the lenticular arrangement of the quartz granules in between. This foliation may make any angle with the bedding (S11620) [NN 1159 5455], and may itself be crossed by a later strain-slip cleavage. The arrangement of the biotite porphyroblasts is distinctly less regular than that of the muscovite flakes in the groundmass. While marked schistosity is so common, it is not the invariable rule. Occasionally a quartzose band occurs consisting for the most part of small, evenly distributed grains of quartz and flakes of mica, with so little orientation that there is an approach to the "cobble-structure" more characteristic of hornfelses.

In the Leven Schists, near the various "granite" masses, both andalusite and cordierite are of widespread occurrence; while corundum has been found in certain xenoliths of Eilde Schists (S11519) [NN 1592 5970]. Sillimanite has only been detected in a couple of xenoliths (S10309) [NN 134 549], (S10310) [NN 136 558] from the An t-Sròn "Granite" (Fault-Intrusion of Glen Coe). It is associated with corundum, and the second of the two slides mentioned is a very typical example of sillimanite-cordierite-corundumhornfels rich in almost opaque green spinel.

The andalusite is very easily recognised in thin slices owing to its high refractive index; very occasionally, too, it shows strong pleochroism (S15450) [NN 1732 6938]. In form its crystals are, as a rule, intensely irregular, but all the same they not infrequently possess rectangular boundaries parallel to a prismatic cleavage. Although the mineral can rarely be determined in the field, it is responsible for many of the excrescences which weather out on the surface of the hornfelses (S11484) [NN 181 485]; there are, moreover, capital exposures, just at the margin of the map, at the edge of the Ben Nevis "Granite", north of Aonach Mòr [NN 193 730], where certain bedding surfaces of the Leven Schists are covered with prominent little prisms of andalusite about three-eighths inch long (S13921) [NN 199 734]; very conspicuous crystals of the mineral are also exposed in Reservoir Schists in the bed of the river Leven, a third of a mile west of the Moor of Rannoch "Granite". It is generally admitted that the presence of andalusite in an aureole, in place of sillimanite, shows that the granite responsible for the metamorphism was not excessively hot.

Cordierite is often more conspicuous in the field than under the microscope. The mineral tends to occur in spots, sometimes slightly elongated along the foliation, and these weather freely, leaving a pitted surface. Glen Nevis affords a magnificent series of spotted cordierite-hornfelses belonging to the Leven Schist Group.

When examined under the microscope the cordierite is not easy to detect until a considerable familiarity with the mineral has been obtained. It never builds regular crystals, and its refractive index and birefringence make it closely resemble quartz and the felspars. It sometimes occurs in bundles of crystals with subparallel orientation (S13921) [NN 199 734], and it also frequently shows very complicated twinning (S13837) [NN 1935 7186], so that between crossed nicols it attracts attention by a patchy uncertain illumination. In other cases where the crystals extinguish uniformly, their comparatively large size may help to distinguish them from associated grains of quartz and felspar. Cordierite too, in the rocks under consideration, has a distinct tendency to enclose rather numerous small crystals of magnetite, and its presence is often betrayed in consequence. As confirmatory tests we may rely upon the straight extinction referred to the cleavage, the mode of weathering, the wide-angled biaxial figure, and above all the faint, often very faint, yellow pleochroic halos round inclusions of zircon.

Other mineral changes go hand in hand with the production of the andalusite and cordierite. They are the destruction of muscovite, chlorite, garnet, and quartz, and the building up of felspar, in the main of alkali composition. Biotite is probably decomposed to a considerable extent, too, in many cases; but this is often merely a matter of inference (see below), for recrystallised, or freshly synthesised, biotite is a characteristic constituent of most of the hornfelses. In the contact-metamorphism of the igneous rocks, to be discussed in a later section of this chapter, biotite has been synthesised very freely indeed. The completeness of the destruction of the muscovite depends upon the conditions of the metamorphism: round the Fault-Intrusion of Glen Coe there seems to have been a regeneration of muscovite at a late stage, in a manner suggesting pneumatolysis; it will be remembered that permeation phenomena are well marked in this same zone. The destruction of quartz is a by-process, as it were, of the other reactions; such quartz as is not required to help build up the andalusite and cordierite merely recrystallises without change. Magnetite is liberated in some of the reactions, such as the destruction of the garnets, and is perhaps absorbed in other reactions, such as the recrystallisation or synthesis of biotite. It is more idiomorphic in the hornfelses than in the original schists.

The destruction of muscovite and chlorite leads to the elimination of the volatile constituent water, and so, as has been pointed out in connection with the alteration of the limestones, has much in common with the decomposition of calcite and dolomite. The replacement of garnet is of course on a different footing; like the disappearance of quartz in so many of these rocks it may perhaps be a secondary reaction involved in the destruction of the muscovite.

There can be no reasonable doubt that andalusite has arisen according to the following equation:

$H_2KAl_3(SiO_4)_3 + SiO_2 = Al_2SiO_5 + KAlSi_3O_8 + H_2O$

Muscovite + Quartz = Andalusite + Orthoclase + Water

The association of andalusite with alkali-felspar required by this equation is of extremely common occurrence in the Leven Schist hornfelses. A simple example from Beinn Ceitlein, east of Glen Etive, has thin dark layers rich in biotite, separated by quartzose layers, in which granules of quartz occur in a matrix made up of small grains of alkali-felspar and large exceedingly irregular crystals of andalusite, the latter in part altered to shimmer aggregates (S11484) [NN 181 485]. A specimen from the margin of the Ben Nevis "Granite" illustrates the alteration of a less siliceous rock where all the quartz has been required to carry through the reaction. It consists of layers, some mainly composed of andalusite and others of cordierite (Plate 12) C. Biotite in small, oblong crystals is fairly abundant, and has no parallel orientation, but instead is collected into nests and layers for the most part attached to crystals of iron oxide. The central portions of the andalusite crystals are sometimes solid, but the outer portions are built up of an infinite number of minute parallel rods, and between these rods a high power objective reveals alkali-felspar with a refractive index lower than balsam.

While most of the felspar in these hornfelses is alkali-felspar, instances are known in which andesine occurs. This is the case in a specimen taken, like the last, from near the border of the Ben Nevis "Granite". Andalusite and cordierite are commingled here instead of being in separate layers (S13921) [NN 199 734]. The matrix between the various crystals of these two minerals carries abundant biotite, with more or less parallel orientation, associated with granular andesine; there is also a small amount of muscovite present. The andesine is distinguished from cordierite through a tendency to central decomposition and a faint zonal structure. Its lowest refractive index, by comparison with balsam, appears to be rather higher than the lowest of quartz, while a grain examined in convergent light proved to be optically neutral; it may be taken as andesine with 30–40 per cent. anorthite, and it has probably derived its lime from epidote in the original schist.

In a specimen of Reservoir Schist, 300 yards from the edge of the Moor of Rannoch "Granite" (S11529) [NN 2422 6053], there is much andalusite, but so little felspar that one is tempted to suppose that alkali may have been used up in regenerating biotite from chlorite, or in some such change. Muscovite and quartz are both still well represented in this rock.

The development of corundum may be taken as a result of the decomposition of muscovite in the absence of sufficient quartz to yield andalusite.

$H_2KAl_3(SiO_4)_3 = KAlSi_3O_8 + Al_2O_3 + H_2O$

Muscovite = Orthoclase + Corundum + Water

Corundum was first found in the West Highlands by Teall among the hornfelses bordering the Cruachan "Granite" in Sheet 45, Geol. In the district at present dealt with the mineral is apparently restricted to xenoliths. It is quite common in enclosures of Eilde Schist in the Fault-Intrusion of Glen Coe (S11519) [NN 1592 5970]

It is impossible to write down equations for the production of cordierite $(Mg,Fe)_4Al_4Si_5O_{18}$ owing to the indefiniteness of its own composition and of those of the minerals from which it must have derived its magnesia and iron. Three possible sources of magnesia and iron are present in the unhornfelsed schists, to wit, biotite, chlorite, and garnet. Writing biotite $(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$ it appears that, making allowance for the alumina and silica which will be retained by the potash to yield felspar, additional alumina and silica will be required to convert all its magnesia and iron to cordierite; these constituents will be derived from reaction with muscovite and quartz respectively. The same two minerals will also be called upon to help in the production of cordierite from chlorite $H_{40}(Fe,Mg)_{23}Al_{14}Si_{13}O_{90}$. As for garnet, without a local analysis it is not worth while writing down a formula.

Turning to the slides we find cordierite occurring in two distinct ways. It either forms part, or nearly the whole, of certain pseudomorphs after chlorite (or perhaps biotite) and garnet, or else it builds aggregates, or spots, and other independent growths. In the pseudomorphs which appear to be after chlorite, the cordierite is found forming the termination of biotite porphyroblasts, and enclosing lines of magnetite which obviously mark the former position of biotite cleavages. It seems probable in such instances that first the biotite has weathered terminally yielding chlorite with the usual discharge of iron oxides, and then this chlorite has been itself metamorphosed to cordierite. The change is well illustrated in a series of specimens (S8269) [NN 117 494]; (S8270) [NN 112 505]; (S8271) [NN 112 505] from ¾ mile north of the Cruachan "Granite", and in a slide from Glen Nevis (S15447) [NN 1589 6849]. The replacement of garnet by biotite, cordierite, and magnetite, with, in certain cases, muscovite and quartz, is represented in the slides just noted from the north of the Cruachan "Granite" (Plate 12) B. It is also shown in a specimen from the road-cutting, ½ mile east of the Ballachulish "Granite" (S15368) [NN 0640 5880], and in another from the Glen Nevis gorge, ¼ mile from the Ben Nevis "Granite" (S15870) [NN 1746 6897].

It is probable that the garnets, like the biotites, were in part changed to chlorite before the intrusion of the granites. At the same time it is fairly certain that garnets not previously chloritised have also been pseudomorphed, since only one slide in the collection (S11785) [NN 1680 4927] shows a highly altered rock retaining any garnet at all; and, in this case even, the garnet occurs as mere remnants in the heart of a cordierite pseudomorph.

That cordierite has sometimes derived its ferromagnesian constituents at the expense of biotite is inferred because neither chlorite nor garnet seems to be present in sufficient quantity in the unmodified Leven Schists to account for the great abundance of cordierite developed in the hornfelses.

Before passing on to consider the somewhat aberrant types from the neighbourhood of the Fault-Intrusion of Glen Coe, a few words may be said about the texture of the rocks already dealt with.

A remarkable amount of contact-alteration may take place without deleting the original schistose texture (*cf.* Barrow 1909, p. 84; Flett and Barrow 1910, p. 64). Andalusite is sometimes abundantly developed in a muscovite-biotitegneiss or schist in which the micas retain their original orientation with great perfection ((S11529) [NN 2422 6053], Reservoir Schist). Cordierite spots in their earlier stages are but meshworks, including mica flakes and quartz lenticles still evenly arranged (S15444) [NN 138 687].

In advanced stages, however, texture is revolutionised: foliation can scarcely be recognised under the microscope; all muscovite is gone; biotite is in clusters of oblong crystals round grains of magnetite (S13837) [NN 1935 7186], or in isolated flakes in a felspathic ground between crystals of the now dominant andalusite and cordierite (S13921) [NN 199 734]; where andalusite and biotite occur in small amount the resulting rock has a well-defined "cobble-structure" designed in quartz, felspar, and cordierite, the latter accompanied by the usual small crystals of magnetite (S15445) [NN 1455 6931]; (S15446) [NN 1460 6944].

The Fault-Intrusion's contact-metamorphism seems often pneumatolytic with muscovite an important end product. In an Eilde Schist specimen (S15363) [NN 1875 5946] from near the "granite" margin, in the tributary valley entering Allt Coire Mhorair [NN 195 600], north of Glen Coe, very little quartz is left, and it is in an obviously highly corroded condition, and surrounded by alkali-felspar. Most of the rock consists of muscovite, with a tendency to bushy growth, and associated biotite. Porphyroblasts of the last-named are in part replaced by muscovite, especially at their margins. Irregular crystals of andalusite, with late-formed quartz moulded upon it, are also present in the closest possible conjunction with the muscovite.

In a Leven Schist specimen (S11622) [NN 1186 5471] taken by Maufe, at 100 yards from the An t-Sròn "Granite" of Glen Coe, the original foliation is merely indicated by a certain elongation of the quartz grains; the latter lie in a recrystallised matrix of cloudy alkali-felspar and unorientated muscovite. The porphyroblasts of biotite are easily recognised, but their outer portions are replaced by muscovite, and their kernels, apparently as a result of recent weathering, by chlorite. The muscovite throughout has a brush-like tendency of growth.

At two feet from the same "granite", further south, at the head of Gleann Fhaolain [NN 150 520], the Leven Schist has entirely lost its schistose structure (S11626) [NN 1312 5376]. There is a considerable amount of quartz, but this has all recrystallised, and occurs in interspaces, including idiomorphic crystals of cloudy alkali-felspar and certain oblong pseudomorphs; the latter are probably after cordierite, and are occupied by plumose muscovite, either alone or associated with yellow chloritic pinite (*cf.* Flett 1907, pl. vi, fig. 1). Muscovite of a similar habit occurs in abundance in the felspathic portions of the rock, and in both positions appears to be a product of the contact-alteration. It therefore seems probable that cordierite, developed in earlier stages of the metamorphism, has been destroyed in later stages as a result of pneumatolysis. Biotite occurs in abundant little, stumpy, new-formed crystals, and the original porphyroblasts of this mineral can also be recognised, now largely replaced by muscovite.

Appin Phyllites

Unaltered rocks of the Appin Phyllites have not been specially studied microscopically; but the group is of interest as yielding very fine examples of spotted cordierite-hornfels on both sides of the Ballachulish "Granite". This type of alteration extends for about a quarter of a mile from the "granite", and is well exhibited near Kentallen on the west and in the valley of Allt Guibhsachain on the east.

As specimens of these conspicuous dark-spotted hornfelses can be very readily obtained by any one visiting Kentallen, a detailed description of a typical example is here appended (S14300) [NN 0136 5839]. The spotting is very well seen on the weathered surface. The spots are dark and spherical and make up the bulk of the rock, while the interspaces are pale and slightly pink. Under the microscope the spots are best perceived by reflected light, for then the interspaces are pink, while the spots remain dark owing to their transparency. By transmitted light the spotting is seen to have very little influence on the general "cobble-structure" of the rock, which is that of a quite unfoliated granulite composed in the main of very abundant small grains of quartz, twinned albite-oligoclase (and probably some orthoclase), and small oblong crystals of brown biotite; there are also larger poikilitic muscovites. The spotting is determined by the presence of cordierite crystals, measuring ■ inch across, which constitute the basis of the spots and enclose the minerals mentioned above in poikilitic fashion. The cordierite has a higher refractive index than quartz, shows yellow pleochroic halos round zircon inclusions, has a strong tendency to marginal decomposition along its cleavages, and is sometimes wholly replaced by a shimmer aggregate of muscovite. Whether fresh or decomposed itself, the minerals it encloses are wonderfully unaltered, whereas in the interspaces between the spots the biotites are highly weathered with liberation of iron oxide, and the felspars are often cloudy. It is this susceptibility of the minerals to decomposition where not enclosed in the cordierite which makes the matrix of the spots pale in the hand specimen as compared with the spots themselves. Notwithstanding this, on an exposed surface the spots disintegrate more quickly than the matrix.

In regard to the origin of these spots it is certain that they are new segregation structures developed during the contact-metamorphism. They cannot be ascribed to the former presence of garnet, for the Appin Phyllites here lie entirely outside the garnet zone.

Ballachulish Slates

Rocks of the Ballachulish Slate group at a distance from the "granites" have a very fine crystallisation, much finer than that of the Leven Schists on the one side of them or the Appin Phyllites on the other. This denotes a selective regional metamorphism which is probably connected with the large amount of finely disseminated carbon present in the group. Garnet has been reported only from Glen Coe and Coire Mhorair (pp. 75, 80). Big cubes of pyrites, however, are a common feature, and Harker (1889) has described composite eyes in Ballachulish Slate with pyrites centres and quartz at both extremities due to pressure acting upon the slates after the formation of the pyrites — but examples of this phenomenon are very rare, at any rate in the main quarry.

The general micaceous base is too fine for profitable microscopic investigation with ordinary powers. It encloses numerous minute lenticles of quartz (S15383A) [NN 085 583] and a few of chlorite. In the latter the chlorite occurs as single crystals, each one with rounded outlines and with the cleavage making a high angle to its greater length.

The group comes within the range of the Ben Nevis, Mullach nan Coirean and Ballachulish "Granites", and gives splendid examples of spotted cordierite-hornfelses. In these the foliation is lost, and large poikilitic crystals of cordierite are very abundant (S14393) [NN 053 529]. Quartz in small grains and a pale biotite in little flakes are the other main constituents. Muscovite, biotite and, sometimes, tourmaline build poikilitic little porphyroblasts; while iron oxide or another nearly opaque mineral is present in small grains. Much of the carbon is retained, and iron sulphide has recrystallised, moulded on quartz (S14392) [NN 053 529].

In the 1916 edition of this memoir the slide last mentioned (which comes from the aureole of the Ballachulish "Granite") was stated to show recrystallisation of pyrites. This must be corrected, for Neumann has demonstrated that pyrites, FeS2, in the Ballachulish aureole has been decomposed to yield pyrrhotite Fe_nSn_{+1} and sulphur (1950). The pyrrhotite has crystallised in aggregates replacing the pyrites cubes, and the surplus sulphur has disappeared. Neumann has further shown that this change occurs well beyond the limits of other signs of alteration. For instance, he found all the pyrites of the North Ballachulish [NN 052 603] roadside slate quarry to have been converted. Neumann saw that it was impossible to assign an exact temperature for the dissociation, since this depends upon facility of removal of the liberated sulphur; but he pointed out that the equilibrium sulphurvapour-pressure of pyrites at 600°C is only 20 mm of mercury.

Pyrrhotite is decomposed by acids with liberation of sulphuretted hydrogen. Accordingly, Neumann's discovery solves two long-standing puzzles: the first is the weathering out of the iron sulphide crystals in the North Ballachulish [NN 052 603] slate quarry in contrast with their stability in the main quarry south of Loch Leven; and the second is the smell of sulphuretted hydrogen which the Ballachulish Limestone emits when broken in its outcrops south of the Ballachulish Pluton. As already pointed out (p. 240) this phenomenon extends for a mile beyond the limit of the Ballachulish aureole as drawn in (Figure 39).

In an interesting slide of Ballachulish Slate hornfels from the Stob Bàn ridge, in the Mullach nan Coirean aureole, cordierite is seen springing in crystal aggregates from layers of carbon, marking the course of strain-slip cleavages in the original slate (S15371) [NN 1388 6634]. The rest of the slide is made up of flakes of pale biotite or phlogopite, with very imperfect orientation, and accompanied by numberless minute granules of green spinel. The latter often marks out the course of an early cleavage or foliation which has later been crossed by the strain-slip cleavage already referred to. Last of all, of course, came the contact-alteration.

Reservoir Flags

The only psammitic group which we shall discuss here is that of the Reservoir Flags. These rocks consist for the most part of fine-grained quartzo-felspathic gneisses carrying abundant muscovite and biotite, and are thoroughly well banded owing to the alternation of more and less micaceous layers. The foliation, as indicated by the orientation of the micas, is more regular than in the pelitic schists, and usually runs parallel to the banding. The felspar, which is often as abundant as the quartz, is alkali. Garnet, epidote, sphene, iron ore, and zircon occur as accessories. The rocks recall many descriptions, published by Barrow (1904) and others, of Central Highland "Moine" gneisses.

The Reservoir Flags come within the aureole of the Moor of Rannoch "Granite" for a considerable distance, and there exhibit changes quite comparable with those of the pelitic rocks. Andalusite develops (S11530) [NN 2448 6045]; (S15367) [NN 240 571], and the biotite recrystallises in small unorientated flakes. Only two slides have been cut from these hornfelsed flags, otherwise it is tolerably certain that cordierite would have been found as well as andalusite.

Quartz xenoliths

Muir has described important reactions between quartz xenoliths and the Ballachulish quartz-diorite (1953b). His specimens came from the mostly northerly of the roadside "granite" quarries near Kentallen. The xenoliths are a few inches in diameter, and are margined by ferromagnesian coronas up to three-quarters of an inch thick. The inner part of an individual corona may be rich in pale green augite (Anals. I, A, (Table 5)); while the outer, much wider portion is mostly composed of hornblende (Anals. II, B). For some little distance beyond a corona the quartz-diorite is still notably modified but in reciprocal fashion with strong development of quartz (Anal. III). Inside a corona there may be considerable felspathic crystallisation rich in orthoclase.

Muir discusses the evidence in detail and supplies a valuable review of more or less similar occurrences elsewhere in the world. According to appearances in such cases (Bailey and McCallien 1956, p. 468) it would seem that silica, dissolved from xenoliths and diffusing outwards, has led to ferromagnesian precipitation, giving augite at first, often followed at lower temperatures by hornblende. Felspathic constituents have meanwhile been free to migrate inwards until finally checked by falling temperature. There is some slight experimental support for this interpretation since the eutectic melting-point of diopside-and-silica is 1362°C, whereas the corresponding values for diopside-and-anorthite and diopside-andalbite are 1270°C and 1085°C respectively (Bowen 1928, pp. 26, 48, 49). That the ferromagnesian precipitation should start with augite rather than hornblende in the case of the Ballachulish quartz-diorite is not surprising considering the chemical composition of the rock. Also Walker has noted that "in a few sections one or two small crystals of pyroxene were observed enclosed in hornblende" (1924, p. 550). E. B. B.

(Table 5) Analyses illustrating reactions between quartz xenoliths and Ballachulish quartz-diorite

	I	A	II	B	III	IV	C
SiO_2	59.94	49.71	59.43	46.30	62.53	5911	45.15
$A1_2O_3$	5.04	2.85	5.54	8.60	16.49	17.85	8.10
Fe_2O_3	2.00	2.76	4.63	2.78	1.82	1.78	2.10
FeO	4.97	7.45	7.08	10.16	2.99	3.24	12.97
MgO	8.30	13.35	7.89	13.15	2.80	3.85	13.30
CaO	14.72	22.36	9.05	13.55	4.78	5.05	12.84
Na_2O	1.87	0.60	1.65	1.05	4.17	4.10	0.66
K_2O	0.14	0.04	0.58	0.48	2.12	3.06	0.32
Etc.	2.52	1.13	4.55	3.82	2.53	1.66	4.10
Total	99.50	100.25	100.40	99.89	10023	99.70	99.54

All analyses by I. D. Muir.

I. Augite-rich inner zone of corona.

A. Augite from I.

II. Hornblende-rich outer zone of corona.

B. Hornblende from H.

III. Modified IV, 2 inches outside corona.

IV. Normal Ballachulish quartz-diorite.

C. Hornblende from IV.

Contact-altered lavas of Glen Coe and Ben Nevis

We may begin by reproducing the gist of an account of the contact-alteration of the hornblende-andesites and rhyolites of Glen Coe, which Kynaston had furnished before leaving the Survey (Sum. Prog. 1901, p. 82).

Hornblende-andesites

Excellent sections of the contact between the Cruachan "Granite" and the hornblende-andesites of Glen Coe may be seen: at the west end of the Meall a' Bhùiridh ridge (Sheet 54, Geol.; see (Figure 29), p. 164); on the ridge running due north from the summit of Clach Leathad [NN 240 493]; and on the west side of the corrie at the head of Càm Ghleann [NN 247 515]. Contact-alteration of the andesites may be recognised in the field by gradual replacement of the normal dark-grey or almost black colour of these rocks by pale grey, and concurrent development of a fine holocrystalline texture in their groundmass. The altered lavas also lose their sharp angular fracture. Such changes do not extend for more than about 300 yards from the "granite" contact.

A large number of micro-sections of the altered andesites have been examined. The brown idiomorphic hornblende appears to be the first mineral to be attacked. It is replaced by clusters of small biotite flakes, usually associated with aggregates of granular green hornblende and magnetite (S9163) [NN 247 502]; (S9174) [NN 245 501]. At first the form of the original crystal is clearly seen, but in the later stages it is completely lost. Frequently the replacing aggregate consists almost entirely of grains of green hornblende, though in the pyroxene-bearing varieties north of Clach Leathad [NN 240 493] the brown hornblende is replaced almost entirely by biotite, with a little magnetite. In the commencing stages of the alteration portions of the original hornblende may be seen surrounded by a dense cluster of small biotite flakes, the outer margin of which retains the characteristic form of the hornblende crystal (S9179) [NN 2378 5045]. The felspar phenocrysts are usually marked by a peculiar cloudiness, also observed in the altered andesites of the Cheviot district and other places; but they show a marked stability, and sometimes appear to maintain their individuality even at the actual contact (S9169) [NN 245 499]. The microlites of the groundmass become indistinct, and gradually the entire groundmass is replaced by a clear granular mosaic, consisting probably largely of felspar with some quartz (S9171) [NN 245 499]; (S9174) [NN 245 501]. At times a relatively coarse aggregate of clear micropoikilitic felspar is seen in the more advanced stages, as in (S9176) [NN 2378 5045]. This last is a junction specimen, where a profusion of small biotite flakes, often in aggregates, and frequently accompanied by green hornblende and granules of magnetite, lies scattered throughout. The green hornblende is sometimes in excess of the biotite (S9177) [NN 2378 5045]; (S9178) [NN 2378 5045]. Grains of sphene occur at the actual contact (S9176) [NN 2378 5045]. The pale greenish augite present on the ridge north of Clach Leathad [NN 240 493] may be replaced by a pale green hornblende, but it shows far more stability than the phenocrysts of brown hornblende (S9179) [NN 2378 5045]. At the contact the "granite" is sometimes fairly coarse and of an acid type. It often encloses small fragments of andesite (S9169) [NN 245 499].

Rhyolites

Several well-marked contacts between the rhyolitic rocks of Glen Coe and the Cruachan "Granite" may be seen on the west slopes of Sròn na Crèisee [NN 240 522], not named in (Figure 29) but just north of Stob Ghlas Choire [NN 240 515] and east of the River Etive. On approach to the "granite" the rhyolites entirely lose their normal compact and flinty texture, assume a pale greyish or pale pinkish colour, and somewhat resemble fine-grained quartzo-felspathic granulitic rocks. A specimen of one of them shows a peculiar appearance under the microscope (S9735) [NN 234 522]. It looks as if originally a spherulitic rhyolite, owing to the presence of numerous circular and oval-shaped patches, and elongated bands with rounded ends; but these portions now show no spherulitic texture, instead breaking up into a relatively coarse microcrystalline granular aggregate. The surrounds are usually considerably finer grained. The aspect between crossed nicols is that of a curious intermixture of relatively coarse and fine-grained areas.

Another specimen (S9736) [NN 233 522], a few feet from the "granite", shows some remains of felspar phenocrysts and patches of secondary flakes of chlorite and pale green biotite; but the greater part of the rock is a fine granulitic quartzo-felspathic aggregate with an unusual micropoikilitic structure. H. K.

Lavas in general

Further examination of the material, now greatly extended, has suggested that the contact-alteration affected lavas sometimes already much weathered. But before considering this point it will be well to show how the continuation of the aureole about the Cruachan "Granite" has been followed through the portion of the district not examined by Kynaston.

South-east of Lairig Gartain [NN 200 544], Grabham collected numerous striking specimens which illustrate the contact-alteration of the lavas, both north (S12462) [NN 2042 5329]; (S12464) [NN 2057 5366]; (S12465) [NN 2061

5336]; (S12466) [NN 2076 5348]; (S12467) [NN 2043 5356]; (S12510) [NN 2101 5274]; (S12511) [NN 2116 5283]; (S12512) [NN 2037 5314] and south (S12756) [NN 1710 5140]; (S12757) [NN 1706 5172]; (S12758) [NN 1727 5204]; (S12759) [NN 1733 5237]; (S12760) [NN 1768 5224]; (S12761) [NN 187 520]; (S12762) [NN 180 525]; (S12763) [NN 1795 5139]; (S12764) [NN 189 519]; (S12765) [NN 1902 5256]; (S12766) [NN 1902 5256] of the "granite" there exposed; while Maufe has investigated the same subject on the other side of the valley from Buachaille Etive Beag [NN 192 548] to Dalness (S11602) [NN 1717 5191]; (S11605) [NN 1696 5207]; (S11607) [NN 165 515]; (S11607) [NN 165 515]; (S12437) [NN 1850 5526]; (S12438) [NN 1841 5457]; (S12441) [NN 1955 5457]; (S12442) [NN 1985 5477]; (S12443) [NN 1929 5461]; (S12444) [NN 1984 5451]; (S12445) [NN 1911 5451]; (S12446) [NN 1845 5442]; (S13768) [NN 172 516]; (S13769) [NN 1817 5412], and has shown that contact-alteration is recognisable at about three-quarters of a mile from the "granite" margin (S11605) [NN 1696 5207]; (S11606) [NN 1654 5090].

Clough has found, as might be expected, that all the lavas lying south of the River Etive in the Dalness district fall within the contact zone (S11455) [NN 1809 5111]; (S11487) [NN 1785 5103]; (S11488) [NN 1741 5093]; (S11489) [NN 1735 5069]; (S11490) [NN 1735 5069].

Similar contact phenomena have been recorded by Maufe from Ben Nevis (S8825) [NN 1507 7173]; (S13734) [NN 1505 7173]; (S13743) [NN 1515 7121]; (S14022) [NN 1683 7215]; (S14023) [NN 1711 7176]; (S14024) [NN 1717 7165]; (S14422) [NN 1379 7185].

It has already been mentioned that there is reason to believe that the contact-alteration was sometimes superinduced upon an earlier decomposition, probably due in the main to weathering. This circumstance is fairly clear in many cases where the new hornblende and biotite have been formed along the courses of cracks — presumably previously occupied by such minerals as calcite, chlorite, and perhaps epidote (S9174) [NN 245 501]; (S9179) [NN 2378 5045]; (S12757) [NN 1706 5172]. In like manner tremolite has replaced earlier amygdale minerals (S11456) [NN 181 511]. Clouding of felspar will be discussed later (p. 259).

The indications of weathering outlined above recall those upon which Harker and Marr (1891) laid stress in describing the contact-altered andesites near the Shap Granite of the north of England. Moreover, the conditions which reigned during contact-alteration were similar in both cases, leading to an abundant formation of biotite and hornblende — the latter resulting, as Harker and Marr pointed out, wherever a source of lime was available, such as calcite or epidote. Potash, an essential constituent of biotite, seems to have been comparatively mobile in the heated rocks. Magnetite, as, for instance, the magnetite of the resorption borders round original hornblendes and biotites, has often helped to locate growing clusters of biotite, and has been eventually more or less completely digested. It is, of course, probable that the proximity of unstable minerals, such as chlorite and calcite, has powerfully influenced comparatively stable minerals, such as augite and hornblende, and in a good many cases led to their destruction.

The various minerals which have resulted from contact-alteration have tended to develop in all directions. As a result the altered rocks assume somewhat granulitic and poikilitic characters. This feature is best illustrated in the base of altered glassy rocks, for the most part rhyolites (S12756) [NN 1710 5140]; (S12758) [NN 1727 5204]. In the andesites the lath-structure of the original is strikingly modified in the same sense, but never obliterated (S9730) [NN 242 506]; (S9731) [NN 242 506]; (S12512) [NN 2037 5314]. There can be considerable development of biotite and hornblende before this tendency towards a granulitic texture becomes in any way marked. E.B.B.

Contact-altered sediments of Glen Coe

Breccias

At the junction between the hornblende-andesites and the underlying breccias at the west end of Meall a' Bhùiridh ((Figure 29), p. 164), some altered rocks occur which, though of an andesitic appearance, probably belong to the breccias rather than the andesites. They are rich in quartz grains and fragments of quartzose schist as well as andesite. The pieces of schist appear to be gradually losing their individuality; their sharp outlines become indistinct, and under the microscope (S9170) [NN 245 499] the fragments tend to merge into the surrounding rock. The main mass of the section examined consists in part of a mosaic of quartz and felspar throughout which are scattered numerous small flakes of secondary biotite, minute greenish grains (? hornblende), and magnetite, and in part of quartz grains in a fine brownish matrix. Other portions, again, break up into a mosaic of micropoikilitic felspar, in which the secondary minerals are embedded. Sometimes there is a marked parallel arrangement, and sometimes an appearance of brecciation (S9173) [NN 250 498]. In the less altered specimens the andesitic portions retain their original texture (S9172) [NN 245 501].

The contact between the Cruachan "Granite" and the breccias is well seen at the head of Càm Ghleann and to the west beyond the hornblende-andesites of Stob Glas Choire [NN 240 515] (Sròn na Crèise [NN 240 522]). In the field the usual dark and almost compact matrix of these rocks becomes a pale-grey or sometimes pinkish colour; and it feels sandy to the touch in the more weathered specimens, no doubt owing to the rock assuming a secondary granulitic texture. The microscope again shows (S9733) [NN 232 518]; (S9734) [NN 234 522] that the distinction between fragments and groundmass has become much less clear than in the normal unaltered rocks, except where the fragments consist of andesite, or in rare cases of "granite" (S9734) [NN 234 522]. The groundmass would appear to have undergone reconstruction, and now constitutes a microcrystalline quartzo-felspathic mosaic, which may closely resemble in texture the included fragments. When these are felsitic, they are usually finer grained than the ground-mass. Patches of small flakes of secondary biotite and some chlorite may also be seen scattered about, with here and there some original quartz grains and felspars.

Fine sediments

The sedimentary band intercalated in the andesites of Stob Glas Choire [NN 240 515] ((Figure 29), p. 164) shows considerable induration at a distance of about half a mile from the Cruachan "Granite". The band consists of fine-grained dark shale interlaminated with more gritty portions. Its beds break just as easily across the lamination as parallel to it. Close to the "granite" considerably greater alteration may be observed, and portions of the rock have been converted into a fine-grained spotted hornfels, with minute dark spots on a paler background. A section under the microscope (S9739) [NN 239 504] shows that these spots are roughly oval patches of minute, densely packed flakes of secondary biotite together with small grains of quartz. They tend to coalesce along certain bands which are slightly coarser than the rest of the rock. H. K.

Well-marked induration has been recorded by Kynaston in a band of purple shales which occurs on the east side of a gorge on the north-eastern slopes of An t-Sròn [NN 134 550]; on the south side of Glen Coe. The shale is adjacent, across the Boundary-Fault, to "Granite" of the Fault-Intrusion; and its alteration is undoubtedly attributable to the same; but the impressive phenomenon, here as elsewhere, is how little this intrusion has achieved in the way of contact-alteration inside, as compared with outside, the Cauldron-Subsidence.

Contact-altered intrusions

Introduction

The district furnishes several interesting examples of contact-alteration of intrusions. Maufe first detected this phenomenon in a dyke of the Etive Swarm cutting the Ben Cruachan "Granite" close to the margin of the Starav Granite, a quarter of a mile east of Glenceitlein [NN 148 479] cottage, Glen Etive. He ascribed the contact-alteration in this case to the effect of the Starav Granite, and other instances in confirmation have since been found. Maufe further showed that dykes of the Ben Nevis Swarm are altered by the Inner "Granite" of the same complex. In addition a few early dykes are known to be altered by the Main Fault-Intrusion of Glen Coe, others by the Cruachan "Granite". Contact-alteration of plutonic intrusions, big or small, is generally less demonstrable; but examples in the Early and Main Fault-Intrusions of Glen Coe, the Moor of Rannoch "Granite", the Glen Ure [NN 070 475] augite-diorite and the kentallenite of Kentallen are discussed below.

Dykes earlier than the Main Fault-Intrusion and the Cruachan "Granite".The thin north-east lamprophyre dyke (S11523) [NN 1592 5970], noted on p. 196 as veined by the Fault-Intrusion in the permeation area north of Glen Coe, carries pseudo-morphs composed of bladed aggregates of pale-green hornblende accompanied to a minor extent by brown biotite. Its neighbour (S11524) [NN 1592 5970], also mentioned, is completely reconstructed into an augite-biotite-quartz-granulite. A comparably granulated lamprophyre (S11575) [NN 1376 5645], with unknown field relations, has been collected 300 yd S.W. of the exit of Loch Achtriochtan. Here again contact-alteration must be referred to the Main Fault-Intrusion.

The porphyrite (S12345) [NN 1613 5852] and felsite (S12344) [NN 1613 5852], shown in (Figure 23) as contiguous dykes flanking a branch of the Boundary-Fault of the Glen Coe Cauldron north of Meall Dearg [NN 163 585], have both suffered intense granulation at the hands of the Fault-Intrusion.

Another early felsite (S11460) [NN 1808 4989]; (S11461) [NN 1836 5008]; (S11462) [NN 1808 4989]; (S11463) [NN 1808 4989], this time altered by the Cruachan "Granite", comes from Beinn Ceitlein, Glen Etive. It is remarkable for a rich development of minute flakes of muscovite and biotite, which are sometimes grouped along fluxion bands, or else margin reconstructed spherulites.

Certain altered dykes cutting the calc-silicate-hornfels south of Glen Ure [NN 070 475] were regarded by Kynaston as belonging to the hornblende-schist suite referred to on p. 69. They may, however, be pre-Cruachan-"Granite" forerunners of the Etive Swarm.

Dykes of the Etive Swarm

A porphyrite dyke veined by the Meall Odhar Granite, 930 yd south-east of the southern lochan on Beinn Ceitlein, shows characteristically clouded felspars. Moreover, its groundmass is suspiciously coarse (S11496) [NN 1791 4767].

There are only a few slides of dykes showing contact-alteration undoubtedly due to the Starav Granite. Two come from Allt Dochard [NN 203 440] in Sheet 45, Geol. Their felspars are to some extent clouded, and characteristic aggregates of brown biotite and green hornblende have been developed along with a very perfect granulitic texture (S14182) [NN 1956 4565]; (S14183) [NN 1975 4556]. This stream section is very interesting, for, as has already been pointed out, there can be no doubt that its numerous dykes are earlier than the closely adjacent Starav Granite, since they are freely cut by aplite veins. A suite of slides was accordingly prepared, and the general failure to detect clear evidence of contact-alteration in them confirms the view that fresh igneous rocks are not readily susceptible to conspicuous contact-alteration. The two cited above had been sheared before or during the heating process.

A very beautiful example of contact-alteration is afforded in Sheet 53 by a dyke exposed near the Starav Granite in the bed of Allt Ceitlein [NN 150 477], a quarter of a mile E.S.E. of Glenceitlein [NN 148 479] cottage (S13762) [NN 1504 4768]. There is a suggestion here of previous albitisation, with slight introduction of soda. Another good example comes from across Glen Etive, from Allt nan Gaoirean [NN 130 477], nearly 600 yd above the schoolhouse (S14178) [NN 1383 4746]. Other slides from Allt nan Gaoirean [NN 130 477] suggest contact-alteration in the coarseness of their ground, but the appearances are scarcely decisive (S14175) [NN 1392 4747]; (S14177) [NN 1391 4742].

Apart from the cases quoted above, there are a few other hypabyssal rocks known in the district, showing definite contact-alteration, which cannot, however, be ascribed with certainty to any particular intrusive mass.

A porphyrite dyke (S11502) [NN 1812 4734], cutting the Meall Odhar Granite in a burn, 1167 yd S.E. of the south lochan on Beinn Ceitlein, shows unmistakable contact-alteration in the condition of its felspar and ferromagnesian phenocrysts. The dyke has probably been altered by the Starav Granite, as it is within half a mile of the latter.

Another example in which contact-alteration is very strongly suggested is a thin microdiorite dyke (S11506) [NN 1706 4928], cutting the Fault-Intrusion 667 yd N.E. of the 2897-ft [NN 166 488], and one and a half miles north of the Starav Granite.

Dykes of the Ben Nevis Swarm

Many of the dykes cutting the Outer "Granite" of Ben Nevis have a suspicious appearance under the microscope, and in several slides contact-alteration is undeniable. It shows itself in much the same manner as in the lavas through the development of criss-cross brown biotite and pale-green hornblende, in place of original ferromagnesian constituents

(S8820) [NN 1341 7205]; (S14049) [NN 1421 7064], and of characteristic clouds of minute opaque inclusions in the felspars (S14048a) [NN 1821 7386]; (S14425) [NN 1400 7177]; (S14427) [NN 1379 7185]; (S14428) [NN 1360 7189]; (S14440) [NN 1763 7490]; two of the specimens showing altered felspars come from the Ben Nevis path within about a quarter of a mile of the margin of the Inner "Granite". One or two specimens (S14047) [NN 1817 7396] show a fairly perfect granulitic texture. This slice represents the chilled edge of a dyke cutting Outer "Granite", while a slice from the centre of the same dyke (S14048) [NN 1821 7386], cut across by Inner "Granite", is a microdiorite.

Early Fault-Intrusion, Glen Coe

Some very good examples of contact-alteration are afforded by the Early Fault-Intrusion in its small outcrops in the tributary valley leading into Allt Coire Mhorair [NN 195 600] from the west. The hornblende phenocrysts are replaced by criss-cross brown biotite, while pale-green hornblende and biotite are abundantly developed in the groundmass (S12359) [NN 1853 5935]; (S12360) [NN 1868 5947].

Main Fault-Intrusion. — The contact-alteration of the Main Fault-Intrusion of Glen Coe by the Cruachan "Granite" is quite clear in slides from the district south of Dalness (S11503) [NN 1794 5023]; (S11504) [NN 173 500]; (S11505) [NN 1685 4958]. Criss-cross brown biotite has been developed to a considerable extent in place of the original biotite phenocrysts, while pale-green hornblende is abundant in the groundmass; the felspar phenocrysts in some cases show the tell-tale cloudiness (S11505) [NN 1685 4958], and it is interesting to note that previous incipient albitisation, probably accompanied by introduction of soda, is evidenced by veins of more alkali felspar extending along what seems to have been a system of cracks; this more alkali felspar is unclouded.

Moor of Rannoch "Granite"

Only one of the slides which Grabham had cut of the Moor of Rannoch "Granite" at its junction with the Fault-Intrusion in the Coupall and Etive Rivers shows contact-alteration of the type discussed in the preceding paragraphs. In this slide (S12751) [NN 2379 5521] an aplite vein runs between the Fault-Intrusion and the Rannoch "Granite", and the biotites of the latter seem to have been partially recrystallised as aggregates. Even here it is possible that the biotite clusters really belong to xenoliths digested by the Rannoch "Granite".

Glen Ure Augite-Diorite

The small boss of augite-diorite cut by the Cruachan "Granite" in Glen Ure [NN 070 475] affords a good example of contact-alteration. Most of what appear to have been originally large crystals of augite are now replaced by bladed aggregates of pale-green hornblende in (S10125) [NN 060 475]. In another slide (S15877) [NN 0604 4745], cut across the actual contact, the nature of the alteration is less obvious. Here the big augite crystals are pseudomorphed by single hornblende crystals which retain small irregular relics of the originals.

Kentallenite at Kentallen

In the 1916 edition of this memoir, Kynaston, as we have seen above, pointed out that a characteristic clouding of felspars (by dust or minute oriented needles) is a very common result of contact-alteration. The present writer further suggested that such clouding, though undoubtedly a contact-effect, had resulted during regeneration of felspar previously modified by weather or some other agent of change. Since then MacGregor has studied the phenomenon over a wide field and has come to the conclusion that previous alteration is not indicated (1931, pp. 526–7). It is probable that the truth lies somewhere between these two alternatives: perhaps in some cases preparatory alteration may have been required; while in others it may not have been essential. An instance where it seems to have been important has already been discussed in relation to the type kentallenite at Kentallen, west of the Ballachulish Pluton (p. 212).

Effects resembling contact-alteration

There are certain intrusions which show effects sufficiently like those produced by contact-metamorphism to be worthy of mention in this chapter. Some of the more or less horizontal lamprophyre sheets have a conspicuous development of green mica (S11527) [NN 1829 6189]; (S12888) [NN 2244 6707]; (S12889) [NN 2171 6399], in part pseudomorphing hornblende. Tremolite has also been produced (S12889) [NN 2171 6399]. Similar changes are seen in various microdiorite and allied dykes (S11475) [NN 1810 5112]; (S11550) [NN 2129 4756]; (S11581) [NN 1229 5291]; (S14410) [NN 1538 5160]; (S14411) [NN 1538 5160]; (S14416) [NN 1538 5160]; (S14417) [NN 1538 5160]; (S14419) [NN 1538 5160], the last five from the multiple dyke of (Figure 34). The biotite in these cases differs from that produced by contact-alteration in its greener colour and its tendency to occur with a chloritic habit in radiating growths or wavy bundles.

Similar hornblende and biotite aggregates have been described by Flett as characteristic of a group of lamprophyres in Perthshire (1905, pp. 125–130). More recently Flett (1910, p. 304) has shown that hornblende and green biotite figure among the decomposition products of the quartz-dolerites of Central Scotland, both in pseudomorphs after augite and in patches in the groundmass. In these quartz-dolerites contact-alteration by an independent intrusion is out of the question.

In the light of the available evidence it seems probable that this particular type of alteration is in many cases a juvenile decomposition. In other instances, however, it may well have had an external cause, for it is often strikingly developed in the Early Fault-Intrusion (S12932) [NN 200 580]; (S13405) [NN 207 575]; (S14109) [NN 1928 5876] within the contact zone of the Fault-Intrusion proper, north of Glen Coe. E. B. B.

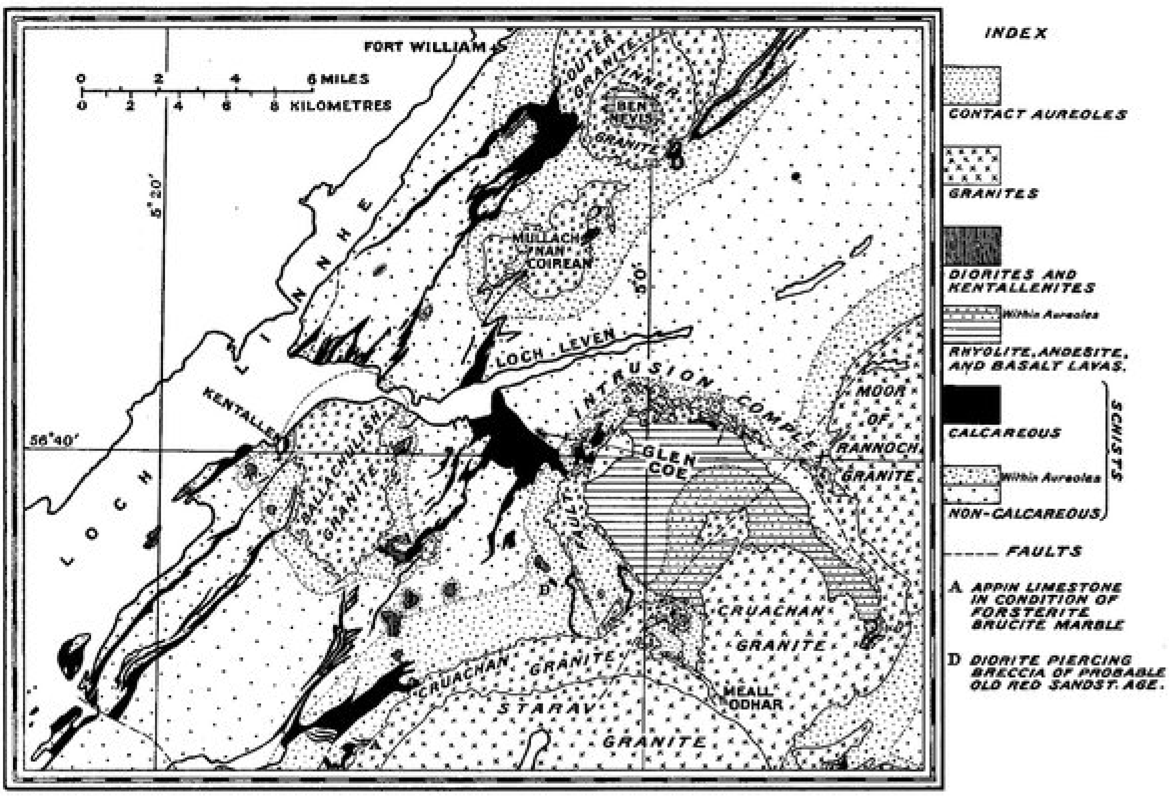


FIG. 39. Map of contact-aureoles south-east of Loch Linnhe
The limits drawn include alteration sufficiently intense to convert impure limestone into calc-silicate-hornfels

(Figure 39) Map of contact-aureoles south-east of Loch Linnhe. The limits drawn include alteration sufficiently intense to convert impure limestone into calc-silicate-hornfels.

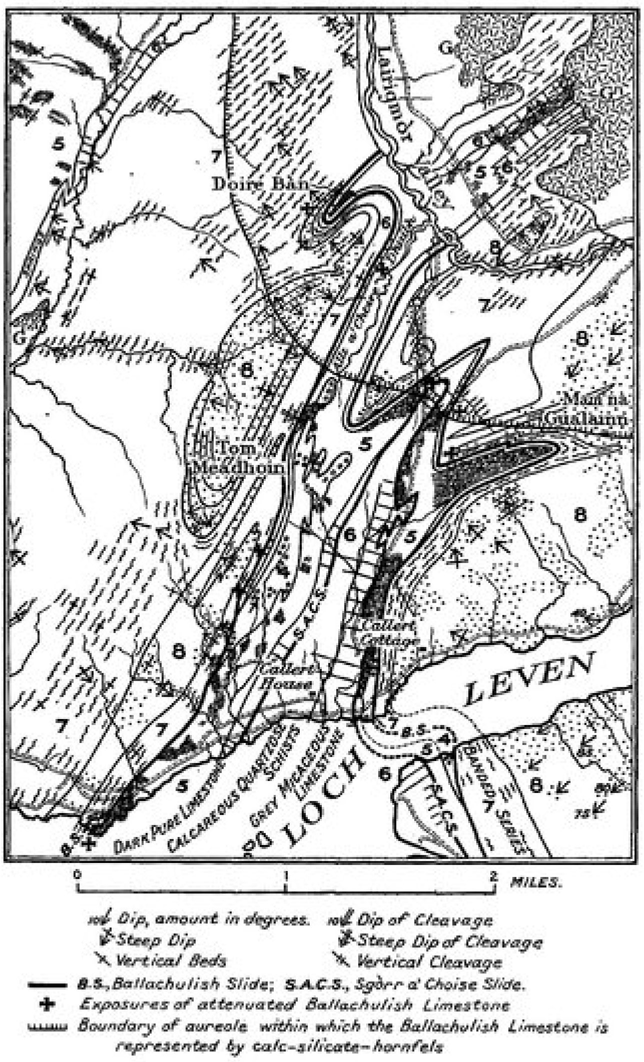


FIG. 8. Map showing outcrops in Callert district

4, Appin Quartzite (youngest); 5, Ballachulish Slates; 6, Ballachulish Limestone; 7, Leven Schists; 8, Glen Coe Quartzite; G, Granite

(Figure 8) Map showing outcrops in Callert district 4, Appin Quartzite (youngest); 5, Ballachulish Slates; 6, Ballachulish Limestone; 7, Leven Schists; 8, Glen Coe Quartzite; G, Granite.

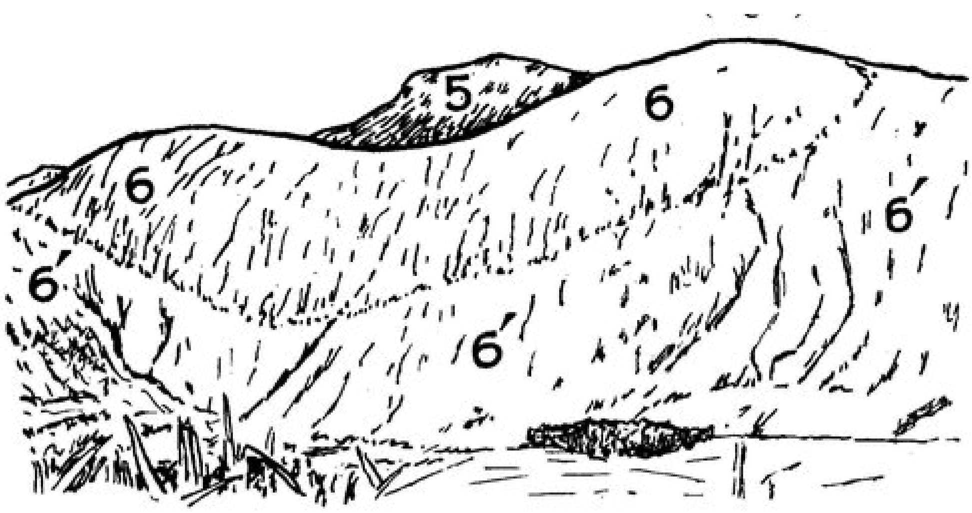


FIG. 3. Sketch of Appin Fold sectioned in S.W. wall of Glen Nevis

5, Baked Ballachulish Slates (youngest); 6, Marble of Ballachulish Limestone; 6′, Calc-silicate-hornfels of Ballachulish Limestone

(Figure 3) Sketch of Appin Fold sectioned in S.W. wall of Glen Nevis 5, Baked Ballachulish Slates (youngest); 6, Marble of Ballachulish Limestone; 6′, Cale-silicate-hornfels of Ballachulish Limestone.

TABLE 4

Analyses of Appin Limestone

	1	2	3	4	5	6	7	8	9	Dolomite
SiO_2	3·4	13·9	1·9	1·3	3·5	3·3	25·9	3·7	—	—
Al_2O_3	1·2	5·3	1·8	—	2·1	—	5·0	—	—	—
Fe_2O_3	—	5·1	1·3	—	3·3	—	1·8	—	—	—
FeO	0·2	—	—	—	—	—	—	—	—	—
MgO	9·0	8·0	18·5	20·0	17·1	21·8	5·4	20·9	18·4	21·8
CaO	42·5	33·7	31·7	30·7	29·7	29·1	28·9	28·9	26·7	30·4
CO_2	43·1	34·3	44·6	45·9	44·0	46·8	29·3	45·6	41·1	47·8
Etc.	0·5	0·2	0·9	—	—	0·6	4·1	—	13·1	—
Total	99·9	100·5	100·7	—	100·2	—	100·4	—	—	100·0
$MgCO_3$	18·8	15·2	38·0	41·8	35·7	45·7	11·4	43·8	38·6	45·7
$CaCO_3$	75·6	60·0	56·4	54·8	52·9	52·0	51·6	51·6	47·6	54·3
Surplus MgO	0·0	0·8	0·4		0·0		0·0			0·0
Surplus CO_2	0·0	0·0	0·0		2·1		0·9			0·0

1. Waterfall in stream 50 yd E. of Kentallen railway station (contact-altered). Anal. I. D. Muir.
2. Onich shore, 400 yd W. by S. of church (S 15376). Anal. B. Lightfoot.
3. Three hundred yards above path S.W. of Sgòrr a' Choise (contact-altered, S 15379, 15380). Anal. B. Lightfoot.
4. Dalnatrat, near Duror station. Supplied by Stewarts and Lloyds, Ltd.
5. Hillslope, 200 yd N.E. of Portnacroish (Appin station). Anal. B. Lightfoot.
6. Dalnatrat, near Duror station. Supplied by Steetley Lime and Basic Co., Ltd.
7. Marble Quarry, pathside, River Laroch, 660 yd S. of Laroch Bridge, Ballachulish. The full analysis by A. Muir and H. G. M. Hardie (1956, p. 20) shows Na_2O 1·95, K_2O 1·00.
8. Tributary of River Laroch, 660 yd S. 23°W. of Laroch Bridge, Ballachulish.
9. East of Duror railway station.

Pure dolomite is quoted for comparison.

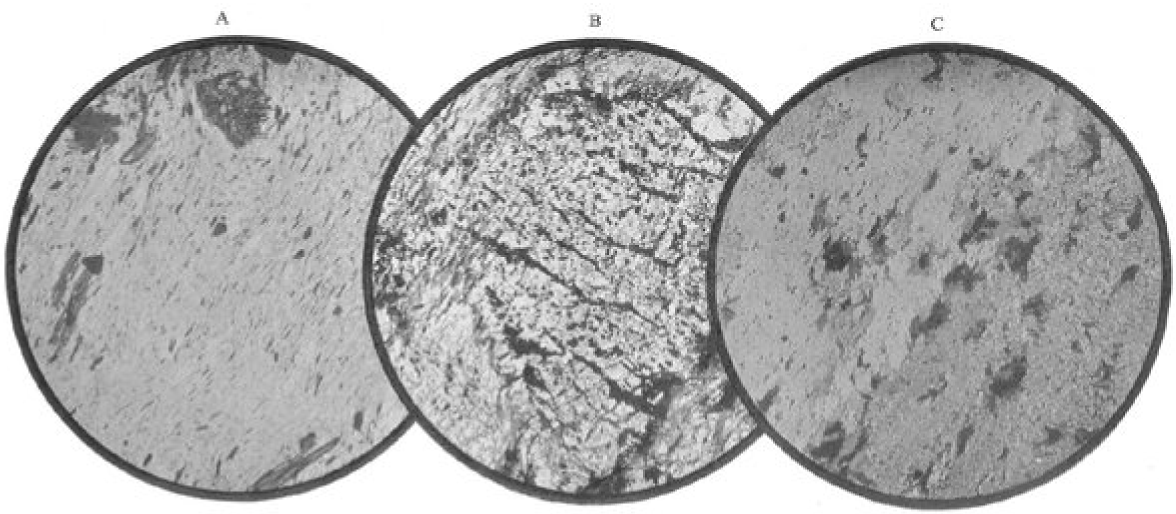
Analyses of Xenolith and of Contaminated and Normal Ballachulish Quartz-Diorite

	A	B	C	D	E	F
SiO_2	54·73	59·24	62·51	59·81	59·11	51·61
Al_2O_3	7·42	20·80	19·10	16·61	17·85	2·18
Fe_2O_3	1·71	0·29	0·65	1·50	1·78	1·04
FeO	5·03	0·99	0·41	2·80	3·24	9·28
MgO	8·11	1·20	0·23	2·49	3·85	11·29
CaO	18·32	7·13	2·01	3·20	5·05	22·86
Na_2O	2·35	7·47	2·18	3·49	4·10	0·43
K_2O	1·19	0·85	11·47	7·92	3·06	0·07
Etc.	1·05	2·22	1·50	2·05	1·66	1·09
Total	99·91	100·19	100·06	99·87	99·70	99·85

Analyses by I. D. Muir (1953a).

A. Xenolith of Appin Limestone transformed through immersion in Ballachulish quartz-diorite (see E. below). The specimen was taken 50 yd from 1 of previous Table.
B. Plagioclase zone enveloping A, and 1-2 inches thick.
C. Potash syenite zone enveloping B, 3 inches.
D. Augite-syenite zone enveloping C, a few inches.
E. Quartz-diorite of Ballachulish Pluton unmodified by Appin Limestone.
F. Diopside from D.

(Table 4) Analyses of Appin Limestone; Analyses of xenolith and contaminated and normal Ballachulish quartz-diorite.



(Plate 12) Photomicrographs of Leven Schists before and after contact-alteration. × 21 Dia. A. Not contact-altered, Glen Leac na Muidhe (S11618) [NN 1126 5486]. Porphyroblasts of biotite, garnet and magnetite in well foliated base of muscovite, quartz and magnetite. B. Slightly contact-altered, ¾ mile from Cruachan "Granite", Glen Etive district (S8270)

[NN 112 505]. Pseudomorph, largely of cordierite and magnetite, after garnet in well foliated base of muscovite, quartz and magnetite. C. Completely reconstructed to cordierite-andalusite-hornfels, near Ben Nevis "Granite", Aonach Beag (S13837) [NN 1935 7186]. Cordierite, pale, N.W. half; andalusite, darker, S.E. half; biotite and magnetite, dark to black.

TABLE 5

Analyses illustrating Reactions between Quartz Xenoliths and Ballachulish Quartz-Diorite

	I	A	II	B	III	IV	C
SiO_2	59·94	49·71	59·43	46·30	62·53	59·11	45·15
Al_2O_3	5·04	2·85	5·54	8·60	16·49	17·85	8·10
Fe_2O_3	2·00	2·76	4·63	2·78	1·82	1·78	2·10
FeO	4·97	7·45	7·08	10·16	2·99	3·24	12·97
MgO	8·30	13·35	7·89	13·15	2·80	3·85	13·30
CaO	14·72	22·36	9·05	13·55	4·78	5·05	12·84
Na_2O	1·87	0·60	1·65	1·05	4·17	4·10	0·66
K_2O	0·14	0·04	0·58	0·48	2·12	3·06	0·32
Etc.	2·52	1·13	4·55	3·82	2·53	1·66	4·10
Total	99·50	100·25	100·40	99·89	100·23	99·70	99·54

All analyses by I. D. Muir.

I. Augite-rich inner zone of corona.
A. Augite from **I.**
II. Hornblende-rich outer zone of corona.
B. Hornblende from **II.**
III. Modified **IV**, 2 inches outside corona.
IV. Normal Ballachulish quartz-diorite.
C. Hornblende from **IV.**

(Table 5) Analyses illustrating reactions between quartz xenoliths and Ballachulish quartz-diorite.

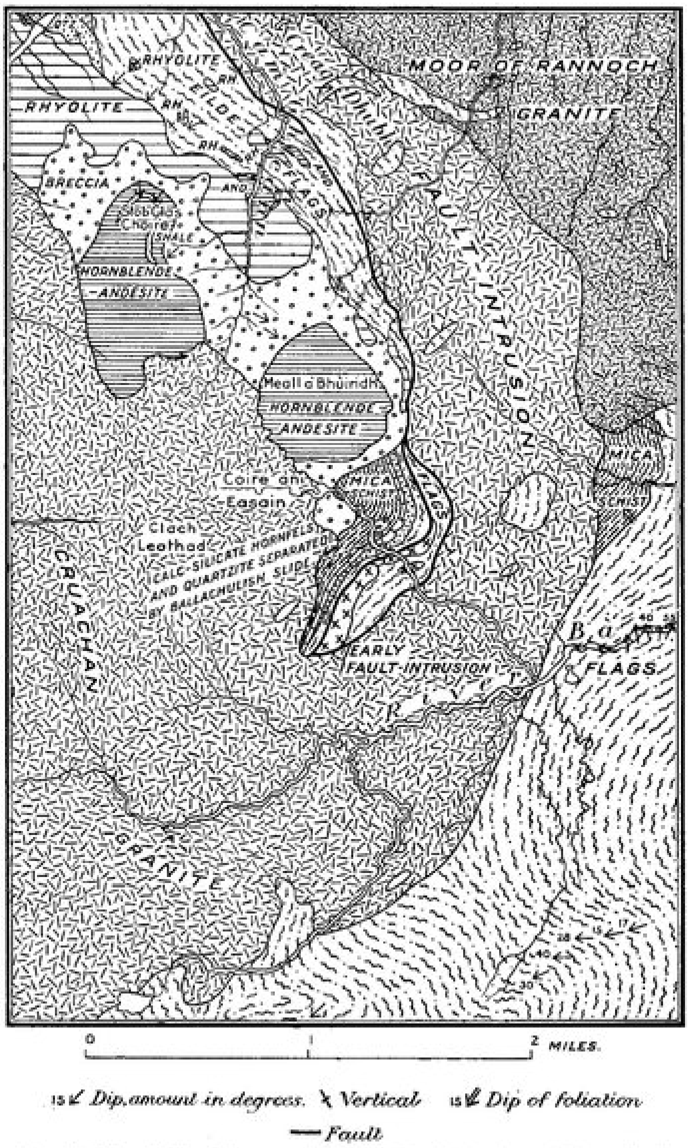


FIG. 29. Map of Càm Ghleann and Coire an Easain. North-east dykes omitted

(Figure 29) Map of Càrn Ghleann and Coire an Easain. North-east dykes omitted.

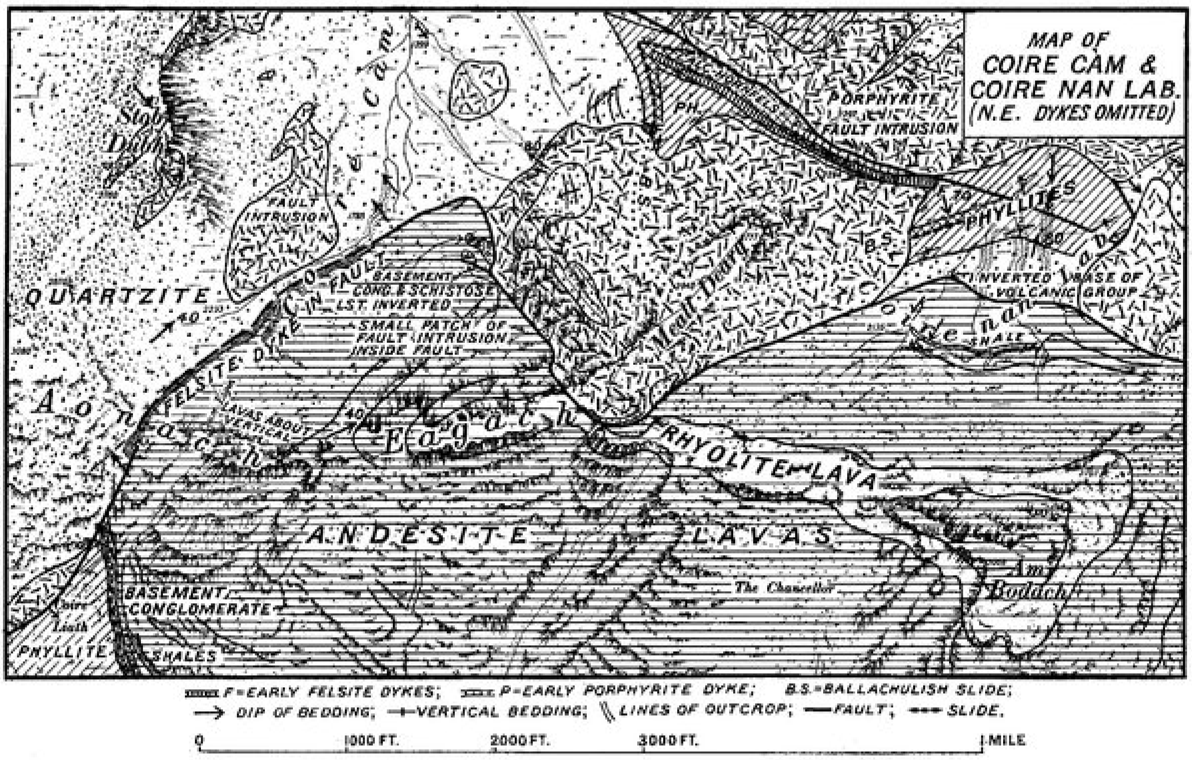


FIG. 23. Map of Coire Càm and Coire nan Lab. North-east dykes omitted. (The Fault-Intrusion is chilled at its contact with the early dykes north of Meall Dearg)

(Figure 23) Map of Coire Càm [NN 154 585] and Coire nan Lab [NN 167 584]. North-east dykes omitted. (The Fault-Intrusion is chilled at its contact with the early dykes north of Meall Dearg [NN 163 585]).

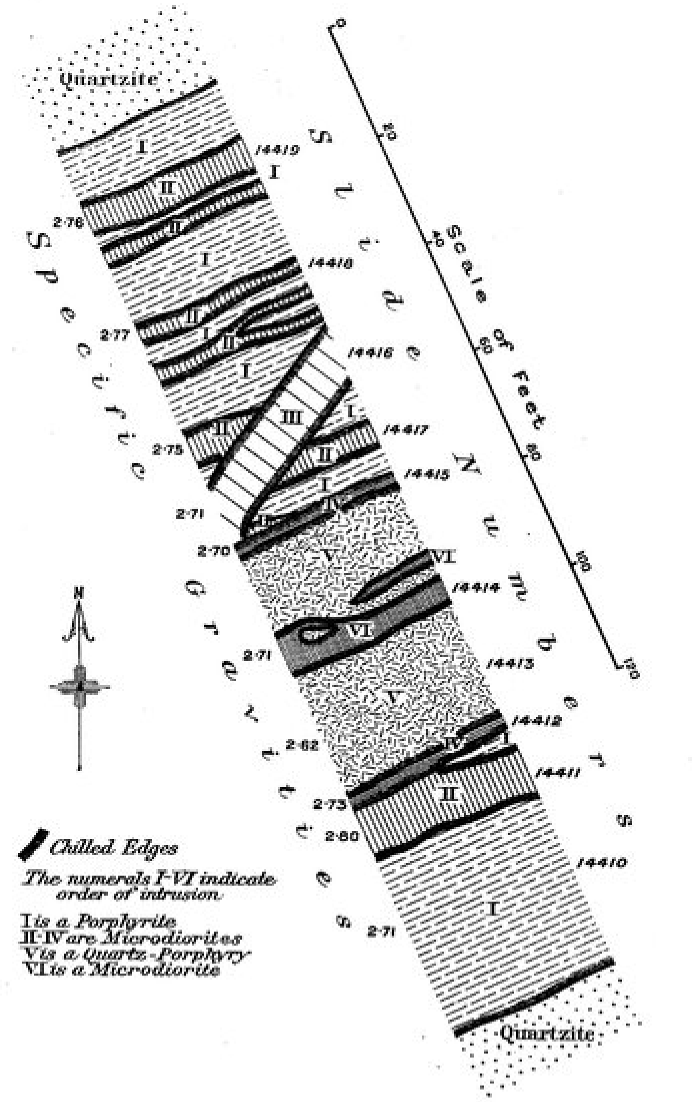


FIG. 34. Map of multiple dyke in the bed of Allt Fhaolain, ½ mile above the bridge, Glen Etive

(Figure 34) Map of multiple dyke in the bed of Allt Fhaolain [NN 158 510], ½ mile above bridge, Glen Etive.