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# Geology of the Epidiorites of the Ardrishaig-Tarbert Area, Argyllshire, S.W. Scotland.

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# I. INTRODUCTION.

This thesis is based on field work in the Ardrishaig-Tarbert area, Argyllshire, on the west coast of Loch Fyne, during the summers of 1948 and 1949. The study was undertaken primarily to obtain information regarding the petrology and metamorphism of the numerous epidiorite sills occurring in the area. A study of the country rocks, mainly quartzites and schists, was also made together with the local geological relations of the known mineral veins and disseminations containing copper, lead, zinc and iron with traces of gold and silver.

The term 'epidiorite' was introduced into geological literature by von Gumbel in 1874, and he defined it as a rock composed of pale-green fibrous hornblende with plagioclase, chlorite, ilmenite or magnetite, and occasional augite. To British petrographers the name signifies a metamorphosed basic igneous rock usually containing hornblende. In this paper the term is used in the latter sense.

The location of the area under study is shown in Fig.1. It includes the southern part of Knapdale and forms a part of the Mull of Kintyre. Its eastern boundary corresponds with the western coast of Loch Fyne.

## (i) Physiography.

The frequent repetition of ridge and hollow, loch and island, add character to the scenery of the district. The ridges show a concordance of summit-level at about a thousand feet, apparently resulting from dissection of a plateau at or near this height. Peach (1911,

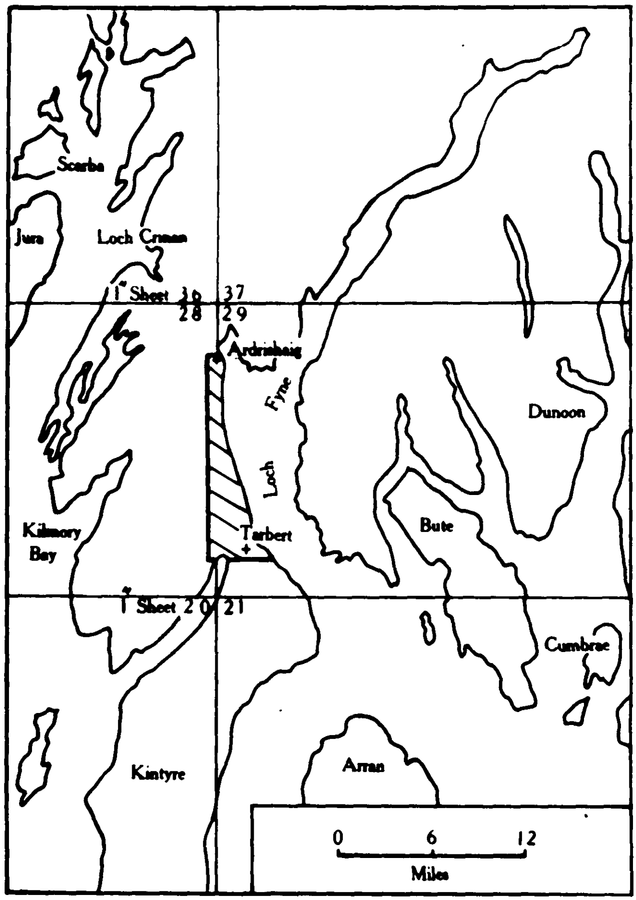


Fig. 1 Index Map showing the Location of the Area

p.2) remarked that the origin of the plateau feature is not clear. He suggested that it may be regarded as a plane of marine denudation or as a peneplane of sub-aerial erosion. It is equally uncertain, he continued, whether its level has been affected by warping subsequent to its formation. The topography apart from this plateau feature bears an intimate relation to the geological structure. The foundation of the area is an assemblage of psammitic and pelitic schists of Dalradian age, including numerous intercalated bands of epidiorite. The regional strike is N.E.-S.W. and this trend has conditioned the succession of parallel ridges and hollows characteristic of this region.

The western coast of Loch Fyne is markedly different from the eastern coast. Escarpments are absent along the former and it drops suddenly into the loch from heights of 500 to 800 ft. and the general profile is very slightly convex. The eastern coast on the other hand consists of a series of escarpments running out into low blunt promontories and numerous low islands. The general features of the coast are characteristic of submergence though the 25', 50', and 100' raised beaches may imply later emergence. Especially good illustrations of submergence are afforded by Loch Caolisport, east and west Loch Tarbert, the sound of Jura, and the basins of Loch Sween, all representing the drowning of an ancient valley system. The basin formed by Loch Gilp and lower Loch Fyne, however, shows no clear relation to the strike of the schists, and the inception of this trough has perhaps been determined by a shear-belt coincident with the present trend of the Loch (Peach and others, 1911, p.2).

(ii) Previous Research.

A detailed geological survey of this region was carried out by the Officers of the Geological Survey (Peach and others, 1911). Their work established the fact that the epidiorites are intrusive sills and perhaps lavas, as inferred from occasional pillow or vesicular structure (op.cit. p.83). McCallien continued research in the S.Knapdale and Kintyre region and published his results in a series of papers (1925, 1926, 1929, and 1935) in which he discussed mainly the structure and metamorphism of the country rocks; but the epidiorites did not receive much attention from him. Wiseman (1934) made a detailed study of the progressive metamorphism of the epidiorites in the S.W.Highlands as a whole, largely without reference to the subject of stratigraphy and tectonics because he was of the opinion that the rocks were in a metamorphosed condition before the great overfolding and thrusting postulated by Bailey and others took place and to which he assigned many of the retrograde changes that had occurred in the epidiorites (op.cit. p.357).

The writer, however, feels that the geological history of the epidiorites in this region is closely related tothe tectonics and metamorphism of the Dalradian rocks within which these occur. Consequently a brief summary of the views of previous research-workers as regards the tectonics and metamorphism of the Dalradian rocks is given below.

Tectonics.

Various tectonic theories, widely diverging in principle, have been advanced, but no general agreement has yet been reached. All such interpretations belong to three more or less clear types. The first of these, championed by Geikie, Barrow and Gregory entirely dispenses with recumbent folding and sliding and asserts that the Highlands consist of a series of gentle synclines and anticlines. Bailey is the chief exponent of of the second interpretation which involves recumbent folding and sliding. He has modified his views considerably since he stated them first in 1922. In their modified form they have much in common with the third interpretation, advocated by Peach (1930) and involving recumbent folding and sliding. Accor-to this third view the entire Highlands are made up of Lewisian, Torridonian, Cambrian and Ordovician rocks, the structure of which results from the approa-ch of two rigid blocks, one from the N.N.W. and the other from the S.S.E.

Metamorphism.

Barrow (1893) mapped out seven zones of metamorphism in the S.E.Highlands marked by the 'incoming' of the following minerals with increase in grade :- (1) clastic mica, (2) digested mica, (3) biotite, (4) garnet, (5) staurolite, (6) Kyanite and (7) sillimanite. Bailey (1923) employed different indices from those of Barrow and recognised the following zones in the S.W.Highlands :- (1) mica inconspicuous, (2) mica conspicuous, (3a) mica with garnet, (3b) mica with albite. Tilley (1925) and Elles and Tilley (1930) have traced the distribution of three metamorphic zones in the S.W.Highlands including Islay and Jura, using the index minerals chlorite, biotite and almandine-garnet.

Barrow (op.cit.) considered the metamorphic zones to be of the nature of gigantic aureoles around intrusions of Older granite, whilst Read (1927, 1939, and later) suggested that orogenic grani-tisation is responsible for the metamorphic zones and that metamorphism is later than the large-scale movements. Bailey and others have regarded the metamorphism as partly contemporaneous with large-scale movements though mainly post-tectonic. Tilley (1925) and Elles and Tilley (1930), Harker (1932) and Wiseman (1934) believe that metamorphism is pre-tectonic and has no relation to igneous action and also that the metamorphic zones can be recumbently folded. Reynolds (1942) ascribes metamorphism to igneous action but regards the phenomenon as syntectonic. Kennedy (1948) views the metamorphic zones of the Highlands as essentially the expression of a simple pitching anticline of 'thermal surfaces', obviously not related to the surface tectonics of the region but to some major element of basement structure.

(iii) Stratigraphy.

The group of rocks encountered in this region belong to the Dalradian series and the following succession is found in a traverse along the coast of Loch Fyne from Ardrishaig in the north to Tarbert and beyond in the south, with each member dipping below the one above in a N.W. direction (Fig.2).

Ardrishaig phyllites.

Stronchullin phyllites.

Erins quartzites.

Stonefield schists.

Loch Tay limestones.

Glen Sluan schists.

Green beds.

Beinn Bheula schists and grits.

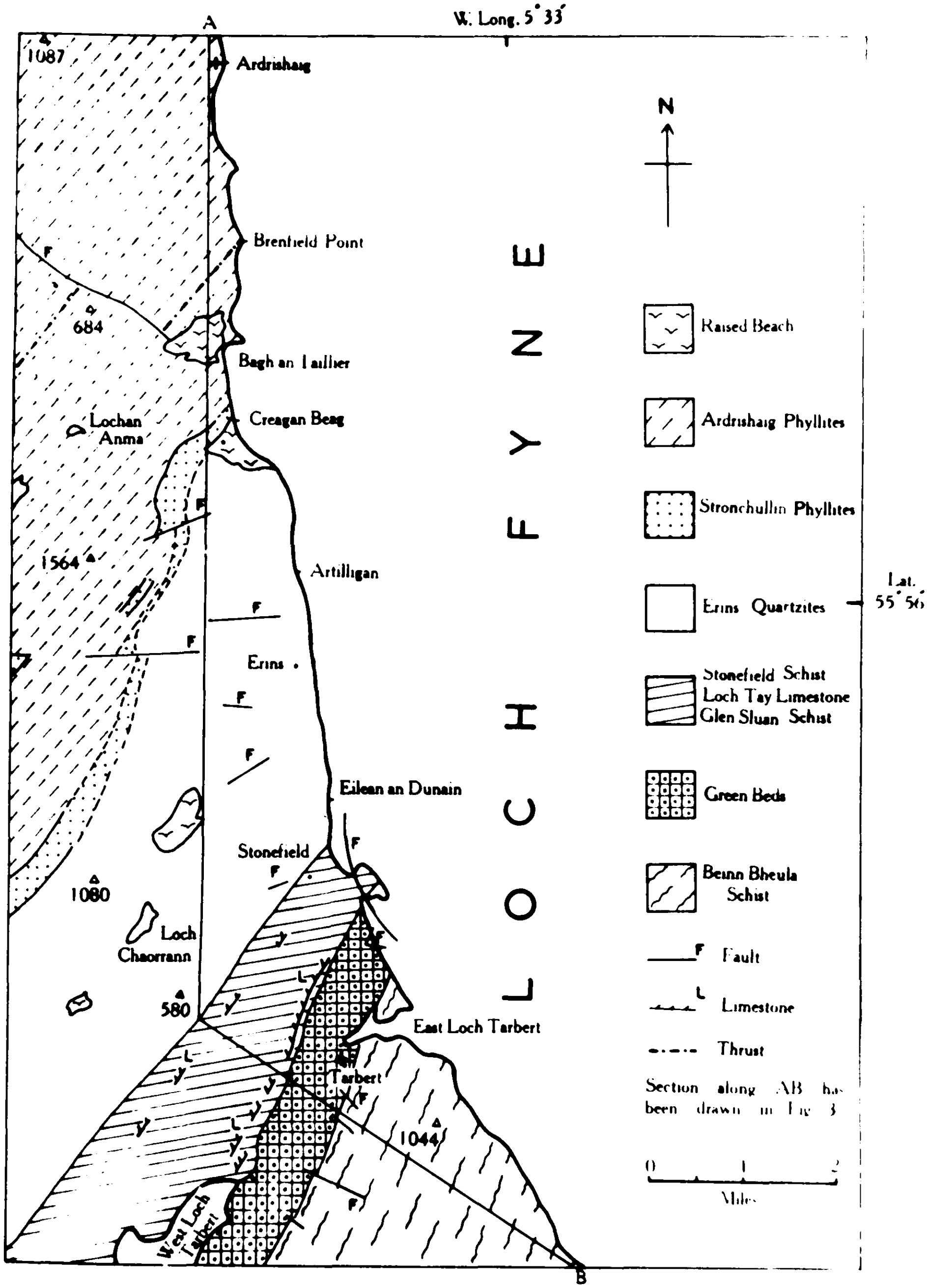


Fig. 2. Stratigraphic Map of the Ardrishaig Tarbert Area

According to one group of geologists (e.g. Geikie, Barrow, Cunningham-Craig, Wilson, Gregory, Hill and Green) who do not believe in large scale inversion of portions of the Dalradian sequence, the above represents a normal order of stratigraphic succession with the youngest rocks (Ardrishaig phyllites) at the top and the oldest rocks (Beinn Bheula schists and grits) at the bottom. But according to another group of geologists (e.g., Bailey, E.M.Anderson, Peach, Elles, Tilley, Henderson and J.G.C.Anderson) who believe in large-scale inversion of portions of Dalradian rocks, the same succession may be interpreted as inverted. The Ardrishaig phyllites thus become the oldest rocks and the Beinn Bheula schists and grits the youngest. Recent investigations by various geologists based on current-bedding and graded-bedding have confirmed the second of these views.

Bailey (1922) put forward an entirely different interpretation of the above succession, which he postulated as formed of two nappes separated by a thrust, as shown below :-

| | | |
|---|---|---|
| Loch Awe Nappe --- | Ardrishaig group | Ardrishaig phyllites. |
| | | Stronchullin phyllites.(local) |
| | | Erins quartzites. |
| | THRUST | |
| Iltay Nappe --- | Ben Lui group | Beinn Bheula schists and grits. |
| | | Green beds. |
| | | Glen Sluan schists. |
| | | Loch Tay limestones. |
| | | Stonefield schists. |

(In stratigraphical order : youngest bed at top.)

Later Bailey (Discussion, Allison 1940) abandoned the idea of a thrust separating his Loch Awe nappe from his Iltay nappe and supported Peach's interpretation (1930, Pl.XVIII, section 1) of the structure and stratigraphy of this part of the Highlands in principle. He accepted the correlation of (1) the Ben Lui schists with the Crinan grits and quartzites, (2) the Loch Tay limestone with the Tayvallich limestone and (3) the pitlochry schists and green beds with the Loch Avich grits, slates and green beds. These changes in views, on the part of Bailey, involve the following stratigraphic correlation of the rocks in the S.Knapdale and N.Kintyre region with those in the Loch Awe region :-

| S.Knapdale and N.Kintyre. | Loch Awe (Read and MacGregor 1948, p.23). |
| --- | --- |
| Beinn Bheula schists and grits. | Loch Avich grits etc. |
| Green beds. | Loch Avich lava group. |
| Glen Sluan schists. | Tayvallich slates and lavas. |
| Loch Tay limestone. | Tayvallich limestone. |
| Stonefield schists. | Crinan grits and slates. |
| Erins quartzites. | |
| Stronchullin phyllites. | -- |
| Ardrishaig phyllites, calcareous schists and quartzites. | Shira limestone. Ardrishaig phyllites. |

With the elimination of Bailey's thrust in this region, the Stronchullin phyllites become stratigraphically very important. Correlating the Stronchullin phyllites with the St. Catherines graphite schists in Cowal, Bailey (1913, p.280) was at one time of the opinion that the Erins quartzites belonged half to the Ardrishaig group and half to the Ben Lui group, but later on structural grounds (1922) he included the whole of the Erins quartzites within the Ardrishaig group. McCallien (1925, p.378) is of the opinion that the Stronchullin phyllites mark the centre of an isoclinal fold and as such are a representative of the Ardrishaig phyllites folded within the Erins quartzites. The writer, however, is inclined to go back to Bailey's earlier suggestion (op.cit.). The lower limit of the Ardrishaig group in Cowal was originally taken by Clough (1897) at the horizon of the St. Catherines graphite schists. Following the same horizon in S.Knapdale the Stronchullin phyllites thus represent the boundary of the Ardrishaig group. Therefore, the band of quartzites to the north of this horizon belong to the Ardrishaig phyllites whereas the band to the south is the Erins quartzites forming the base of the Stonefield schists. The correlation of the S.Knapdale and N.Kintyre succession with that of Cowal and with the standard Perthshire succession is shown below (Read and MacGregor, 1948, p.22) :-

| S.Knapdale and N.Kintyre. | Cowal. | Perthshire. |
|---|---|---|
| | Phyllites and schistose pebbly grits. | Leny grits. |
| | Bull Rock greywacke schists. | |
| | Dunoon phyllites. | Aberfoyle slates. |
| Beinn Bheula schists. | Beinn Bheula schists. | Ben Ledi grits. |
| Green beds. | Green beds. | Green beds. |
| Glen Sluan schists. | Glen Sluan schists and grits. | Pitlochry schists and grits. |

| | | |
|---|---|---|
| Loch Tay limestone. | Loch Tay limestone. | Loch Tay limestone. |
| Stonefield schists. | | |
| | Ben Lui garnetiferous mica-schists. | Ben Lui garnetiferous mica-schists. |
| Erins quartzites. | | |
| Stronchullin phyllites. | St. Catherines graphite schists. | |
| Ardrishaig phyllites. | Ardrishaig phyllites. | Ben Lawers schists. |

(iv) Tectonics.

It has been established that the metamorphic rocks of S.Knapdale and N.Kintyre are a continuation to the S.W. across Loch Fyne of part of the Cowal rocks, and that the structures in both districts are similar. Bailey (1938) holds the view that structurally the Cowal rocks consist of a recumbent anticline, namely the Carrick Castle fold and a complementary recumbent syncline, the Ben Lui fold. The repetition of beds on both sides of the Ardrishaig phyllites brings out the presence of a recumbent anticline, corresponding to the Carrick Castle fold, in this region. Thus the Loch Awe succession north of the Ardrishaig phyllites forms the uninverted upper limb and the S.Knapdale and N.Kintyre succession the inverted lower limb of this recumbent anticline. The latter succession may also be looked upon as the upper limb of the Ben Lui recumbent syncline. The Cowal anticline which is not a normal one indicated by bedding but a pseudo-anticline shown only in the foliation, emerges on the western shore of Loch Fyne and traverses the central portion of Kintyre thus arching up the Beinn Bheula rocks into a major open anticline. These structural features are illustrated in Fig.3.

A marked foliation affects all the rocks of

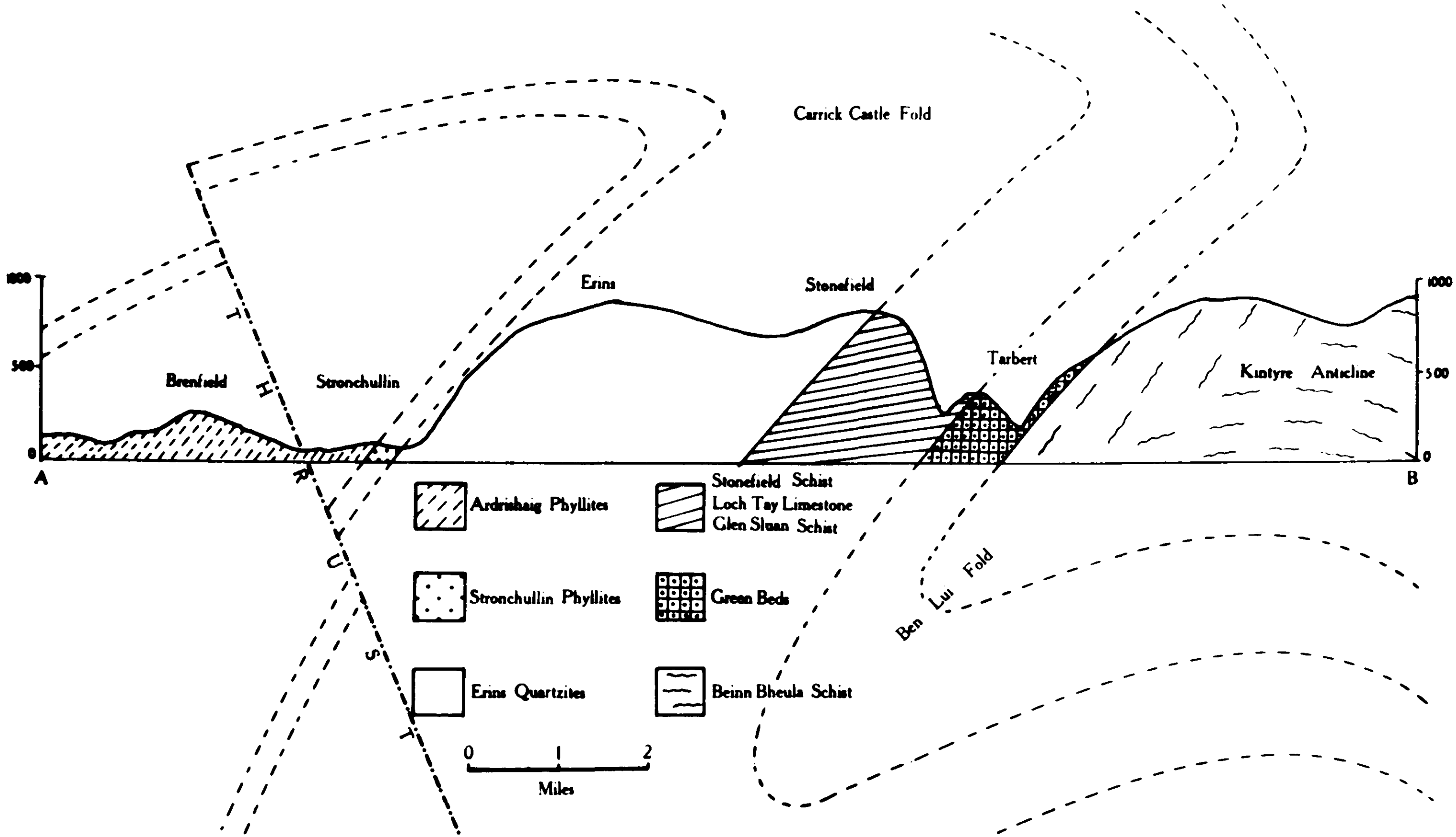


Fig. 3. Section along AB as indicated in Fig. 2.

this region. This foliation has developed parallel to the bedding planes in these rocks and is seldom found to cut across such planes. Southwards from Ardrishaig the schists show low angles of rolling dip ranging from 20° to 40° to the N.W. as far as Bagh an Taillier. From this point to Stonefield the schistosity is folded into a series of minor and open anticlines and synclines, with gently sloping N.W.-limbs but comparatively steep S.E.-limbs, the axes thus being inclined in a N.W. direction. The axial inclination increases towards Stonefield when some very highly inclined schists occur. From Stonefield southwards the dip approaches verticality and at Glenralloch sharply swings into the opposite direction i.e., S.E. The direction of dip changes back again to N.W. at Tarbert and continues in a rolling manner further south, where again minor anticlines and synclines appear in close succession. Thus it appears that the intensity of deformation increases from Ardrishaig southwards, reaches a maximum in the neighbourhood of Tarbert, and decreases again further south.

Minor structural features noticed in these schistose rocks are the following :-

(a) Drag folds - small folds of this nature are very common in the Ardrishaig phyllites, especially when the schists are sandwiched between quartzite beds. These folds may have developed in the schistose rocks due to relative movement of the quartzite beds along their bedding planes. Leith (1923, p.176) believes that drag between major competent formations in anticlinoria and synclinoria may cause drag folds as well as minor folds.

(b) <u>Fracture cleavage or False cleavage or Strain-slip cleavage</u> -

Schistose rocks frequently cleave along surfaces of rupture. Such surfaces may originate in more than one way and may later be modified or intensified by post-tectonic crystallisation of new mineral grains. These have been attributed by many writers to superposition of a second deformation upon that responsible for the main schistosity. Becker (1907) on the other hand offered an ingenious explanation for the simultaneous development of (1) schistosity resulting from plastic flow on one set of planes of maximum shearing stress, and (2) fracture cleavage originating by rupture on the second set of planes, during deformation involving rotational strain. Modern students of rock-fabrics e.g., Sander and Eskola, attach great importance to Becker's theory. Ingerson (1936), Knopf and Ingerson (1938), and Turner (1940) have suggested that strain-slip cleavage, apart from being the superposition of one deformation upon another, may also be due to a change in the movement-plan in the later stages of a long-continued deformation.

Clough recognised two great stages in the movement-history of the district leading respectively to :-

(a) the deformation of a series of isoclinal folds with their main foliation lying parallel to their axial planes.

(b) the formation of secondary anticlines and synclines affecting the limbs of the isoclinal folds mentioned in (a) and arching them up.

Bailey (1923, p.317) from metamorphic considerations supports Clough's idea. The conception of the universal presence of isoclinal folds in the Highlands has, however, recently been repudiated by several geologists. McCallien (1926) reports that in the Beinn

Bheula schists isoclinal folds are exceptional. Allison (1940) from stratigraphical considerations and also from observations on graded bedding came to the conclusion that the essential structure of the Tayvallich, Danna, and Kilmartin districts consists of a series of visible anticlines and synclines. The writer finds that the main folds in these group of rocks, as exposed along the coast of Loch Fyne in S.Knapdale and N.Kintyre, are broad and open, though with inclined axes, and it appears that the sort of structure Allison has described in Tayvallich region continues into this area.

The writer recognises three distinct stages in the movement-history of this region. The first can be recognised in the development of schistosity and its deformation, the second in the major folding and arching of the schists, and the third in the development of widespread dislocations resulting in thrusts and faults. The process of the development of schistosity and its deformation during the first stage will be discussed later (p.92). The major open folds are the Kintyre anticline (a continuation of the Cowal anticline) and the Loch Awe syncline. A thrust occurring just north of Bagh an Taillier is a representative of the third stage of movement. Elles and Tilley (1930) have described this thrust in detail and are of the opinion that it is a continuation of the Ericht-Tyndrum fault occurring further N.E. and that the driving force for this thrust came from the S.E. A fault cuts across the line of thrust and can be followed along the valley of the Inverneil burn. Southwards from Inverneil a number of minor faults with a general W.N.W. trend occur. All these dislocations are shown in Fig.2.

(v) Petrology.

In later pages of this account the petrological characters of the epidiorites and the country rocks from the chlorite, biotite, and garnet zones of metamorphism are described separately. Their place in the metamorphic facies classification as given by Turner (1948) is pointed out, and the chemistry of five analysed specimens of epidiorite is discussed. The three zones of metamorphism mapped by Tilley (1925) and Elles and Tilley (1930) in this part of the S.W.Highlands are shown in Fig.4 and the distribution of epidiorite outcrops mapped in selected areas in these zones, as indicated in Fig.4, is shown in Figs.5, 6, 7, and 8.

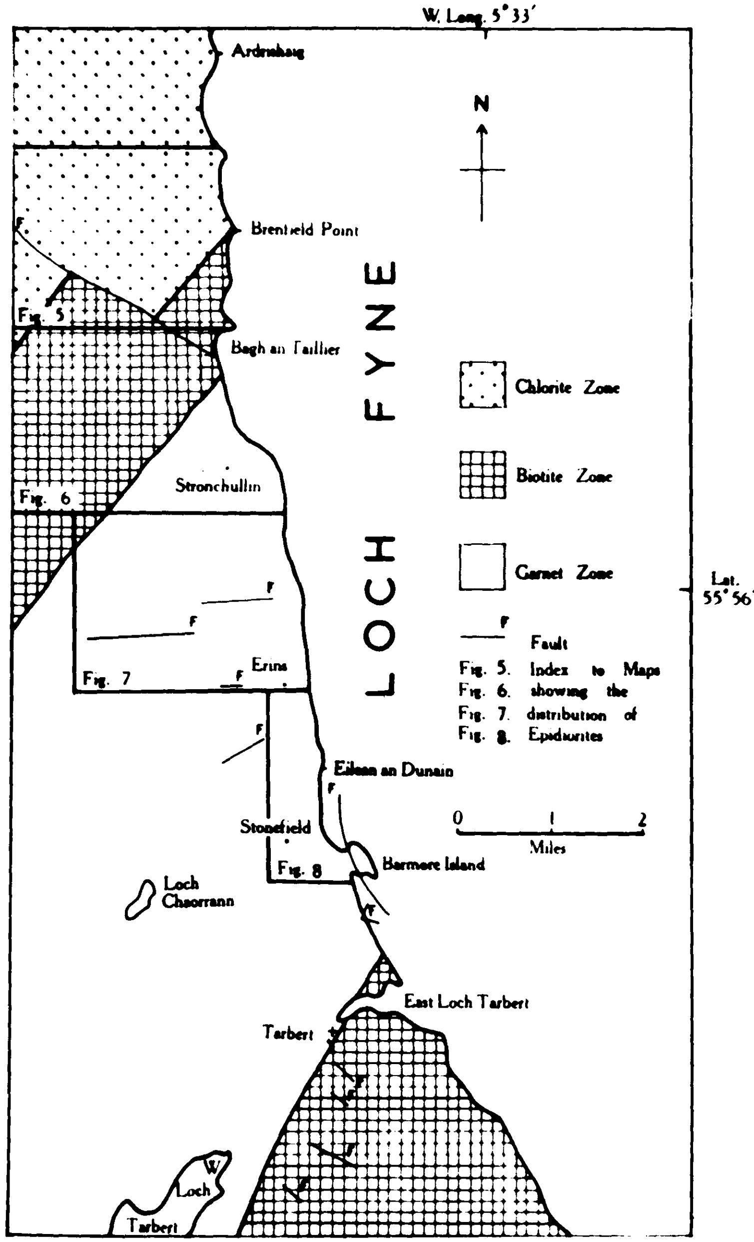


Fig. 4. Metamorphic Map of the Ardrishaig – Tarbert Area.

## II. CHLORITE ZONE.

### A. Epidiorites.

Distribution.

The distribution of the epidiorites mapped in the chlorite-zone is shown in Fig.5. The largest outcrop is the Cnoc nam Muc sill almost in the middle of this zone. It is 1 1/4 mile long and is more than 300 yds. broad in places. It is well-exposed throughout its outcrop being broadest at its southern end and tapering out northwards. It is flanked on both sides by minor epidiorite sills. Smaller sills occur (1) near Beinn Bheag at the N.W. corner of the map, (2) west of Cruach Mhea-dhonach, (3) at and near Cruach Brenfield, N.W. of Cnoc nam Muc, and (4) at Creag Auchbraad, S. of Cnoc nam Muc. Besides these, minor thin sills of epidiorite outcrop throughout the chlorite zone. The outcrop of the epidiorites covers about 27.7% of the total area of the chlorite zone mapped.

Megascopic features.

In hand-specimens the epidiorites from the chlorite zone vary widely in their characters. The colour varies from very dark green to pale green, the lustre varies from silky to dull. Massive types range from fine-grained, through medium-grained to very coarse-grained varieties. The texture varies from coarse equigranular and gneissose to thinly schistose types. Chlorite is the predominant mineral and is easily identified megascopically. Plagioclase and hornblende are conspicuous. Quartz is visible in some specimens and is occasionally blue in colour. Specks of pyrite are common. Occasionally thin quartz-calcite-albite veins

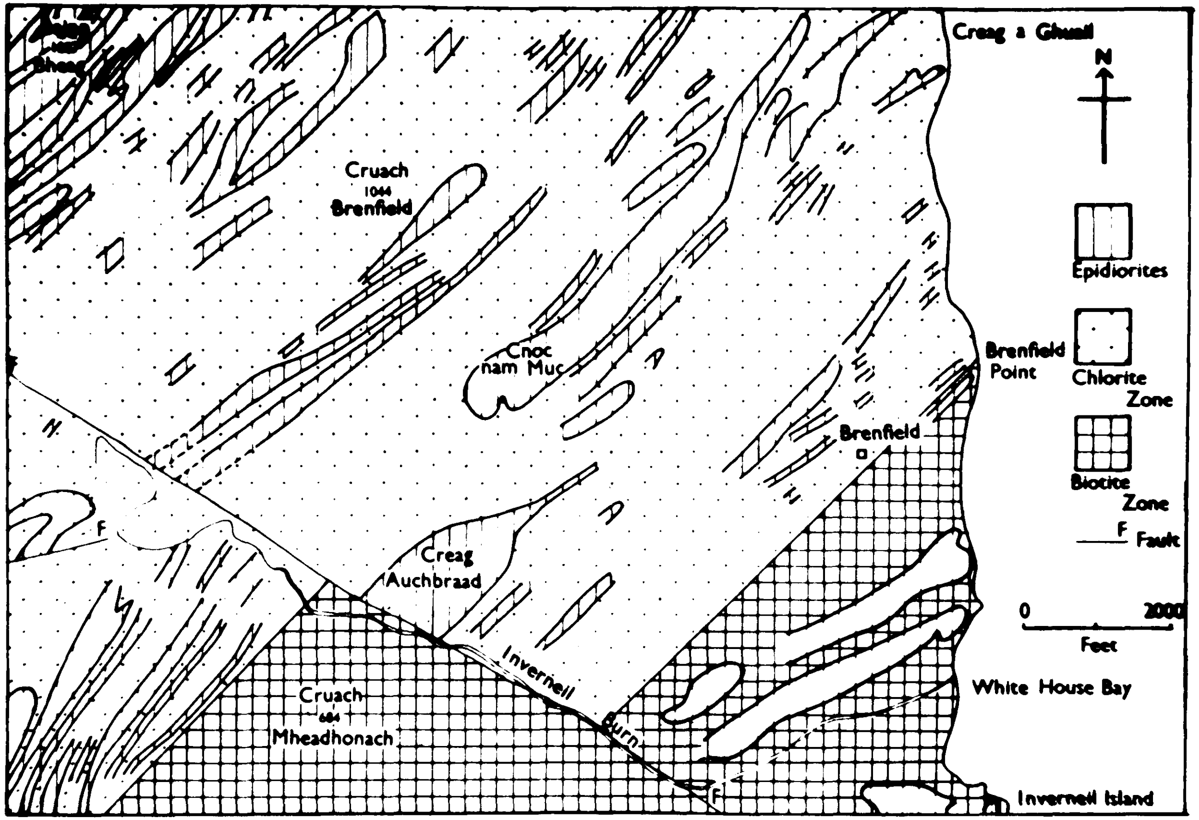


Fig. 5. Map of the Outcrop of Epidiorites in the Chlorite and Biotite Zones as Indicated in Fig. 4.

traverse the epidiorite sills. Such veins are generally parallel to the schistosity but sometimes cut across it. Massive types of epidiorites are invariably free from such veins. A few occurrences of milky white vein-quartz, occasionally metalliferous, have been noticed in epidiorites from fault zones.

Texture.

In thin section the epidiorites are extremely variable in both texture and mineralogy. Textural varieties include relict, cataclastic, pseudo-cataclastic, micrographic, myrmekitic, crystalloblastic, and symplektitic.

1. Relict textures (Pl.I).

Textures distinctive of primary igneous rocks, such as porphyritic, ophitic, poikilitic, granitic, can be recognised as relicts in these epidiorites, and such textures have been named blastoporphyritic, blastoøphitic, blastopoikilitic and granoblasic respectively (Turner 1948, p.152). In these rocks the primary phenocrysts of augite or plagioclase, though reconstituted, still retain their crystallographic forms but are now represented by pseudomorphs of hornblende and albite or saussurite respectively.

2. Cataclastic texture (Pl.II,1).

A number of slides of epidiorites from zones of dislocation show remarkable cataclastic texture. Gradations from slight shearing and bending of crystals to mylonitic schistosity can be recognised.

3. Pseudo-cataclastic texture (Pl.II,2).

This differs from true cataclastic texture in that the grains of the groundmass are not fragments of the larger grains and also that there is a strong suggestion of corrosion of the larger grains by the groundmass. The groundmass of pseudo-cataclastic texture, in some instances at least, represents the residual portions of the replaced rock, the larger felspar grains being actually metacrysts, the growth of which may have involved both the recrystallisation of minerals already present and the introduction of new materials. Pseudo-cataclastic texture is chiefly of replacement origin and the dominant aspect of this type of texture is one of corrosion rather than of brecciation (Anderson,G.H., 1937, p.54).

4. Micrographic texture (Pl.II,3).

Locally the epidiorites have a handsome micrographic texture and elsewhere a less regular graphic texture. Rosettes of graphically intergrown albite and quartz attain diametres of 2 mm. or even more. A brief survey of some of the more important literature dealing with micrographic intergrowths of all kinds reveal the fact that such textures are characteristic of rocks formed near igneous contacts, as a result of incomplete reaction between liquid magma or magmatic fluids and invaded rocks or xenoliths. Fenner (1926, pp.737,753) has pointed out that graphic intergrowths may be considered as diagnostic criteria of rocks which have originated by reaction between magma and country rocks. Replacement origin for some graphic intergrowths has been proved by their presence in certain adinoles by Gillson (1927, p.8) and Daly (1905, p.190). Although Tyrrell (1927, p.64) regards some graphic textures as of eutectic origin he agrees that others can form in other ways too. Gilluly (1933, p.72) has pointed out that graphic texture may be formed in any of at least four probable ways - (1) simultaneous intergrowths not in eutectic proportions, (2) by eutectic crystallisation, (3) by unmixing of solid solutions, and (4) by replacement. The writer, however, believes that the graphic textures developed in the epidiorites result from replacement of original plagioclase by quartz, large crystals of which now act as hosts to the graphic or vermicular quartz inclusions. This type of origin has already been demonstrated by Sugi (1930, pp.40,66,67) for some myrmekitic intergrowths and by others (Schaller, 1925, p.20) for graphically intergrown quartz and orthoclase.

5. Myrmekitic texture (Pl.II,4).

Typical myrmekitic intergrowths of plagioclase and vermicular quartz have been noticed in many slides. There is a gradation between myrmekitic and graphic textures and their close association suggests a common origin for both. Myrmekite is recognised as a replacement product in both metamorphosed and unmetamorphosed rocks. According to Holmes (1920, p.164) the term myrmekite was introduced by Sederholm in 1899 to include intergrowths of "plagioclase and vermicular quartz, generally replacing potash felspars, formed during the later or paulopost stages of consolidation or during a subsequent period of plutonic activity." Later writers (Tilley 1921, pp.87,88 ; Read 1931, p.149) have stressed the fact that myrmekite usually developes where crystals of plagioclases are in contact with orthoclase or microcline and it is thus generally held to be a product of replacement of potash felspar by acid plagioclase. Sugi (1930, pp.40,66,67) describes several cases where the myrmekite could not have originated in this way, and shows that in those particular instances the intergrowths were probably produced by partial replacement of plagioclase by quartz. A similar explanation should hold true for the myrmekites under discussion, because these are independent of the presence or proximity of potash felspars. A local source for the soda and silica in myrmekite formation has been generally accepted, but Sederholm admits and Tronquoy demands the presence of circulating alkaline solutions of extraneous source in its formation (Gilluly 1933, p.71).

6. Crystalloblastic texture (Pl.III.1).

Textures resulting from chemical reconstitution and growth of new crystals in an essentially solid medium have been called crystalloblastic (Turner 1948, p.154). The term was introduced by Becke in 1903 to cover structures of the crystalline schists, but now-a days it is generally extended to textures of similar origin and character in rocks resulting from contact or metasomatic metamorphism. In the chlorite zone, albite and quartz are the most perfectly developed crystalloblasts with sharply bounded (idioblastic) crystals, whereas amphibole and chlorite crystalloblasts are generally irregular in outline (xenoblastic).

7. Symplektitic texture (Pl.III,2).

In some of the plagioclase crystals development of swarms of epidote grains accompanied by small hornblende prisms is commonly observed. In some cases, most of the plagioclase has disappeared and its place seems to have taken by large symplektitic associations of epidote, as the host, filled with hornblende, quartz, and scanty fresh acid plagioclase in small enclosures. Similar epidote-quartz-symplektite has been described by Read (1937B, p.218).

Mineralogy and Mineral Habits.

1. Felspars.

The predominant felspar in the epidiorites of the chlorite zone is albite, which has the following characters : maximum extinction angle in the [100-001] zone is 12°-16°; $\alpha$ = 1.532 - 1.535 and $\gamma$ = 1.539 - 1.541 respectively ; (+) 2V = 73° (in S.208). These characters indicate a composition of about $Ab_{95}An_{5}$ to $Ab_{100}$. Sometimes albite forms large plates, up to about 0.5 cm. in length, approximately rectangular, with somewhat irregular edges. Occasionally the prism is the commoner form. Simple carlsbad and lamellar twins are frequent. Two extreme textural types can be recognised, between which there is every gradation ; a type in which albite is almost exclusively formed of large crystals, and a type in which large crystals are few and are formed of irregularly intergrown albite. In sheared specimens albite crystals are strained, bent, and broken (Pl.II,1).

A wide variety of mineralogical habits suggestive of replacement origin can be recognised in the felspars : these include saussuritic, crystalloblastic, clouded, myrmekitic and micrographic, and chess-board types.

(a) Saussuritic felspar (Pl.I,1).

The inner parts of many of the plagioclase crystals are obscured by masses of highly refracting grains of epidote, and sericite, sometimes throughly masking the felspar base in which they are embedded. Little migration of material is generally supposed to have taken place in such saussuritic alterations, the bulk composition of the original being essentially duplicated by that of the mineral aggregate replacing it. Turner (1948, p.121) has discussed saussuritisation of plagioclase felspars in some detail and has pointed out that this process is sometimes complimentary to and intimately connected with, other mineralogical changes such as uralitisation of pyroxene- which takes place simultaneously. He is also of the opinion that saussuritisation may be an independent metasomatic process, the sole result of which is the replacement of plagioclase crystals by albite-epidote pseudomorphs regulated by the equal volume law. From this point of view, however, he regards the conventional equations depicting replacement of the anorthite component of the plagioclase by epidote and minor quartz with loss of $Al_2O_3$ as inadequate, since it would result in a volume decrease of about 20% as shown below :-

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $4CaAl_2Si_2O_8$ | | | | $2Ca_2Al_3(SiO_4)_3(OH)$ | | $2SiO_2$ | | $Al_2O_3$ |
| (Anorthite) | + | $H_2O$ | $\longrightarrow$ | (Clinozoisite) | + | (Quartz) | + | (removed in solution) |
| 1112 gm.= 405 cc. | | | | 908 gm. = 271 cc. | | 120 gm. = 45 cc. | | |

Two alternatives that satisfy the volume requirements have been suggested. The first involves the introduction of lime, silica, and some alumina ( all of which could be contributed as by-products of uralitisation of pyroxene in the same rock ) and can be represented approximately by the following equation :-

$$\underset{\substack{\text{Anorthite} \\ 806 \text{ cc.}}}{8CaAl_2Si_2O_8} + 4CaO + 2SiO + Al_2O_3 + 3H_2O \longrightarrow \underset{\substack{\text{Clinozoisite} \\ 813 \text{ cc.}}}{6Ca_2Al_3(SiO_4)_3(OH)}$$

The second assumes introduction of soda, perhaps as a result of the activity of magmatically derived aqueous solutions containing sodium silicate or carbonate (an instance of autometasomatism). The following equation is offered as satisfactory :-

$$\underset{\substack{\text{Anorthite} \\ 1209 \text{ cc.}}}{12CaAl_2Si_2O_8} + 2Na_2O + 6SiO_2 + 3H_2O \longrightarrow \underset{\substack{\text{Clinozoisite} \\ 813 \text{ cc.}}}{6Ca_2Al_3(SiO_4)_3(OH)} + \underset{\substack{\text{Albite} \\ \text{( removed in} \\ \text{solution).}}}{4NaAlSi_3O_8}$$

The writer favours the second of these equations as likely to have been most effective in bringing about saussuritisation in these epidiorites, because the alteration of hornblendes appear to be closely associated with such changes in these rocks. The third of these equations may have been effective locally.

(b) Crystalloblastic albite (Pl.III,3).

A number of specimens contain water-clear albite with no saussuritic products at all. A clear gradation from water-clear to saussuritic albite can, however, be recognised through two intermediate varieties, (i) those in which secondary minerals e.g., epidote, calcite, sericite, are unevenly scattered through albite crystals giving rise to a mottled surface and (ii) those in which such minerals are evenly distributed and are not concentrated in definite areas. As long ago as 1875 Credner called attention to the fact that nearly pure albite is a good sign of hydrothermal action, and Schaller (1925, p.279) has stated that no felspar more sodic than $Ab_{95}An_5$ could ever be pyrogenic. Whether or not this sweeping generalisation will hold in this case, there can be no question that most felspars so sodic are of non-pyrogenic origin, and ~~can~~ consequently their occurrence here is suggestive of a replacement origin (Gilluly 1933, p.74).

(c) Clouded albite (Pl.III,4).

Clouded albite is common in the chlorite zone epidiorites and the clouding appears to be due to minute inclusions of iron ore. MacGregor (1931) has assembled evidence to show that such clouding is characteristic of many contact altered rocks, and has suggested that the iron, now present as minute inclusions, was originally dissolved in the felspar, though it may have been concentrated to some extent by migration. It has since been shown that clouding is sometimes present in newly-formed felspars developed in rocks which have been recrystallised with concomitant introduction of mafic materials (Grout 1933, p.1041 ; Reynolds 1936, p.341-2), and that it may represent a forward migration of iron, sometimes of country rock origin, through such rocks (Anderson,G.H.,1937, p.65-67). Reynolds (1946, p.435-6) has forecast that further investigation of clouding of felspars may show that, when present, it may be a useful criterion in the recognition of rocks produced by the basification of pre-existing types. The presence of clouded felspars in Rock No.208 ( for petrographic and chemical description see pp.36-9) associated with abundant sphene and apatite appears to support this view.

(d) Micrographic and Myrmekitic albite (Pl.IV,1).

Sometimes individual crystals of albite show lace-like myrmekitic fringes. More often these show intimate intergrowth relations with quartz giving rise to micrographic albite. The genetic significance of these textures has already been discussed (pp.16-18) and the cumulative evidence indicates a replacement origin for both.

(e) Chess-board albite (Pl.IV,2).

Chess-board albite is characterised by a blocky twining, the twin lamellae being short and broad and discontinuous, giving the crystal an appearence similar to that of a chess-board. Becke considers this to have originated by the complete replacement of orthoclase by albite (Anderson,G.H.,1937,p.64). King (1942, p.158) has suggested that the same may have been due to stress during albitisation. The occurrence of this variety of albite, commonly regarded as typical of replacement (Read and others 1926, p.26-7), lends additional support to the more direct evidences in favour of a secondary origin of albite in these rocks, though in Tilley's view (1919, p.328-9) its intrinsic value as evidence is slight.

2. Amphiboles.

Four varieties of amphibole have been recognised in the chlorite-zone epidiorites :-

(a) Green hornblende -

Common hornblende occurs as stout subhedral prisms, up to about 5 mm. long, or as irregular, somewhat rounded grains or aggregates. It often shows twinning. The scheme of pleochroism is : X = pale yellow brown, Y = yellow green, and Z = green. Other optical properties are - $Z \wedge c = 22^\circ - 25^\circ$; and (-) $2V = 55^\circ$ (s.149). The extreme refractive indices determined are $\alpha = 1.655$ and $\gamma = 1.688$ which give a birefringence of 0.013. In a number of slides a good basal section of the mineral can be recognised with cleavages at $125^\circ$ approximately.

(b) Hastingsite -

The blue-green colour and strong pleochroism are the principal diagnostic features of this amphibole. It occurs in independent small flakes and larger prisms and occasionally as rims round hornblende crystals. The scheme of pleochroism is : X = brown yellow, Y = olive green, Z = blue green ; $Z \wedge c = 18^\circ - 23^\circ$; (-) $2V = 65^\circ$ (s.208) ; $\alpha = 1.665$ and $\gamma = 1.675$, which give a birefringence of 0.010. These properties do not indicate any notable content of alkalies. Alkaline amphiboles have higher refractive indices ($\gamma = 1.70$) and smaller optic angles ($2V = 15^\circ - 20^\circ$) as described by King (1942, p.162-3). The properties of these hastingsites agree fairly well with those described by Reynolds and Holmes (1947E, p.31) and their refractive indices higher than hornblende may be due to higher FeO/MgO ratio (Wiseman 1934, p.384).

(c) Actinolite -

Actinolite occurs in ragged needles, spongy prisms, and irregular outgrowths, commonly around but rarely penetrating hornblende crystals. It also occurs independent of hornblende crystals and is generally closely associated with grains of iron ore and tiny blebs of clear albite. It has a characteristic pale green colour distinct from hornblende or hastingsite. The scheme of pleochroism is : X = pale yellow green, Y = pale green, and Z = pale blue green ; $Z \wedge c = 15^\circ - 20^\circ$ ; (-) $2V = 75^\circ$(s.197) ; $\alpha = 1.645$ and $\gamma = 1.665$, which gives a birefringence of 0.020. Chemically the actinolite contain a very small quantity of $Al_2O_3$ by weight, usually less than 4%. This is in contrast to aluminous hornblendes described elsewhere, e.g., green hornblende or hastingsite (Turner 1948, p.94 ; Wiseman 1934, p. 382-5).

(d) Tremolite -

Tremolite occurs in a similar manner to actinolite and has similar optical properties, but it is distinguished by being paler or even colourless. The pleochroic scheme is : X = very pale yellow green, Y = pale green, and Z = pale blue green ; $Z \wedge c = 16^\circ - 20^\circ$; (-) $2V = 85^\circ$(s.3) ; $\alpha = 1.635$, and $\gamma = 1.655$, which gives a birefringence of 0.022. Chemically tremolite is poorer in FeO than actinolite.

The four varieties of amphibole occur closely associated and appear to be genetically related. Turner (1948, p.98) has suggested the following genetic connection with decreasing grade of metamorphism in basic igneous rocks :-

Brown hornblende or Augite ( high temperature igneous facies)

↓

Common green hornblende ( amphibolite facies )

↓

Blue green hornblende ( albite-epidote-amphibolite facies )

↓

Actinolite or Tremolite ( green-schist facies )

Thus brown hornblende or augite under suitable physico-chemical conditions would give rise to actinolite in the chlorite zone; and this change may not always be direct but may pass through intermediate phases, in accord with the law of Oswald. Such intermediate phases may be recognised in the presence of green hornblende and blue-green hornblende (- hastingsite) in the chlorite zone, which remain as stable relics. The writer has noticed no relics of brown hornblende or augite in these epidiorites but others have recorded such occurrences in neighbouring areas (Peach and others 1909, p.52 ; Wiseman 1934, p.369).

3. Chlorite.

Chlorite is almost constantly present in all the epidiorites from this zone. It occurs in relatively well-developed laths and has a faint pleochroism. In some cases, however, the colour is intensely green and the pleochroism is more marked. It generally has a very low birefringence and hence the interference colours are low, sometimes anomalous browns or violets. Refractive index ($\beta$) determinations on twenty samples vary from 1.61 to 1.635, out of which thirteen are optically positive and the rest optically negative. Evidently the positive chlorites are ripidolite (Winchell, Vol.II, 1948, p.284) with Mg:Fe = 60:40 to 40:60. The negative chlorites are probably diabantite, which Winchell (op.cit. p.283) has described as a ferriferous clinochlore with Mg:Fe = 60:40 to 40:60.

The chemical composition of a chlorite out of an epidiorite (Rock No.178, see p.40) from the chlorite zone has been approximately estimated in Table 1., after subtracting 16.4% of linearly estimated quartz and by allotting all the $CO_2$ of the bulk analysis to calcite, all the alkalies to felspar, and all the $TiO_2$ to iron ores. This chlorite (A) is compared below in Table 2. to two others, (B) and (C) respectively. (B) has been calculated out of an epidote-quartz-ripidolite skarn by Reynolds and Holmes (1947E, p.46) and (C) out of a chlorite-albite schist by Wiseman (1934, p.362). (A) and (B) are both ripidolite and are very similar in chemical and optical properties, whereas (C) is a prochlorite. It is more ferriferous and has a higher refractive index than either (A) or (B).

4. <u>Stilpnomelane</u>.

Stilpnomelane is commonly associated with chlorite in the epidiorites but is not as abundant. It is generally brown but occasionally green in colour. It is strongly pleochroic with X = yellow brown, Y = Z = dark brown or greenish brown , optically negative, and its refractive index ($\beta$) varies from 1.625 to 1.645. This mineral has sometimes been mistaken for biotite or green biotite from the chlorite zone. According to Winchell (1948, Vol.II, p.435) it closely resembles biotite in optical properties but is chemically related to chlorite. It has a distinctly lower birefringence than biotite. Turner (1934, p.171) and Turner and Hutton (1935)

Table 1.

| | M.P. | Quartz | Cal-cite | Apa-tite | Iron ore | Felspar | | | Chlorite | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 16.4% | | | | Ortho-clase | Albite | Anor-thite | M.P. | % in rock | Compo-siton% |
| $SiO_2$ | 743 | 273 | - | - | - | 12 | 270 | 24 | 164 | 9.84 | 27.20 |
| $Al_2O_3$ | 124 | - | - | - | - | 2 | 45 | 12 | 65 | 6.63 | 18.98 |
| $Fe_2O_3$ | 6 | - | - | - | - | - | - | - | 6 | .96 | 2.72 |
| FeO | 153 | - | - | - | 21 | - | - | - | 132 | 9.50 | 26.89 |
| MnO | 5 | - | - | - | - | - | - | - | 5 | .39 | 1.07 |
| MgO | 116 | - | - | - | - | - | - | - | 116 | 5.64 | 13.14 |
| CaO | 168 | - | 153 | 3 | - | - | - | 12 | - | - | - |
| $Na_2O$ | 45 | - | - | - | - | - | 45 | - | - | - | - |
| $K_2O$ | 2 | - | - | - | - | 2 | - | - | - | - | - |
| $H_2O+$ | 196 | - | - | - | - | - | - | - | 196 | 3.53 | 9.99 |
| $CO_2$ | 153 | - | 153 | - | - | - | - | - | - | - | - |
| $TiO_2$ | 21 | - | - | - | 21 | - | - | - | - | - | - |
| $P_2O_5$ | 1 | - | - | 1 | - | - | - | - | - | - | - |
| % | - | 16.4 | 15.38 | .33 | 3.20 | 1.11 | 23.58 | 3.33 | - | 36.49 | 99.99 |

M.P. = Molecular proportion.

Calculated mineral composition of Rock No. 178, based on a linear estimation of 16.4% of quartz.

Table 2.

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 27.20 | 27.42 | 28.20 |
| $Al_2O_3$ | 18.98 | 18.73 | 24.9 |
| $Fe_2O_3$ | 2.72 | 4.99 | 0.2 |
| FeO | 26.89 | 24.36 | 26.8 |
| MnO | 1.07 | 0.78 | - |
| MgO | 13.14 | 13.49 | 10.9 |
| $H_2O$ | 9.99 | 10.23 | 9.0 |
| | 99.99 | 100.00 | 100.00 |

A. Chlorite out of a chlorite-albite-calcite schist (Rock No. 178) ; Locality - from the S.W. edge of Cnoc nam Muc sill, near Ardrishaig, S. Knapdale.
For the chlorite, $\beta$ = 1.625, optically (+) ve.

B. Chlorite out of an epidote-quartz-ripidolite skarn (355), from the lower sill, White Cow Rock, Pebble Strand, Malin Head, Co. Donegal, Eire.

For the chlorite, $\beta$ = 1.627, optically (+) ve.

(Comptes Rendus de la Societé geologique de Finlande N:O XX, p.46, 1947)

C. Chlorite out of a chlorite-albite schist (248/5), eastern side of Eilean Traighee, W. of Tayvallich, S. Knapdale.

For the chlorite $\beta$ = 1.637, optically (-) ve.

(Q.J.G.S. Vol XC, p.362, 1934).

have pointed out that the very occurrence of this mineral in rocks representing an extremely low grade of metamorphism supports its identification as stilpnomelane. Biotite is always developed in an advanced grade of metamorphism. Finally the characteristic mode of occurrence of this mineral, as a close associate of chlorite and in no way dependent upon the presence or proximity of sericite, is in itself strong evidence against identification as biotite.

5. Epidote.

The epidote group of minerals are constantly present. All three types e.g., zoisite, clinozoisite, and epidote have been recognised. Zoisite has straight extinction and is usually associated with tremolitic amphiboles. Clinozoisite and epidote, with oblique extinction and both (+) and (-) elongation, are more abundant and occur associated with ferriferous amphiboles. The epidote has a strong tendency to occur in moderately large crystals. In some slides epidote crystals tend to be seggregated together whereas in others these are almost absent. This has been explained by Sundius (1923) as being due to the mobility of epidote.

The iron content of the epidotes is variable. In some specimens interference colours characteristic of clinozoisite can be observed, while in others the epidote gives third order carmine colours and has a strong yellowish pleochroism. Sometimes zoned epidote crystals can be recognised, the shell being more ferriferous than the core. Part of the ferric-ion contained in the epidote may have originated from the magnetite or ilmenite in the original rock, because the production of albite and epidote is generally concomitant with leucoxenisation or production of sphene.

6. Quartz.

Quartz-content is usually small in these rocks but varies greatly, and unusual abundance has been noticed in some. Generally it has a clear appearence ; but occasionally it is full of inclusions of rutile needles (Pl.IV,3) which in hand specimens give the quartz a bluish appearence. It is noteworthy that rutile, specially in needle form, is commonly regarded as of hydrothermal origin and that it is the commoner titanium mineral in many rocks rich in albite and quartz (Gilluly 1933, p.74).

7. Tourmaline.

Dark brown or dirty brown or bluish needles of tourmaline occur sporadically in many slides. Read (1940, p.250 ; 1948, p. 180) attaches great importance to the ubiquitous presence of tourmaline in the crystalline schists as suggesting close connection between metamorphism and igneous action. Boron, being an atom of small radius could be expected to travel far if influx is permitted in metamorphism. Balk and Barth (1936, p.792), Turner (1933A, p.182; 1934, p.170; 1935, p.374), Turner and Hutton (1941, p.223) and Hutton (1940, p.60) have supported the view that the presence of tourmaline may be due to permeating boron vapours. As opposed to this view Sederholm, Tilley (Williamson 1935, discussion, p.421) and McCallien (1934, p.18) hold that sedimentary rocks contain enough boron to provide the tourmaline in their metamorphic derivatives. As the writer holds that

(P.T.O.)

igneous action is responsible for the metamorphism in this region (p.76) he feels it more probable that tourmaline in these epidiorites is due to permeating boron vapours.

8. Sphene, Leucoxene and Ilmenite.

Widespread occurrence of sphene and leucoxene on the one hand and ilmenite on the other in the same slide is a commonly observed phenomenon. Sometimes cores of ilmenite can be recognised within sphene (Pl.IV,4) and in such cases sphene may be taken to have originated from ilmenite by the addition of silica and lime and the subtraction of iron during metasomatism, but Wiseman (1934, p.374) has found it difficult to explain the frequent presence of ilmenite to the exclusion of sphene. The writer feels that such ilmenite probably indicates introduction of titanium during metasomatism of primary basic igneous rocks when the primary ilmenite is changed into sphene and later introduced titanium and iron forms ilmenite. Lindgren (1900, p.604) has pointed out that leucoxene in white flocculent masses is formed by free titanic acid and is not an alteration product from titaniferous minerals.

9. Other minerals.

Apatite in small amounts has a general occurrence but is sometimes abundant in elongated needles and small anhedral prisms. Calcite in idioblastic tablets have frequently been noticed. Pyrite and sericite occur sporadically.

Petrographic types.

The petrographic types from the chlorite zone may be classed under three ideal types with variations produced by the addition of calcite. Epidote is generally present but may be occasionally absent. Some of these from zones of displacement show shearing effects and cataclastic texture.

1. Chlorite-albite-(epidote)-amphibolite.
2. Chlorite-stilpnomelane-albite-(epidote)-amphibolite.
3. Chlorite-albite-(epidote)-schist.

1. Chlorite-albite-(epidote)-amphibolite (Pl.V,1).

Rock No.207 collected from the N. end of the Cnoc nam Muc sill belongs to this type and in thin section is a sheared chlorite-epidote-albite-amphibolite. Two generations of amphibole are recognisable. The first is evidently green hornblende and it occurs in large ragged and sheared plates. It constitutes about 30% of the rock by volume. It is replaced round the edges by actinolite ($\gamma = 1.645$) which forms fibrous intergrowths with chlorite and also occurs in small prisms. Cracks in hornblende plates are healed up by chlorite ($\beta = 1.615$) which forms about 18.1% of the rock. The groundmass shows very finegrained mosaic of quartz and felspar. The felspar is albite ($\gamma = 1.540$), with a clouded appearence. It has a tendency towards idioblastic habit with occasional chess-board twinning. Epidote forms about 21% and sphene, apatite, sericite and iron ore together about 5% of the rock.

The bulk composition of this rock is given in

Table 3 (a).

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 47.52 | 48.20 | 49.06 |
| $Al_2O_3$ | 17.24 | 14.40 | 15.70 |
| $Fe_2O_3$ | 2.73 | .69 | 5.38 |
| FeO | 7.60 | 8.32 | 6.37 |
| (Total FeO) | (10.63) | ( 9.08) | (12.34) |
| MgO | 8.22 | 12.75 | 6.17 |
| CaO | 8.84 | 8.40 | 8.95 |
| $Na_2O$ | 1.85 | 1.59 | 3.11 |
| $K_2O$ | 0.27 | 0.24 | 1.52 |
| $H_2O$ + | 3.77 | 3.80 | 1.62 |
| $H_2O$ - | 0.33 | 0.40 | - |
| $TiO_2$ | 1.28 | 0.90 | 1.36 |
| $P_2O_5$ | 0.17 | 0.08 | 0.45 |
| MnO | 0.35 | 0.25 | 0.31 |
| $CO_2$ | - | - | - |
| | 100.17 | 100.02 | 100.00 |

A. Chlorite-epidote-albite-amphibolite (207), from N. end of Cnoc nam Muc sill, near Ardrishaig, S.Knapdale. Analyst - W.H.Herdsman.

B. Chlorite-clinozoisite-albite-amphibolite (49/4); north-western face of Creagan Cuilean, near Achahoish, S.Knapdale. Analyst - W.H.Herdsman. (Wiseman, 1934, Q.J.G.S. Vol.XC, p.372)

C. All basalt - average of 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites (Daly - Igneous Rocks and Depths of the Earth, p.17, 1933).

Table 3 (b).

C.I.P.W. Norm of Rock No. 207.

| | | | |
|---|---|---|---|
| Quartz | | | 1.98 |
| Orthoclase | | | 1.11 |
| Albite | | | 15.19 |
| Anorthite | | | 38.36 |
| Diopside | $CaO.SiO_2$ | 1.85 | 3.57 |
| | $MgO.SiO_2$ | .52 | |
| | $FeO.SiO_2$ | 1.20 | |
| Hypersthene | $MgO.SiO_2$ | 9.50 | 28.80 |
| | $FeO.SiO_2$ | 19.30 | |
| Magnetite | | | 3.94 |
| Ilmenite | | | 2.43 |
| Apatite | | | .33 |
| Water | | | 4.11 |
| | | | 99.81 |

Mode.*

| | |
|---|---|
| Quartz, Albite | 15.6 |
| Hornblende | 30.6 |
| Actinolite | 9.5 |
| Chlorite | 18.1 |
| Epidote | 21.0 |
| Sphene, Apatite, Sericite, Iron Ore | 5.0 |
| | 99.8 |

(* Determined by means of Dollar's Integrating Micrometer).

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Table 3 (a), and is compared with the analysis of (1) a chlorite-clinozoisite-albite-amphibolite, from Achahoish, S. Knapdale, and (2) the All basalt of Daly (1933, p.17 - average of 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites). Compared to the amphibolite from Achahoish this rock (207) is richer in $Al_2O_3$ and poorer in MgO, but otherwise their bulk composition is very similar. Compared to the All basalt on the other hand it shows increase in $Al_2O_3$ and total FeO + MgO, but decrease in total alkalies and in the sum of $TiO_2$ + $P_2O_5$ + MnO. CaO remains almost constant. On a comparison of the C.I.P.W. norm of this rock with its mode as shown in Table 3 (b), it appears that the total quartz and albite in the mode agrees fairly well with that in the norm. The little amount of $K_2O$ shown in the orthoclase must be present in the sericite of the mode.

2. Chlorite-stilpnomelane-albite-(epidote)-amphibolite (Pl.V,2).

A specimen (Rock No.208) collected from the middle part of the Cnoc nam Muc sill belongs to this type and is a chlorite-stilpnomelane-albite-hastingsite-calcite schist. The chlorite ($\beta$ = 1.635) is optically positive and is associated with abundant stilpnomelane ($\beta$ = 1.645) The amphibole is identified as a member of the hastingsite series and it has a deeper blue-green colour and higher ($\gamma$ = 1.685) refractive index than any other hastingsite from the chlorite zone. The felspar is albite ($\gamma$ = 1.541) and it occurs in coarse idioblastic crystals with well-developed carlsbad and lamellar twinning. It has a clouded appearence due to minute inclusions of iron ore. Occasionally with quartz it gives rise to micrographic and myrmekitic textures. Abundance of coarse plates of sphene and anhedral prisms of apatite is remarkable. Calcite and tourmaline are also present. Similar petrographic types but containing different amphiboles e.g., actinolite or green hornblende, have frequently been noticed in this zone.

The bulk analysis of this rock (208) is shown in Table 4 (a) and is compared (1) to that of an epidiorite from near Crinan Loch, Argyllshire, and (2) to that of the All basalt of Daly (1933, p.17). The epidiorite from near Crinan Loch consists of large irregular crystals of hornblende, patches and isolated flakes of biotite, large crystals of leucoxene after ilmenite, oligoclase-albite felspar, and abundant apatite with large areas of chlorite, calcite, abd iron-epidote (Sea-board of Mid-Argyll, Mem. Geol. Surv. Scot., 1909, p.55). The epidiorite from Ardrishaig is similar in bulk composition to this rock but is richer in FeO and poorer in CaO. This discrepancy may be due to the abundance of stilpnomelane and chlorite in Rock No.208 as against abundance of hornblende in the rock from near Crinan Loch. Compared to the All basalt on the other hand this rock (208) shows considerable increase in total FeO + MgO and in the sum of $TiO_2$+ $P_2O_5$ + MnO, but decrease in CaO, whereas $Al_2O_3$ and total alkalies remain more or less constant. These chemical characters together with the association of clouded felspar, abundant ilmenite, sphene, and apatite indicate the highly basic nature of this rock which may be due to later basification of a pre-existing type as suggested by Reynolds (1946, p.435-6 ; 1947B, p.106).

It now remains to compare the C.I.P.W. norm with the modal analysis of this rock (208) as set out in Table 4 (b). Total felspar and quartz in the mode is almost equal to the total alkali felspars in the norm. Obviously orthoclase is in excess in the norm. Sericite and felspars account for some of the $K_2O$ shown in the orthoclase of the norm and the surplus may be expected to be present in the stilpnomelane. Winchell (1948, Vol.II, p.435) reports stilpnomelane containing as much as 2.62% of $K_2O$. Calcite, epidote, apatite, and sphene together with 10.7% of hastingsite account for the CaO shown in the anorthite of the norm.

Table 4 (a).

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 41.87 | 42.36 | 49.06 |
| $Al_2O_3$ | 14.19 | 14.09 | 15.70 |
| $Fe_2O_3$ | 2.23 | 2.17 | 5.38 |
| FeO | 15.39 | 10.48 | 6.37 |
| (Toatl FeO) | (17.86) | (12.88) | (12.34) |
| MgO | 6.33 | 5.70 | 6.17 |
| CaO | 6.58 | 10.05 | 8.95 |
| $Na_2O$ | 1.64 | 3.26 | 3.11 |
| $K_2O$ | 2.83 | 0.80 | 1.52 |
| $H_2O$ + | 2.32 | 2.92 | 1.62 |
| $H_2O$ - | 0.18 | 0.12 | - |
| $TiO_2$ | 3.68 | 4.95 | 1.36 |
| $P_2O_5$ | 0.69 | 1.02 | 0.45 |
| MnO | 0.39 | 0.28 | 0.31 |
| $CO_2$ | 1.50 | 1.73 | - |
| | 99.82 | 100.02 | 100.00 |

A. Chlorite-stilpnomelane-albite-hastingsite-calcite-schist (208) ; middle part of Cnoc nam Muc sill, near Ardrishaig, S.Knapdale. Analyst - W.H. Herdsman.

B. Epidiorite, N.E. of Ardifur, N. side of Crinan Loch, Argyllshire. 1" Geol.Sheet 36, Scotland. Analyst - E.G.Radley.
(Mem. Geol. Surv. Scot. 'Sea-board of Mid-Argyll' 1909, p.55).

C. All basalt - average of 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites (Daly 1933, p.17).

## Table 4 (b).

**C.I.P.W. Norm of Rock No. 208.**

| | | |
|---|---|---|
| Orthoclase | | 16.68 |
| Albite | | 13.62 |
| Anorthite | | 19.73 |
| Corundum | | 1.22 |
| Hyperstheme | $MgO.SiO_2$ - 6.00<br>$FeO.SiO_2$ - 8.05 | 14.05 |
| Olivine | $2MgO.SiO_2$ - 6.86<br>$2FeO.SiO_2$ - 9.90 | 16.85 |
| Magnetite | | 3.01 |
| Ilmenite | | 6.99 |
| Apatite | | 1.34 |
| Calcite | | 3.40 |
| Water | | 2.50 |
| | | 99.39 |

**Mode.***

| | |
|---|---|
| Quartz, Felspar | 31.9 |
| Hastingsite | 10.7 |
| Stilpnomelane | 30.3 |
| Chlorite | 8.4 |
| Epidote, Calcite | 5.1 |
| Apatite, Sericite, Sphene, Iron Ore | 13.2 |
| | 99.6 |

(* Determined by means of Dollar's Integrating Micrometer).

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3. Chlorite-albite-(epidote)-schist (Pl.V,3).

Rock No.178 collected from the S.W. edge of the Cnoc nam Muc sill is, in thin section, a chlorite-albite-calcite schist and belongs to this petrographic type. It is widely represented in the chlorite zone. The schistosity is due to the alternation of leucocratic and melanocratic bands. The leucocratic bands consist almost entirely of chlorite and a little calcite while the melanocratic bands are composed essentially of quartz, felspar, and calcite. Minute myrmekitic intergrowths of quartz and albite have been noticed. The chlorite ($\beta$ = 1.625) is optically positive and has deep purple and ultramarine interference colours. Apatite, sphene, and a little iron ore is also present. Complete absence of amphibole is remarkable.

The bulk analysis of this rock (178) is recorded in Table 5 (a) and is compared to (1) the analysis of an epidote-quartz-ripidolite-skarn from Co. Donegal, Eire, and (2) the All basalt of Daly (1933, p.17). Compared to the epidiorite from Donegal, this rock (178) is poorer in $Al_2O_3$, $Fe_2O_3$, MgO, and $TiO_2$ but richer in FeO, total alkalies and $CO_2$. This difference in composition is due to the difference ~~in the difference~~ in the mineral constitution of these two rocks. The sample from Donegal contains more chlorite (45%), less albite (8%) and Calcite (3.96%) than this rock (178), the mineral composition of which is shown in Table 5 (b). Compared to the All basalt on the other hand this epidiorite (178) shows increase in CaO, and in the sum of $TiO_2$ + $P_2O_5$ + MnO, but decrease in $SiO_2$, $Al_2O_3$, total FeO + MgO, and total alkalies. The calculated modal composition of this rock (Table 1, p.28) is compared below to its C.I.P.W. norm. Excess $Al_2O_3$ shown in the norm indicates the aluminous nature of the chlorite.

Turner (1948, p.52) has pointed out that the petrographic types described from the chlorite zone could be derived from basic igneous rocks by a process of selective diffusion in pore solutions during metamorphism in the presence of water. The presence or absence of $CO_2$ determines the presence or absence of calcite. This, he says, involves

Table 5 (a).

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 44.58 | 44.98 | 49.06 |
| $Al_2O_3$ | 12.66 | 14.44 | 15.70 |
| $Fe_2O_3$ | 0.97 | 3.02 | 5.38 |
| FeO | 11.02 | 10.98 | 6.37 |
| (Total FeO) | (12.09) | (14.33) | (12.34) |
| MgO | 5.64 | 6.08 | 6.17 |
| CaO | 9.42 | 8.24 | 8.95 |
| $Na_2O$ | 2.84 | 0.16 | 3.11 |
| $K_2O$ | 0.23 | 1.23 | 1.52 |
| $H_2O$ + | 3.53 | 5.19 | 1.62 |
| $H_2O$ - | 0.28 | 0.18 | - |
| $TiO_2$ | 1.68 | 2.92 | 1.36 |
| $P_2O_5$ | 0.21 | 0.29 | 0.45 |
| MnO | 0.39 | 0.35 | 0.31 |
| $CO_2$ | 6.77 | 1.74 | - |
| | 100.22 | 99.80 | 100.00 |

A. Chlorite-albite-calcite-schist (178), from the S.W. edge of the Conc nam Muc sill, near Ardrishaig, S.Knapdale. Analyst - W.H.Herdsman.

B. Epidote-quartz-ripidolite-skarn (No.353), from the Lower sill of the White Cow Rock (Locality C), Pebble Strand, Malin Head, Co. Donegal, Eire. Analyst - W.H.Herdsman.

C. All basalt - average of 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites (Daly 1933, p.17).

## Table 5 (b).

**C.I.P.W. Norm of Rock No. 178.**

| | | |
|---|---|---|
| Quartz | | 11.40 |
| Orthoclase | | 1.11 |
| Albite | | 23.58 |
| Anorthite | | 3.33 |
| Corundum | | 6.63 |
| Hypersthene | $MgO.SiO_2$ - 11.60<br>$FeO.SiO_2$ - 17.29 | 28.89 |
| Magnetite | | 1.39 |
| Ilmenite | | 3.19 |
| Apatite | | 0.33 |
| Calcite | | 15.30 |
| Water | | 3.81 |
| | | 98.96 |

**Modal Composition from Table 1, p.28.**

| | |
|---|---|
| Quartz | 16.40 |
| Orthoclase | 1.11 |
| Albite | 23.58 |
| Anorthite | 3.33 |
| Chlorite | 36.49 |
| Calcite | 15.38 |
| Apatite | 0.33 |
| Iron Ore | 3.20 |
| | 99.82 |

---

little change in bulk composition apart from addition of water. The following equation represents the changes involved :-

Augite (or Hornblende) + Plagioclase + Ilmenite + Water $\longrightarrow$

Actinolite + Chlorite (aluminous) + Epidote + Albite + Sphene.

In the absence of $CO_2$, actinolite can be converted to chlorite only by removal of CaO from the system, which must then be regarded as open for CaO but closed for the other components. The following reaction has been suggested for such a case :-

$$\text{Actinolite} + H_2O \longrightarrow \text{Chlorite} + \text{Quartz} + CaO,$$

and the resultant mineral assemblage is chlorite-albite-epidote-quartz. Withdrawl of the appropriate quantity of CaO is accomplished by diffusion through the pore-solutions and into the moving solution (Turner, op.cit., p.53). In rocks having a high FeO/MgO ratio, stilpnomelane takes the place of chlorite. If, however, $CO_2$ is present, actinolite is further broken up according to the following equation and gives rise to calcite bearing types :-

$$\text{Actinolite} + CO_2 + H_2O \longrightarrow \text{Chlorite (non-aluminous)} + \text{Calcite} + \text{Quartz.}$$

Wiseman (1934) puts forward a different view as regards the derivation of these petrographic types from basic igneous rocks. His conception is essentially that of a closed system. The amphiboles and chlorites are regarded as of simultaneous origin from pyroxenes and olivine (if present), the excess $Al_2O_3$ required in the process being supplied by the plagioclase felspar. The liberated CaO is supposed to form epidote, and with ilmenite sphene. The normal trend of equilibrium relations in such a case is towards the assemblage chlorite-albite-epidote (op.cit., p.360). Hornblende is regarded as a mineral metastable or perhaps in a state of forced equilibrium in the chlorite or biotite zones, due probably to a deficiency of water (op.cit., p.372). The occurrence of calcite in these rocks is explained as a product of retrogressive metamorphism, when chlorite is formed after hornblende and the liberated CaO forms calcite (op.cit., p.399). The writer, however, feels that textural and mineralogical evidences is more in favour of an open system of metamorphism rather than a closed one. This point is developed in more detail later (p.77).

## B. Country Rocks.

### Megascopic features.

These consist of phyllites, quartzites, and intercalated limestones and belong to the group of rocks known as the Ardrishaig phyllites. The distribution, structure, and megascopic features of these rocks have been described in detail by Peach and others (1911, pp. 40-41, 48-49). Greenish and greyish silvery calcareous phyllites, in parts highly lustrous, with subordinate intercalations of fissile quartzose mica-schists, quartzites, and narrow rusty brown limestones, ranging from an inch in thickness to the thinnest films, form the major portion of these rocks. Occasionally thicker intercalations of limestone occur e.g., just north of the mouth of the Inverneil burn and in the vicinity of Loch Fuar-Bheinne.

### Microscopic features.

Under the microscope the following petrographic types have been recognised :-

1. Phyllites.
2. Felspathic schists and grits.

3. Chloritic schists.
4. Chlorite-sericite schists.
5. Stilpnomelane-chlorite-sericite-schists.
6. Graphitic schists.
7. Quartzites.
8. Limestones.

A small amount of calcite is almost universally present in all these types.

1. Phyllites.

The essential minerals in order of abundance in these rocks are sericite, quartz, and chlorite. Calcite has frequently been noticed and occasionally carbon. These rocks have a very fine schistose texture and in hand-specimens have a silvery lustre due to the presence of sericite and chlorite. Occasionally idioblastic crystals of pyrite occur. Strain-slip cleavage is common.

2. Felspathic schists and grits (Pl.V,4).

In this type are included a large number of schists in which quartz and albite, in varying proportions, are the dominant minerals, while in addition chlorite and sericite are always important constituents. Albite usually occurs as large porphyroblasts commonly 1 mm. to 2 mm. in diameter. In some of the quartzites it is more common in the groundmass than as porphyroblasts. Lamellar twinning, mainly in the pericline and albite laws, is more common though simple carlsbad twinning is also noted in a few cases. Quartz is equally abundant with albite. The grains of quartz are water clear, irregular in outline, and often show some degree of undulose extinction. Chlorite and muscovite is generally associated with the schistose types. Calcite is a common minor constituent of a number of these rocks. Apatite- pyrite, sphene, and magnetite occur frequently as minor accessory minerals.

3. Chlorite schists, and 4. Chlorite-sericite schists.

Rocks belonging to these two types are abundant from the chlorite zone. Chlorite in the first type and chlorite and sericite in the second are the predominating minerals besides quartz and felspar and accessory epidote, magnetite, apatite and sphene. These are highly schistose rocks with alternating sharp layers rich in chlorite and the light coloured minerals respectively. Some of these schists are corrugated as a result of their original schistosity planes having been crumpled into close isoclinal folds. Strain-slip cleavages are commonly noticed.

5. Stilpnomelane-chlorite-sericite schists.

Stilpnomelane appears in these rocks as an essential mineral. It generally develops in small porphyroblastic flakes crossing the schistosity and hence appears to be a later mineral.

## C. Metamorphic Facies.

According to the facies classification of Turner (1948, p.96) the petrographic types from the chlorite-zone find their place in the muscovite-chlorite subfacies of the Green-schist facies. This includes products of regional and hydrothermal metamorphism of the lowest grade and is defined to include metamorphic rocks which have crystallised at temperatures and pressures within the stability range of the assemblage, muscovite-chlorite, in pelitic rocks.

## III. BIOTITE ZONE.

### A. Epidiorites.

Distribution.

The biotite zone as defined in the pelitic rocks has a very limited outcrop in S.Knapdale. This is due to a major thrust of N.E.-S.W. trend separating the biotite zone from the chlorite zone. Outcrops of epidiorite are consequently few in this zone and are scattered (Figs.5 and 6). The largest outcrop is just N. of White House Bay. It is 2/3 mile long and is about 300 yds. at its broadest. Groups of small epidiorite sills occur (1) at the site of the church opposite Inverneil Island, (2) on the hill-slope opposite Creag Hamilton, and (3) west of An Torr near Stronchullin farm.

Megascopic features.

Dark green epidiorites are more common in this zone than in the chlorite zone. Due to the scarcity of outcrops, the wide variations in colour, lustre, and grain-size, noticed in the chlorite-zone epidiorites is not remarkable in this zone. Biotite is usually present and can often be identified under a lens. In a number of cases muscovite and chlorite appear to have taken the place of biotite. Most of these rocks are schistose in nature.

Texture.

The textural varieties are similar to those

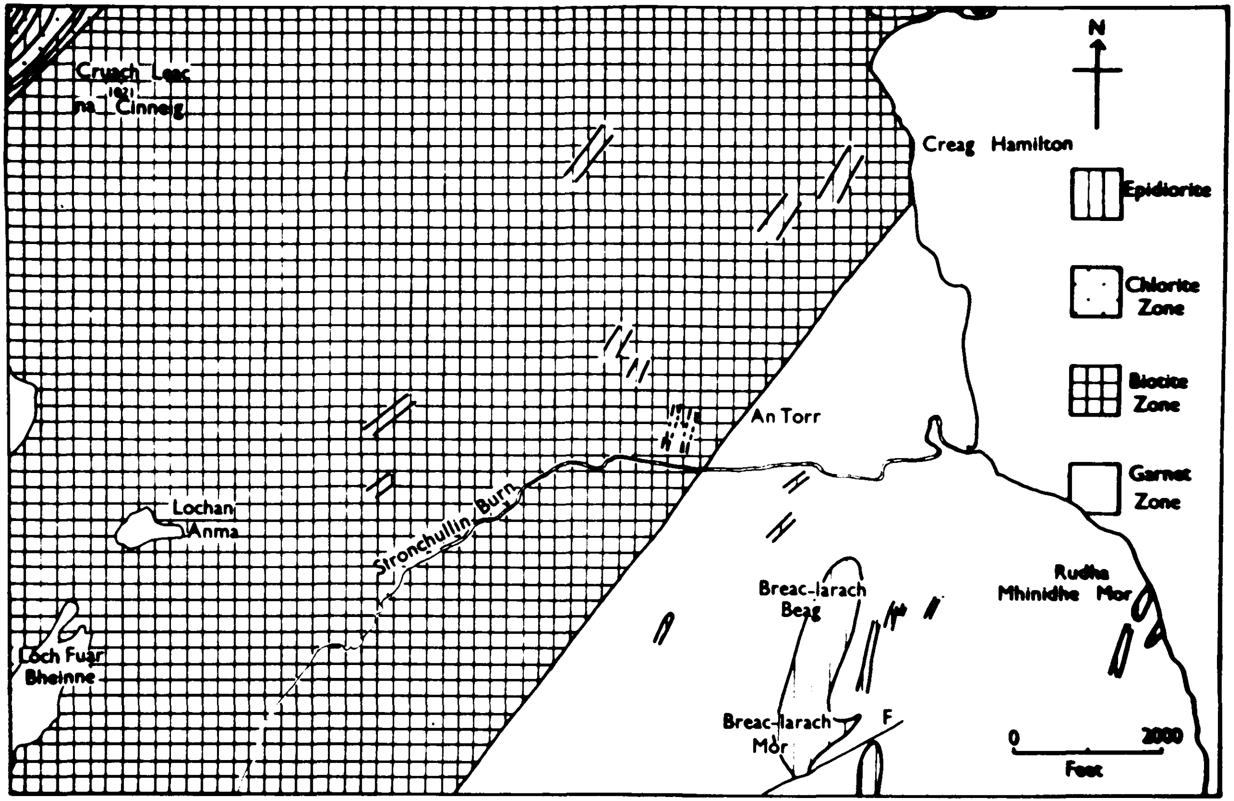


Fig. 6. Map of the Outcrop of Epidiorites in the Chlorite, Biotite and Garnet Zones as Indicated in Fig. 4.

described in case of the chlorite-zone epidiorites.

Mineralogy and Mineral Habits.

Albite is the predominant felspar with similar physical and optical properties as described under the chlorite-zone epidiorites. Myrmekites and other intergrowth textures are frequently present. The occurrence of linear inclusions of muscovite along cleavage lines in some of the felspars from this zone is a remarkable feature (Pl.VI,1). Similar inclusions of mica in porphyroblastic albites of schists in Pennsylvania and Maryland have been described by Ingerson (1938). He is of the opinion that these inclusions develop during the later stages of metamorphism, and constitute an element in the truly metamorphic fabric of the rock and are in no way relict, but are directly related to the crystal lattice of the enclosing albite and that the mica is younger than the albite, being formed during late hydrothermal activity by solutions penetrating the host crystals along planes of greatest permeability. The writer favours a similar mode of origin for the muscovite inclusions in the felspars under discussion.

Biotite is the characteristic mineral of the biotite-zone epidiorites. Amount of biotite present varies widely and it builds flakes from 0.5 mm. to 2 mm. across. It often crosses the foliation and is apparently a later mineral. It generally replaces the primary amphiboles and is presumably formed at their cost. It is itself cut and replaced by hastingsite or actinolite and also by chlorite. The colour varies from light yellow to deep brown with occasional greenish tint. The pleochroic scheme is : X = light brown, Y = Z = deep brown ; 2V small ; and $\beta$ ranges from 1.628 to 1.656.

Two generations of amphiboles can be recognised. Hastingsite is the predominating member of the secondary amphiboles. Out of twenty thin slides examined thirteen were found to contain hastingsite, five actinolite and only two tremolite. Apparently hastingsite is the characteristic amphibole in the epidiorites from the biotite zone.

Chlorite frequently replaces biotite and the amphiboles. It also occurs independently in small flakes. The refractive index ($\beta$) ranges from 1.615 to 1.640. Small idioblastic crystals of garnet have been noticed high up in the biotite zone. Epidote, sphene, sericite, muscovite, apatite, and iron ore are the common accessories. Tourmaline is not noticed in any thin section of these epidiorites.

Petrographic types.

The petrographic types from the biotite zone may be classed under three ideal types with variations produced by the addition of calcite. Some of these have been affected by later displacement and shearing and show cataclastic texture.

1. Chlorite-muscovite-albite-epidote-amphibolite.
2. Biotite-(chlorite-muscovite)-albite-epidote-amphibolite.
3. Biotite-garnet-(chlorite-muscovite)-albite-epidote-amphibolite.

The second of these petrographic types is of the widest occurrence and may be taken as the typical representative of the biotite-zone epidiorites. These mineral assemblages may also have derived from basic igneous rocks by a process of metasomatism during metamorphism not only in the presence of water and $CO_2$, as in the chlorite zone, but also in the presence of $K_2O$ as suggested by the widespread appearence of muscovite and biotite in this zone. Presence of small idioblastic crystals of garnet in a few epidiorites high up in the biotite zone is remarkable. Turner (1948, p.97) reports that the presence of Mn, even in small amounts, leads to the development of spessartite garnet, which is widely distributed as an accessory mineral in schists of the chlorite zone in Otago, New Zealand.

1. Chlorite-muscovite-albite-epidote-amphibolite.

Petrographic representatives of this type come from low down in the biotite zone and are chemically related to the chlorite-zone epidiorites. A specimen (No.227) collected from the Inverneil Island is described as a typical member of this group. In thin section it is a chlorite-muscovite-albite-amphibolite, with some aggregates of calcite. The felspar is albite ($\gamma$ = 1.540) which is replaced by muscovite and clinozoisite and is intergrown with quartz giving rise to myrmekitic texture. Linear trends of muscovite inclusions in albite have been noticed, the genetic significance of which has been discussed before (p.49). Relics of a dirty greenish hornblende can be recognised. It is intimately associated with actinolite ($\gamma$ = 1.635) and chlorite ($\beta$ = 1.615). Occasional brownish tinge in chlorite and its association with muscovite and iron ore suggest part of its derivation from pre-existing biotite. Sphene, leucoxene, apatite, etc., are present. Calcite builds large individuals.

2. Biotite-(chlorite-muscovite)-albite-epidote-amphibolite (Pl.VI,2).

Rock No.81 collected 1/3 mile north of Stronchullin Lodge is in thin section a biotite-chlorite-albite-hastingsite-epidote-skarn and belongs to this petrographic type. It is a medium grained, dark-greenish epidiorite with a somewhat foliated structure due to the parallelism of abundant elongated prisms of hastingsite, optical properties of which are as follows : X = brown yellow, Y = olive green, Z = bluish green ; $Z \wedge c = 19^{\circ}$; $\alpha = 1.663$, $\beta = 1.667$, and $\gamma = 1.675$ ; (-) 2V is large. The other minerals present are albite ($\gamma = 1.539$) intergrown with quartz, finely granular epidote, relatively large grains of biotite, a little sphene, apatite, ilmenite and pyrite. Biotite ($\beta = 1.656$) occurring in ragged tablets replace the amphiboles and are developed both parallel to and at high angles to the foliation of the rock. Sometimes it is replaced by chlorite ($\beta = 1.635$).

The bulk analysis of this rock (81) is given in Table 6 (a) and is compared with the analysis of (1) a biotite-epidote-albite-epidiorite from near Achahoish, S.Knapdale, and (2) the All basalt of Daly (1933, p.17). Chemically it (81) is very similar to the epidiorite from Achahoish, but compared to the All basalt it appears to be slightly basic. Total FeO + MgO and the sum of $TiO_2$ + $P_2O_5$ + MnO show slight increase whereas total alkalies show decrease. CaO shows slight decrease. The C.I.P.W. norm and the modal analysis of this rock (81) is shown in Table 6 (b) and on comparison it appears that the $K_2O$ shown in the orthoclase of the norm is present in the biotite of the mode. There is an excess of albite in the norm, indicating some extra soda, which may be present in the hastingsite of the mode.

Table 6 (a).

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 50.58 | 49.85 | 49.06 |
| $Al_2O_3$ | 14.74 | 16.09 | 15.70 |
| $Fe_2O_3$ | 1.43 | 1.74 | 5.38 |
| FeO | 12.02 | 11.16 | 6.37 |
| (Total FeO) | (13.60) | (13.09) | (12.34) |
| MgO | 5.56 | 3.93 | 6.17 |
| CaO | 8.23 | 8.72 | 8.95 |
| $Na_2O$ | 2.37 | 3.45 | 3.11 |
| $K_2O$ | 0.52 | 0.31 | 1.52 |
| $H_2O$ + | 2.13 | 1.00 | 1.62 |
| $H_2O$ - | 0.12 | - | - |
| $TiO_2$ | 1.64 | 2.32 | 1.36 |
| $P_2O_5$ | 0.18 | 0.27 | 0.45 |
| MnO | 0.36 | 0.30 | 0.31 |
| $CO_2$ | - | - | - |
| | 99.88 | 99.95 | 100.00 |

A. Biotite-epidote-albite-hastingsite-skarn (81) ; 1/3 mile N. of Stronchuin Lodge, near Ardrishaig, S.Knapdale. Analyst - W.H.Herdsman.

B. Biotite-epidote-albite-epidiorite (65/4) ; 0.2 mile N.51°E. from N. end of Loch-na-Craige, near Achahoish, S.Knapdale. Analyst - W.H.Herdsman. (Wiseman 1934, Q.J.G.S. Vol.90, p.379).

C. All basalt - average of 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites (Daly 1933, p.17).

Table 6 (b).

| C.I.P.W. Norm of Rock No.81. | | | | Mode.* | |
|---|---|---|---|---|---|
| Quartz | | | 3.42 | Quartz } Albite } | 14.6 |
| Orthoclase | | | 2.78 | | |
| Albite | | | 19.91 | Hastingsite | 48.8 |
| Anorthite | | | 28.07 | Biotite | 10.4 |
| Diopside | $CaO.SiO_2$ - | 4.87 | 9.85 | Chlorite | 11.6 |
| | $MgO.SiO_2$ - | 2.15 | | Epidote | 8.2 |
| | $FeO.SiO_2$ - | 2.83 | | Sphene } Apatite } Iron Ore } | 6.3 |
| Hypersthene | $MgO.SiO_2$ - | 11.75 | 27.12 | | |
| | $FeO.SiO_2$ - | 15.37 | | | |
| Magnetite | | | 1.85 | | 99.9 |
| Ilmenite | | | 3.04 | | |
| Apatite | | | 0.33 | | |
| Water | | | 2.25 | | |
| | | | 98.62 | | |

* Determined by means of Dollar's Integrating Micrometer.

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3. Biotite-garnet-(chlorite-muscovite)-albite-epidote-amphibolite.

A specimen (59) collected from west of An Torr, in thin section is a biotite-garnet-albite-epidote-hastingsite-skarn and belongs to this type. It is mineralogically similar to the garnet-zone epidiorites to be described next. Hastingsite ($\gamma$ = 1.675) has similar optical properties as described before. Biotite ($\beta$ = 1.656) is abundant and is replaced by hastingsite and chlorite ($\beta$ = 1.635). Garnet is also replaced round the margins by chlorite. Albite ($\gamma$ = 1.541) is very fine-grained and is intimately intergrown with quartz. Epidote, apatite, sphene, and a little iron ore are the common accessories.

## B. Country Rocks.

The biotite zone as defined for the pelitic schists outcrops on the shores of Loch Fyne between Whitehouse Bay and Creagan Beag and consist of quartzose mica-schists and quartzites with intercalated limestones. Phyllites are absent in this zone though stratigraphically these rocks belong to the Ardrishaig phyllites. Appearence of biotite in these rocks, when examined under the microscope, is a distinctive feature from the chlorite-zone rocks. Felspathic schists and grits are common and chlorite still persists in some of the thin slides (Pl.VI,3).

## C. Metamorphic Facies.

According to the facies classification of Turner (1948, p.94) the petrographic types from the biotite zone belong to the biotite-chlorite subfacies of the green-schist facies and thus represent a slightly higher grade of metamorphic conditions than in the chlorite zone.

## IV. GARNET ZONE.

### A. Epidiorites.

Distribution.

Outcrops of epidiorite mapped in the garnet zone are shown in Figs.6,7, and 8. There is a thick outcrop at Breac-larach Beag which continues up to Breac-larach Mo'r, where it is interrupted by a fault. It reappears on the southern side of the fault and stretches up to Stuchd Breac. Between Stuchd Breac and Meall Beag there are a number of major outcrops of epidiorite sills. On the coast of Loch Fyne epidiorite sills occur at (1) Rudha Mhinidhe Mor, (2) Eilean an Dunain and (3) opposite Barmore island. Besides these there are a number of minor outcrops scattered throughout the garnet zone. Absence of epidiorite sills beyond Tarbert is remarkable.

Megascopic features.

The epidiorites from the garnet zone are characterised by their dark green colour almost to the complete exclusion of light green shades. Grain size varies widely as in the chlorite-zone epidiorites. In some coarse-grained types felspars and amphiboles can be identified in the hand-specimens. There is also every gradation from massive to schistose types through foliated varieties. Thick sills are schistose at the edges and massive in the interior (Pl.VIII,2).

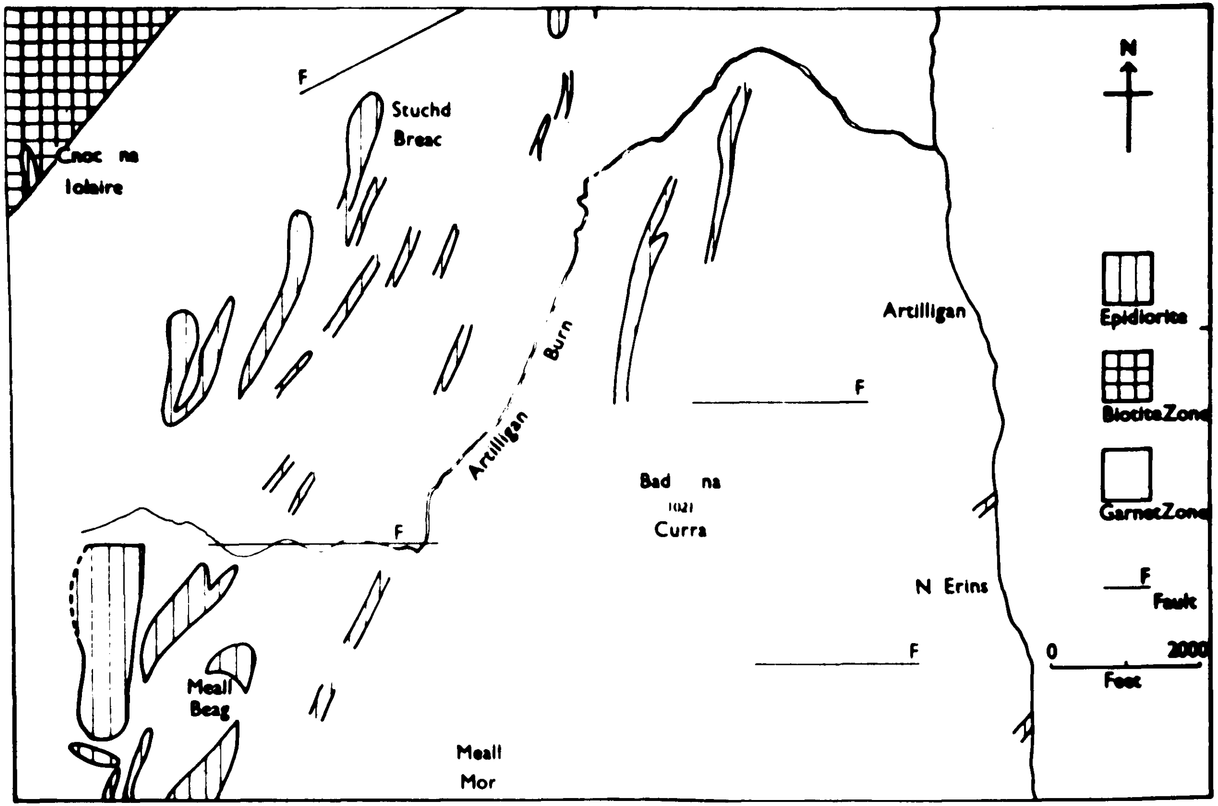


Fig. 7. Map of the Outcrop of Epidiorites in the Biotite and Garnet Zones as Indicated in Fig. 4

Texture.

Textural changes in this zone are in the direction of a marked increase in crystalloblastic and decrease in myrmekitic and micrographic. Relict texture is common and cataclastic texture persists in zones of dislocation.

Mineralogy and Mineral Habits.

Felspar.

The felspar from low down in the garnet zone is albite ($Ab_{95}An_{5}$) but higher up it becomes more calcic ($Ab_{90}An_{10}$). The albite tends toward idioblastic habit and saussuritic types are rare. Quartz changes from a lobate and penetrative to an interstitial form towards the albite and myrmekitic and micrographic textures are almost absent. Another characteristic feature is the total absence of white mica associated with the felspar from this zone as compared to those from the biotite zone. Wiseman (1934, p.386) reports occurrence of both normal and reverse zoning in the felspars from this and the higher zones.

Garnet.

Garnet is common in the epidiorites occurring within this zone though its appearence in many epidiorites even before the commencement of the garnet zone is an easily observed feature. The garnets are, however, sporadic and an epidiorite may be garnetiferous in one portion of its outcrop and non-garnetiferous in another. These are frequently developed inside the felspars and are generally idioblastic, although never attaining any great size. A few epidote and quartz grains occur as inclusions within these, giving rise to what has been described as 'seive-structure' (diablastic structure). This type of fabric is favoured by relatively rapid crystallisation of the host mineral about sparsely scattered nuclei, and hence is typical of minerals such as garnet, cordierite, chloritoid, and staurolite which are purely metamorphic and have not developed by enlargement of seed-crystals present in the parent rock (Turner 1948, p.155).

Wiseman (1934, p.388) has given the analysis of a garnet from an epidiorite collected at the commencement of the garnet zone. It is largely made up of almandine and grossular with smaller proportions of spessartite, pyrope, and andradite.

| | |
|---|---|
| $SiO_2$ | 38.44 |
| $Al_2O_3$ | 20.62 |
| $Fe_2O_3$ | 7.39 |
| FeO | 17.09 |
| MnO | 4.22 |
| CaO | 10.08 |
| MgO | 2.51 |
| | 100.35 |

(Garnet out of garnet-biotite-clinozoisite-albite-amphibolite ; 0.2 miles N.51°E. from northern end of Loch-na-Craige, near Achahoish. Analyst - Naima Sahlbohm. Q.J.G.S. Vol.90, p.388).

<u>Amphibole</u>.

Two generations of amphibole can again be recognised in the garnet zone. The earlier type is replaced to a greater extent by secondary amphiboles than in the chlorite or biotite zones and thus almost obliterating its optical properties. The secondary amphiboles are hastingsite and actinolite. Tremolite has not been noticed. About 80% of thin micro-slides, examined from this zone, contain hastingsite which is thus the characteristic amphibole in these epidiorites. It generally has a higher refractive index than in the biotite zone and $\gamma$ varies from 1.675 to 1.685. Occasionally it goes up to 1.690 (s.87).

It has been noticed that the refractive index of hastingsite in the garnetiferous type of epidiorite is generally higher than that in the non-garnetiferous type from the same exposure at the entrance to the garnet zone. Wiseman (1934, p.384) has chemically investigated this discrepancy and has come to the conclusion (with some confidence) that where garnetiferous and non-garnetiferous epidiorites are closely associated at the entrance to the garnet zone, the hornblende from the garnetiferous epidiorite has generally a slightly higher FeO/MgO ratio corresponding with its higher refractive index than the hornblende from the non-garnetiferous variety. In addition the former has a distinctly greater soda content.

Biotite.

It is generally the brown variety. No green biotite has been found in the garnet zone as compared to the biotite or chlorite zones. The development of a deeper tint in biotite with progressive metamorphism has been recorded by Tilley (1926, p.40), whilst Phillips (1930, p.251) states that ~~that~~ the green biotites of the green beds change with increasing metamorphism into a brown or red variety.

Accessories.

Minerals of the epidote group are moderately abundant in these epidiorites and they show the same features as in the chlorite and biotite zones. Sphene is of fairly constant occurrence but in some epidiorites ilmenite, rutile, and iron ore are present. The amount of quartz present is variable ; in some cases it may be absent or represented by only a few grains, while in others it may greatly preponderate over the felspar. Apatite in small amounts but in coarse idioblastic crystals are common. Tourmaline is not noticed.

Petrographic types.

The petrographic types found in the garnet zone may be grouped under the following four types or as variations of these produced by the addition of chlorite or calcite. Epidote is generally found in all the four types but occasionally specimens without epidote or with very small amount of it have been noticed.

1. Garnet-plagioclase-(epidote)-amphibolite.
2. Garnet-biotite-plagioclase-(epidote)-amphibolite.
3. Biotite-plagioclase-(epidote)-amphibolite.
4. Plagioclase-(epidote)-amphibolite.

1. Garnet-plagioclase-(epidote)-amphibolite (Pl.VI,4).

Rock No.269 collected from an epidiorite outcrop opposite Port an Dunain may be taken as a representative of the garnet-zone epidiorites. In thin section it is a garnet-hastingsite-epidote-albite-skarn and belongs to this petrographic type. The hastingsite has intense pleochroism and high refractive index ($\gamma$ = 1.685). The felspar is albite ($\gamma$ = 1.541) showing intergrowth texture with quartz. Idioblastic crystals of a pink garnet is present and it contains inclusions of a few small quartz grains. The garnet is generally replaced by chlorite ($\beta$ = 1.635) round the margins but sometimes is completely replaced by it.

The bulk analysis of this rock (269) is given in Table 7 (a) and is compared to a garnet-biotite-clinozoisite-albite-amphibolite from near Achahoish, S.Knapdale and to the All basalt of Daly (1933, p.17). Chemically it is similar to the epidiorite from Achahoish and the slight differences in bulk composition is due to the different amounts of mineral present in each rock. Thus the low content of $K_2O$ (0.17%) in this rock (269) may be due to the absence of biotite whereas the higher amount of $K_2O$ (1.20%) in the other may be due to the presence of biotite. Compared to the 'All basalt' this rock (269) appears to be more basic in nature, since CaO, total FeO + MgO, and the sum of $TiO_2$ + $P_2O_5$ + MnO show increase whereas $Al_2O_3$ and total alkalies show decrease.

On a comparison of the C.I.P.W. norm and the modal analysis of this rock as set out in Table 7 (b) it appears that there is an excess of albite in the norm. The excess $Na_2O$ thus represented may be expected to be present in the hastingsite of the mode, which also probably accounts for the $K_2O$ shown in the little amount of orthoclase in the norm since no sericite is recorded in the mode.

Table 7 (a).

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 49.64 | 51.25 | 49.06 |
| $Al_2O_3$ | 12.78 | 13.57 | 15.70 |
| $Fe_2O_3$ | 2.14 | 1.75 | 5.38 |
| FeO | 12.47 | 13.72 | 6.37 |
| (Total FeO) | (14.84) | (15.66) | (12.34) |
| MgO | 5.78 | 3.11 | 6.17 |
| CaO | 9.54 | 8.10 | 8.95 |
| $Na_2O$ | 2.16 | 1.94 | 3.11 |
| $K_2O$ | 0.17 | 1.20 | 1.52 |
| $H_2O$ + | 1.88 | 0.70 | 1.62 |
| $H_2O$ - | 0.24 | 0.10 | - |
| $TiO_2$ | 2.57 | 3.50 | 1.36 |
| $P_2O_5$ | 0.18 | 0.63 | 0.45 |
| MnO | 0.36 | 0.35 | 0.31 |
| $CO_2$ | - | - | - |
| | 99.91 | 99.92 | 100.00 |

A. Garnet-hastingsite-epidote-albite-skarn (269) from Port an Dunain, 2 miles N. of Tarbert, S.Knapdale. Analyst - W.H.Herdsman.

B. Garnet-biotite-clinozoisite-albite-amphibolite (67/4) ; 0.2 mile N.51°E. from N. end of Loch-na-Craige, near Achahoish, S.Knapdale. Analyst - W.H.Herdsman. (Wiseman 1934, Q.J.G.S. Vol.90, p.379).

C. All basalt - average of 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites (Daly 1933, p.17).

Table 7 (b).

C.I.P.W. Norm of Rock No.269.

| | | |
|---|---|---|
| Quartz | | 4.98 |
| Orthoclase | | 0.55 |
| Albite | | 17.81 |
| Anorthite | | 25.02 |
| Diopside | $CaO.SiO_2$ - 8.93<br>$MgO.SiO_2$ - 0.70<br>$FeO.SiO_2$ - 9.10 | 18.73 |
| Hypersthene | $MgO.SiO_2$ -13.70<br>$FeO.SiO_2$ - 8.31 | 22.01 |
| Magnetite | | 3.01 |
| Ilmenite | | 4.86 |
| Apatite | | 0.33 |
| Water | | 2.12 |
| | | 99.42 |

Mode.*

| | |
|---|---|
| Quartz, Albite | 18.6 |
| Hastingsite | 62.3 |
| Epidote | 7.2 |
| Sphene | 7.6 |
| Garnet, Chlorite | 2.4 |
| Apatite, Iron Ore | 2.1 |
| | 100.2 |

* Determined by means of Dollar's Integrating Micrometer.

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2. Garnet-biotite-plagioclase-(epidote)-amphibolite.

A representative of this type occurs 200 yds. south of N.Erins Lodge and in thin section it is a garnet-biotite-hastingsite-chlorite-calcite-epidote-schist (Rock No.266). It shows a marked foliation, dependent on the alternation of narrow melanocratic and leucocratic bands. The former are rich in hastingsite ($\gamma$ = 1.685) and also contain ilmenite, sphene, a little epidote and biotite ($\beta$ = 1.645) ; while the latter consist of albite ($\gamma$ = 1.542), garnet, small crystals of epidote, quartz, and occasional biotite. Abundant biotite is present in the slide as a whole and it almost invariably crosses the schistosity. Garnet occurs in idioblastic crystals. Both biotite and garnet are apparently later than the schistosity and are often replaced by chlorite ($\beta$ = 1.635).

3. Biotite-plagioclase-(epidote)-amphibolite.

Rock No.268 collected from an outcrop opposite Eilean an Dunain is found in thin section to be a biotite-hastingsite-epidote-albite-chlorite-skarn belonging to this petrographic type. It is characterised by the complete absence of garnet. The hastingsite occurs in ragged laths and prisms and has a lower refractive index ($\gamma$ = 1.665) than in the garnetiferous variety described before. The felspar is albite ($\gamma$ = 1.540) with lamellar twinning and idioblastic habit. It is intergrown with quartz, contains abundant inclusions of epidote, and has a highly sinuous margin. Brown biotite ($\beta$ = 1.635) is present but is often altered to chlorite ($\beta$ = 1.625).

4. Plagioclase-(epidote)-amphibolite.

A representative of this type was collected at Breac-larach Beag and in thin section it is an albite-epidote-amphibolite

(Rock No.88). Both biotite and garnet is absent in this rock. It is very coarse grained and amphibole crystals reach a size up to 10 mm. by 5 mm. In thin section the albites ( $\gamma$ = 1.541) are generally clear with well-developed lamellar twinning and symplektitic texture. Occasionally a crossed-hatched twinning has been noticed round the edges of albite porphyroblasts (Pl.VII,2) suggesting the formation of anorthoclase as a result of later replacement by $K_2O$. This possibility is suggested because this particular outcrop of epidiorite is affected by a fault and metalliferous pegmatites along fault-zones have been noticed in the neighbourhood. Two types of amphibole is recognised. The first is uralitic hornblende ( $\gamma$ = 1.666) in large plates with ragged edges and inclusions of iron ore and specks of albite. The second is hastingsite ( $\gamma$ = 1.688) and it is found as small ragged prisms or elongated needles, independent of or associated with the hornblende. A thin vein of hastingsite-albite-quartz cuts across plates of hornblende and early felspars, thus indicating a later origin of the minerals in the vein.

The occurrence of garnet in these epidiorites immediately the garnet zone is reached suggests that some dominant reaction is involved. In discussing the paragenesis of garnet Wiseman (1934, p.389) is of the opinion that if pressure/temperature conditions are suitable, the size and abundance of garnets depend largely on the chemical composition of the epidiorite. Phillips (1930, p.252) has suggested that in the green beds the varying degree to which chlorite survives in the higher grades may be correlated with the variable occurrence of garnet. Though possible in the green beds this suggestion does not explain the paragenesis of garnet in these epidiorites because when associated together, chlorite always appears to be later than garnet. Niggli (1924, p.107) has suggested that when basic igneous rocks are subjected to increased pressure, the following reactions from left to right are favoured, with reduction of total molecular volume in each case :-

| | | | | |
|---|---|---|---|---|
| Olivine + Anorthite | ⇄ | Garnet. | | |
| Augite + Anorthite | ⇄ | Garnet | + | Quartz. |
| Ilmenite+ Anorthite | ⇄ | Sphene | + | Hornblende. |

Turner (1948, p.28), however, does not accept that any of these is actually a pressure-controlled metamorphic reaction and is of the opinion that even where reduction in molecular volume is obvious, temperature rather than pressure may have been the principal controlling factor. He concludes that if, as petrographic evidence suggests, garnet does form by reconstitution of anorthite and either pyroxene or olivine, the process is not adequately represented by either of the two equations cited above, but usually involves participation of yet other associated minerals, or else removal of material from the reacting system. This view appears to be supported by the compositional change in the amphibole at the entrance to the garnet zone and this feature may be closely related to the paragenesis of garnet in these rocks.

The close association of garnet and hastingsite in the garnet-zone epidiorites may best be visualised as having been brought about by reactions similar to the following one suggested by Alderman (1936, p.511) as representing the conversion of basic igneous rocks to eclogite. The obvious modification of this reaction under garnet-zone conditions would be the production of hastingsite instead of omphacite.

$$\begin{matrix} Mg_2Fe_2(Si_4O_{12}) \\ Ca_2Mg_2Fe''Fe'''(Si_5AlO_8) \\ \text{Augite} \end{matrix} + \begin{matrix} Na(AlSi_3O_8) \\ Ca_2(Al_4Si_4O_{16}) \\ \text{Labradorite} \\ (Ab_1An_2) \end{matrix} + \begin{matrix} 2FeTiO_3 \\ \text{Ilmenite} \end{matrix}$$

$$\longrightarrow \begin{matrix} (NaCa_2)MgFeAl(Si_6O_{18}) \\ \text{Omphacite} \end{matrix} + \begin{matrix} (Fe_4Mg_3Ca_2)(Al_5Fe''')(Si_9O_{36}) \\ \text{Almandine-pyrope} \end{matrix}$$

$$+ \begin{matrix} SiO_2 \\ \text{Quartz} \end{matrix} + \begin{matrix} TiO_2 \\ \text{Rutile} \end{matrix}$$

## B. Country Rocks.

### Stronchullin Phyllites.

This band of phyllites outcrop at the entrance to the garnet zone. It is not seen on the coast of Loch Fyne but may be concealed beneath the beach deposits north of Creagan Beag. In its inland exposures it consists of quartzose schists, quartz-mica-schists and silvery grey phyllites which are often calcareous. A shiny bluish black phyllite, portions of which are graphitic, has also been noticed. Under the microscope these rocks have been found to contain garnet, felspar, muscovite, biotite, quartz, calcite, and iron ore.

### Erins Quartzites.

This group of rocks occupy the coast of Loch Fyne between Creagan Beag and Stonefield, and consist essentially of quartzites, coarse grits, and siliceous schists in which blue quartz and felspar lenticles are evident in the hand-specimen. Alternating with these are small bands of puckered mica-schists occasionally studded with biotite flakes. Bands of green schists and impure limestones are occasionally found. Locally this group of rocks are rich in pyrite. Microscopically these rocks are composed of quartz, muscovite, biotite, felspar and garnet. The micas occur in distinct plates and often crosses the schistosity. The garnets are idioblastic and are generally replaced round the edges by chlorite.

Stonefield Schists.

This group of rocks occupy a zone nearly a mile broad between the Erins quartzites and the Loch Tay limestones. Soft mica-schists, extremely puckered and with abundant biotite, are the predominant rocks of this group. At Glenralloch bands of very fine-grained green schists and coarse felspathic grits and normal quartzites occur. At Ashens a band of limestone about 20 ft. broad is well developed. Under the microscope these rocks resemble the pelitic schists from the Erins group. Garnet is not noticed in thin rock slides from the coast but McCallien (1925, p.245) reports abundant garnet in these rocks from their inland exposures.

Loch Tay Limestone.

Outcropping on the shore opposite Barmore Island, the rocks of this group follow a course parallel to the strike of the previous group of rocks, and range from a blue wholly crystalline limestone to pale-coloured calcareous quartz-schists. Occasionally muscovite and black carbonaceous matter has been noticed. On the shores of Loch Fyne at South Bay the Loch Tay limestones are represented by six bands, varying from 10 to 30 ft. in width, and separated from one another by epidiorite.

## Glen Sluan Schists.

The schists of this group outcrop to the south of Loch Tay limestones and stretch from Port nam Seilisdeir to the north of Sgeir na Donie on the coast of Loch Fyne. These rocks consist of micaceous and siliceous schists together with a few bands of green schists. Under the microscope these are albite-mica-schists and siliceous schists with occasional garnet.

## Green Beds.

Outcrops of green-schists have been recorded from many different horizons above and below the Erins quartzites but the Green beds proper in this part of Kintyre consist of two bands of massive green-schists, nearly 300 yds. across, and separated from one another by a belt of normal siliceous and micaceous sediments. These do not appear to be a distinct group but rather grade into the quartzo-felspathic schists with increase of quartz and muscovite. Under the microscope albite occurs in sub-idioblastic porphyroblasts with occasional crystals up to 2 mm. in diametre. A patchy lamellar twinning is common though simple twinning is noted in a few cases. Inclusions of epidote, sphene, and iron ore are common. Clear large plates of biotite are frequent. Green chlorite sometimes associated with a pale green faintly pleochroic actinolite has been noticed. Calcite is abundant in some slides. Sphene, apatite, magnetite, and partly oxidised pyrite constitute the accessory minerals.

## Beinn Bheula Schists.

These rocks outcrop along the shores of

Loch Fyne from Sgeir Port a' Ghuail to the southern limits of the area. Epidiorite sills do not outcrop in these group of rocks, which are made up of schistose grits, abundant biotite and chlorite schists with many bands of albite-schists. Tourmaline has been reported from these rocks as far south as Laggan or the Laggan Lochs (McCallien 1925, p.240).

## C. Metamorphic Facies.

All the rock groups described from the garnet zone, with the exception only of the Beinn Bheula schists, belong to the albite-epidote-amphibolite facies, according to the facies classification of Turner (1948, p.88). This facies corresponds to the almandine zone of regional metamorphism as defined for the pelitic schists. The Beinn Bheula schists belong to the biotite Zone of Tilley (1925, Pl.IX) and thus indicate a decrease in metamorphic grade southwards.

## V. CHEMISTRY.

Specimens of five epidiorites, one each from the garnet and biotite zone and three from the chlorite zone, have been chemically analysed. Chemical characteristics of each analysis have been discussed before while describing the petrographic types to which each belongs ( pp.33, 36, 39, 52, and 60). Each analysis has been compared to a standard of reference, namely the 'All basalt' of Daly (1933, p.17) which may be assumed as, chemically, the nearest approach to the basic igneous magma from which the parent rocks of these epidiorites may have crystallised. In Table 8 the series is taken as a whole, in a decreasing grade of metamorphism, for the purpose of preparing an oxide-variation diagram. The 'All basalt' (B) belongs to an igneous facies and thus represents the highest grade of metamorphism in the series under discussion. It is followed by the garnet-zone epidiorite (I) and then by the biotite-zone epidiorite (II). The three epidiorites from the chlorite zone come next and their metamorphic order has been determined by the amount of chlorite or stilpnomelane developed in each. Thus Rock No.207 (III) with 18.1% of chlorite represents a higher grade than Rock No.208 (IV) with 30.3% of stilpnomelane plus 8.4% of chlorite. Rock No.178 (V) with 36.49% of chlorite represents a lower grade than No.208 because it does not contain any amphibole whereas 10.7% of amphibole is present in the other.

In Fig.9 the variation of oxides in these epidiorites have been plotted against a decreasing grade of metamorphism. Oxide fluctuations from one rock to another is pointed out by joining the corresponding points for each oxide or group of oxides in thin lines. The

Table 8.

| | Decreasing | Grade | of | Metamorphism | → | |
|---|---|---|---|---|---|---|
| | B | I | II | III | IV | V |
| $SiO_2$ | 49.06 | 40.64 | 50.58 | 47.52 | 41.87 | 44.58 |
| $Al_2O_3$ | 15.70 | 12.78 | 14.74 | 17.24 | 14.19 | 12.66 |
| $Fe_2O_3$ | 5.38 | 2.14 | 1.43 | 2.73 | 2.23 | 0.97 |
| FeO | 6.37 | 12.47 | 12.02 | 7.60 | 15.39 | 11.02 |
| (Total FeO) | (12.34) | (14.84) | (13.60) | (10.63) | (17.86) | (12.09) |
| MgO | 6.17 | 5.78 | 5.56 | 8.22 | 6.33 | 5.64 |
| CaO | 8.95 | 9.54 | 8.23 | 8.84 | 6.58 | 9.42 |
| $Na_2O$ | 3.11 | 2.16 | 2.37 | 1.85 | 1.64 | 2.84 |
| $K_2O$ | 1.52 | 0.17 | 0.52 | 0.27 | 2.83 | 0.27 |
| $H_2O$ - | 1.62 | 1.88 | 2.13 | 3.77 | 2.32 | 3.53 |
| $H_2O$ - | - | 0.24 | 0.12 | 0.33 | 0.18 | 0.28 |
| $TiO_2$ | 1.36 | 2.57 | 1.64 | 1.28 | 3.68 | 1.68 |
| $P_2O_5$ | 0.45 | 0.18 | 0.18 | 0.17 | 0.69 | 0.21 |
| MnO | 0.31 | 0.36 | 0.36 | 0.35 | 0.39 | 0.39 |
| $CO_2$ | - | - | - | - | 1.50 | 6.77 |
| | 100.00 | 99.91 | 99.98 | 100.17 | 99.82 | 100.22 |

B. All basalt -(Daly 1933, p.17).

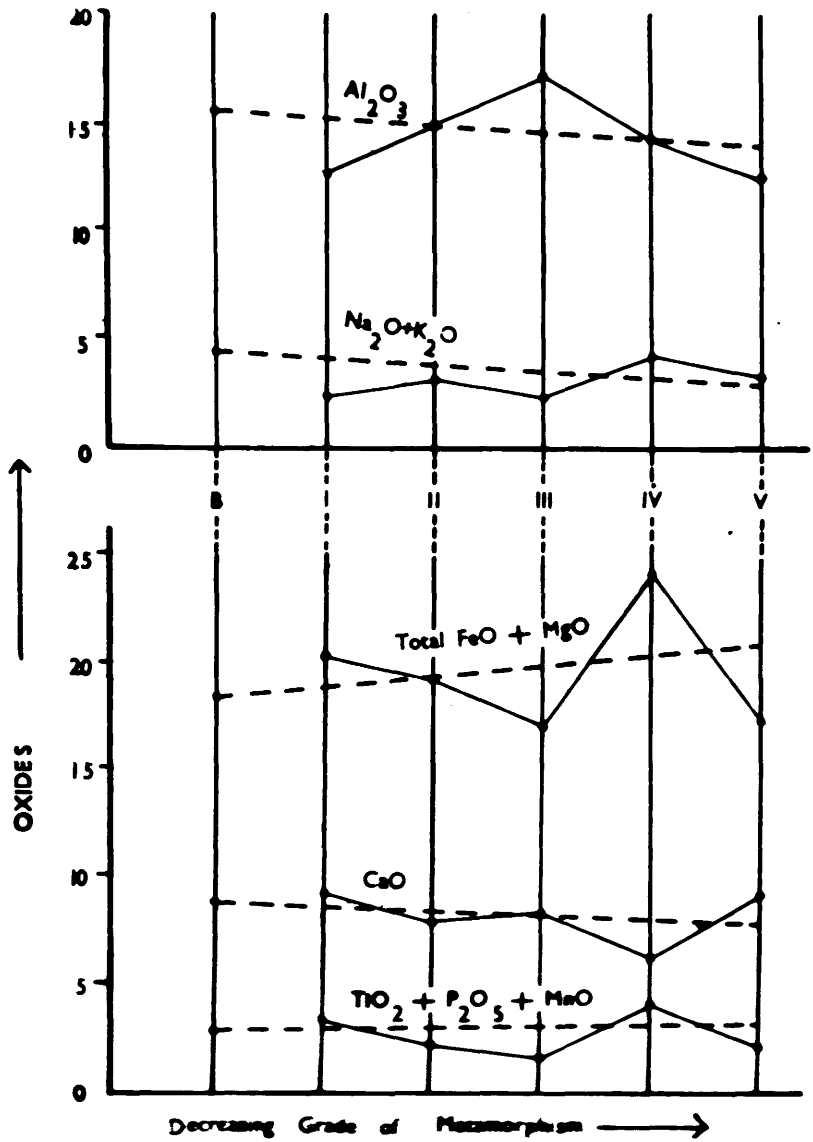
I. Garnet-albite-epidote-hastingsite-skarn (269) from the Garnet Zone (p.60).

II. Biotite-epidote-albite-amphibolite (81) from Biotite Zone (p.52).

III. Chlorite-epidote-albite-amphibolite (207) from Chlorite Zone (p.33).

IV. Chlorite-stilpnomelane-albite-amphibolite (208) from Chlorite Zone (p.36).

V. Chlorite-albite-calcite schist (178) from Chlorite Zone (p.~~39~~ 41).




B. All basic Daly (1933 p. 17)

I. Epidiorites from Garnet Zone [209]

II. .. .. Biotite – [81]

III. Epidiorites from Chlorite Zone [207]

IV. .. .. .. [208]

V. – – .. .. [178]

Fig. 2 Oxide Variation Diagram with Decreasing Grade of Metamorphism thick interrupted lines indicate the trend of variation of the oxides when compared to the 'All basalt' of Daly. These trends cannot, however, be accepted as conclusive. Only a large number of analyses statistically made may be expected to give conclusive results, but the trends are very suggestive and broadly agree with similar trends observed by Lapadu-Hargues (1945). Thus $Al_2O_3$, total alkali ($Na_2O$ + $K_2O$), and CaO tend to decrease while total FeO + MgO and the sum of $TiO_2$ + $P_2O_5$ + MnO show increase with decreasing grade of metamorphism. The net chemical effect may be described as one of progressive basification with decreasing grade of metamorphism.

The above observation finds further support when the rock series is plotted on a triangular variation diagram (Fig. 10) in accordance with Tyrrell's method (Tyrrell, G.W. - Petrographic Kindreds and Regions - A New Method of Graphic Representation. An unpublished manuscript.) which is a modified and extended version of von Wolff's method. Von Wolff first calculates the analysis into molecular proportions and then combines the values of $K_2O$ and $Na_2O$ ; unites MnO, NiO, and CoO with FeO ; $Cr_2O_3$ with $Fe_2O_3$ ; and $TiO_2$, $P_2O_5$ and $ZrO_2$ with silica. The calculation of standard iron ore, pyroxenes and felspars then proceeds exactly as on the lines of the C.I.P.W. norm with the exception that it does not go on to the calculation of the undersaturated minerals such as olivine, nepheline, and leucite. If the total of the silica allotted to pyroxenes and felspars exceeds the silica actually present in the analysis there is a deficiency of silica which represents olivine and/or nepheline or leucite, and the difference is recorded as (-) Q. If on the other hand, the allotted silica is less than the actual silica, there is an excess over that required to form the pyroxene and felspar molecules, which appears as quartz, and is recorded as (+) Q.

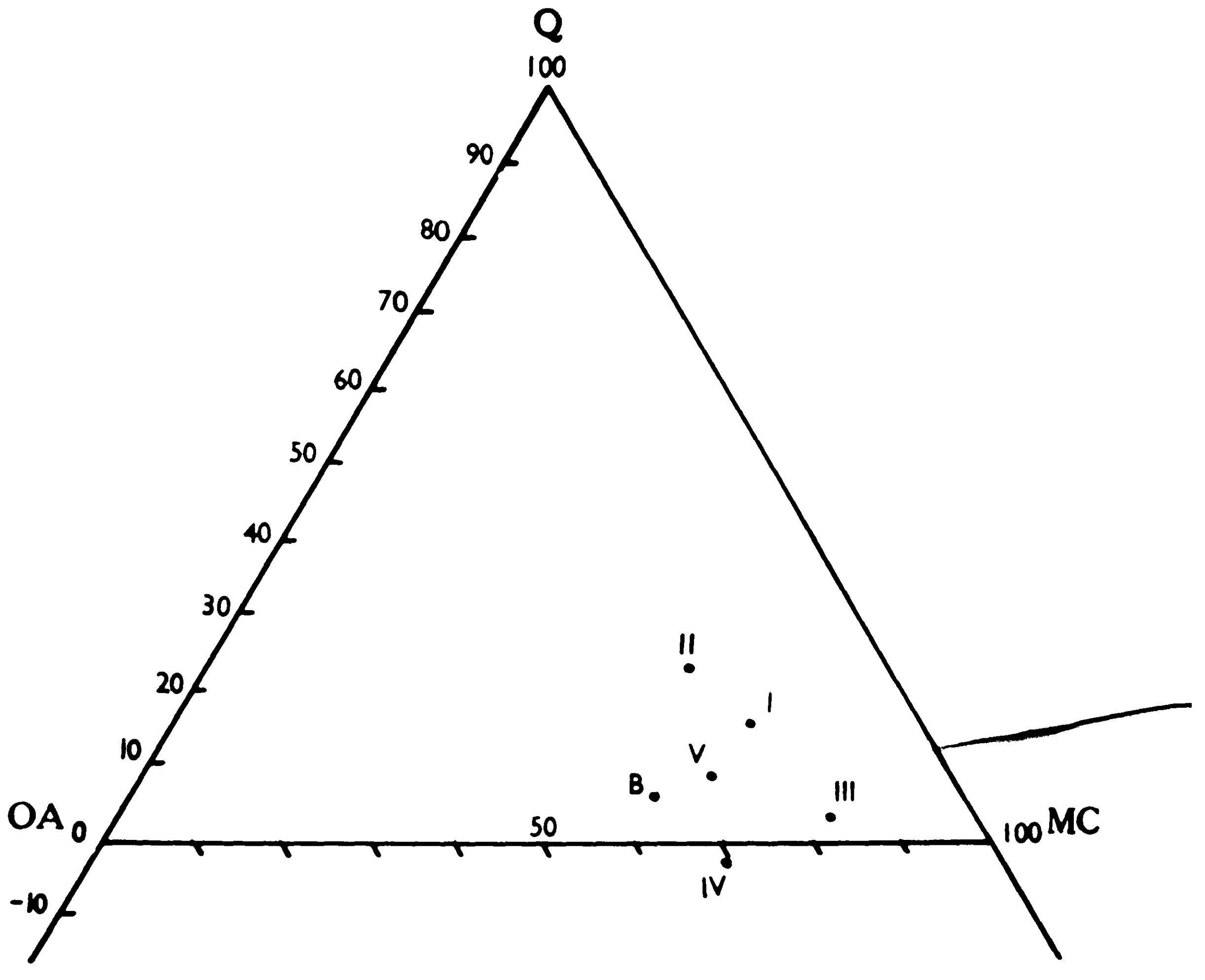



Fig. 10 Triangular Variation Diagram Showing the Relation of the Epidiorites to the All basalt

To obtain the three parameters necessary to fix the position of the point representing the analysis in the tringular net, the molecular amount of iron ores is added to that of pyroxene to form the parameter M. Similarly, the molecular amounts of alkali-feldspars and anorthite are combined to give the parameter F, and ± Q form the third parameter. F, M, and ± Q are finally calculated to 100 per.Cent.

Tyrrell's modification of von Wolff's calculations follows the same preliminary procedure except that $TiO_2$, $P_2O_5$, and $ZrO_2$ are not combined with silica, but since most of ilmenite, titaniferous magnetite and apatite of igneous rocks are early crystallisations, these are allotted to the femic or mafic component. Thereafter the calculation proceeds exactly as in the C.I.P.W. norm. The molecular proportions of each oxide in the analysis are multiplied by 1000 to eliminate decimals, and the various oxides are plotted to form apatite, ilmenite, magnetite, pyroxene, alkali-felspars and anorthite. Aegirine, sodium silicate and corundum may ahve to be calculated in special cases. If $CO_2$ is recorded in the analysis, an equivalent amount of CaO is allotted to form calcite, which is then eliminated from the system. Finally the requisite amounts of silica are allotted to form the pyroxenes and felspars.

A parameter MC is computed by adding the molecular totals of apatite, iron ores, pyroxenes, aegirine and sodium silicate (if present) and calcic felspar (anorthite). The term MC is mnemonic for <u>M</u>afites plus <u>C</u>alcic feldspar (anorthite). A parameter OA ( <u>O</u>rthoclase plus <u>A</u>lbite) is similarly computed from the molecular totals of alkali-felspars Finally the parameter ± Q is obtained by subtracting the total allotted silica from the silica actually present. This allotment of the quasimineral units to the three parameters differs from von Wolff's in one important particular. Anorthite is assigned to the mafites parameter instead of the Felspar parameter. It is contended by Tyrrell that this assignment provides a distribution of points on the diagram much more in accordance with the facts of the mineral composition of igneous rocks than von Wolff's.

Thus plotted all the analyses of the epidiorites except the one from the biotite zone (II) fall nearer to the basic corner in Fig. 10 than the 'All basalt' (B) and the chlorite zone epidiorites (III, IV, and V) appear to be more basic than the biotite zone epidiorite (II). It should be pointed out that in plotting the analysis of Rock No. 178 (V) which contains a high percentage of $CO_2$ (6.77) a slight deviation from the method described above is made in that instead of forming calcite first and eliminating it from the system, anorthite is formed first and the excess CaO is converted into calcite which then is deducted from the system. It is felt that in doing so a more correct chemical representation of this analysis is obtained.

## VI. METAMORPHISM.

Petrographic examination of the epidiodiorites from this area show that these have evolved from primary basic igneous rocks as a result of changes in chemical and mineralogical composition and texture. These alterations include saussuritisation, albitisation, and epidotisation of the plagioclase felspars, formation of secondary amphiboles, garnet, biotite, chlorite, ilmenite, and other secondary minerals with accompanying textural changes. The degree to which these rocks have been altered and the nature of these alterations within the three zones of metamorphism has been described in the previous sections. In this section it is proposed to discuss (1) the processes which controlled the alterations, (2) probable source of the metasomatic agents, (3) nature of the metasomatic agents and their mechanism of migration, (4) the different episodes of metamorphism, and finally (5) the relationship of metamorphism to orogeny.

A variety of relationships has been proposed between regional metamorphism on the one hand and igneous activity on the other. At one extreme is the view that there is the closest connetion between the two processes; at the other is the view that there is no causal relation at all. The writer feels that he has described considerable evidence to support the first of these views. This view has been more or less supported by the work of Barrow, Read, and Reynolds in Scotland ; Vogt in Norway ; Termier, Perrin and Roubault, Jung and Roques, Lapadu-Hargues, Raguin in France ; Wegmann in Greenland ; Backlund in Finland ; Cloos and Hietanen, Balk and Barth in America ; Turner in New Zealand ; and Dunn and Dey in India.

1. Metasomatism.

The microscopic features detailed below suggest that these epidiorites are a product of complex processes of metasomatism of pre-existing basic igneous rocks.

A. Textural features -

(a) Quartz, albite, garnet, and biotite show crystalloblastic texture.

(b) The albites are partial pseudomorphs of more calcic plagioclases.

(c) Some albites show microstructures e.g., micrographic and myrmekitic intergrowths suggestive of replacement origin.

(d) Appearence of later garnet, biotite, and chlorite suggest not only the presence of metasomatic agents but also gradation in temperature-pressure conditions from the garnet to the chlorite zone.

B. Mineralogic features -

(a) The remarkable poverty of anorthite molecule in the felspar indicates a non-pyrogenic origin for albite (Gilluly 1934).

(b) Chess-board albite suggests a replacement origin.

(c) The development of secondary hastingsite associated with primary hornblende suggest enrichment in iron and magnesium.

(d) The widespread occurrence of epidote, chlorite, and sericite suggest hydrothermal processes.

(e) Inclusion of rutile needles in quartz is suggestive again of hydrothermal processes.

From chemical considerations that have been discussed before (pp.71-5) it can be said with some confidence that we are dealing with Fe-Mg metasomatism in these epidiorites which has also contributed minor components such as $TiO_2$, $P_2O_5$, and MnO. Dissemination of iron-sulphides (pyrite and pyrrhotite) in these rocks may be attributed to reaction between iron-bearing silicates (e.g., amphiboles, chlorite or biotite) and magmatically derived $H_2S$. Abundance of calcite on the other hand may be due to hydrothermal reaction with solutions containing $CO_2$ or soluble carbonates at low temperature (Turner 1948, p.129). Widespread occurrence of albite in the low zones may suggest that some process of alkali-metasomatism may also have been effective, but such a view is unwarranted because total alkali shows a downward trend with decreasing grade of metamorphism (Fig.9). Bowen (1928, p.132) however, has favoured an origin by replacement for all albite-rich rocks. Albitisation is cosidered to be the "result of a secondary process of impregnation of solid rock with albite by circulating aqueous solutions.......... There is nothing in the manner of their occurrence to warrant belief in their formation by the simple consolidation of a magma."

Anderson (1937, pp.19-20) has pointed out that the extremely important 'reaction principle' of Bowen may have a profound influence in metasomatism. If magmatic material comes in contact with solid rocks under conditions of moderate temperature and pressure, that remain fairly constant for a considerable period, the changes that take place will depend largely upon the mineralogical composition of the invaded rock, all the minerals of which may not be affected equally or in the same way. Some minerals will be dissolved and actually pass into the solutions ; others will react with these solutions and be changed into new minerals, in equilibrium with the magmatic fluids under given conditions, without being converted into the liquid state. The net change in the chemical composition of the invaded rock may be slight.

2. Source of the Metasomatic Agents.

If the conclusion that the epidiorites owe their present composition to post-magmatic metasomatism is accepted, one is immediately led to consider the possible source of such agents. The metasomatic agents may be thought of as originating (a) from the primary basic magma itself by a process of autometasomatism, or (b) from some deep-seated source.

Bailey and Grabham (1909, p.250) and Flett and Dewey (1911, p.204) included some of the epidiorites associated with spilitic greenstones, salic and soda-rich rocks in a special petrographic group - the spilitic suite. They were of the opinion that the spilitic rocks, at least in those cases where they are rich in decomposition products, were altered by an autometamorphic change, soda and carbon dioxide being retained in solution during the solidification of the magma, after which they acted upon the minerals of the solid rock. In this way a decomposition of the calcic minerals would come about, the CaO-content being fixed in calcite and epidote or possibly carried away. To explain the high soda-content of the spilites they considered the original magma to have a high soda-content and in some cases, where the amount of secondary alteration products is small, an original albite felspar was admitted. Such a process can hardly be expected to account for the Fe-Mg metasomatism in these epidiorites, though it can explain the low CaO-content of these rocks. Such a process, moreover, would leave these rocks richer in alkali, which again is contrary to observation.

As to the second alternative mentioned above, there again are two schools of thought relating to the source of the Fe and Mg added to these rocks. One believe that the mafic oxides are of magmatic origin and derive from granitic magma ( e.g., Turner 1933B, 1937 ; Billings 1937), the other regard the mafic constituents as driven from country rocks which have been granitised (e.g., Wegmann 1935, Backlund 1936). A granitic magma would seem unlikely to be the source of residual solutions consisting essentially of silica, iron, magnesia, and water. Reynolds (1946, p.433) has pointed out that if granitic magma usually crystallised so as to leave such a residual solution, one might expect to find veins and dykes of serpentine rather than pegmatites and aplites associated with granite.

Currier (1938) in a study of the regional granitisation in New England found that the development of alkali felspar, quartz, and muscovite caused the displacement of magnesium, iron, calcium, and titanium. He suggested the probability that these bases driven into the upper zones formed hornblende, garnet, biotite, epidote, and chlorite-schists of common regional aspect. Read (1940) has suggested that the metamorphic zones of the Scottish Highlands, characterised by chlorite, biotite, almandine, staurolite, kyanite, and sillimanite, are metasomatic zones through which material from a central theatre of granitisation migrated, changing in composition and temperature as it advanced from the core. Related to this idea is Reynolds' (1942) view that there was forward migration of potash, iron, and magnesium in the Dalradian rocks of Antrim at the time of the formation of the albite-schists, due to the invasion of an igneous mass.

In Fennoscandia and Greenland, sedimentary rocks in the peripheral zones of migmatite regions were found to be enriched in mafic minerals such as cordierite, garnet, and biotite. Wegmann (1935) correlated this Fe-Mg enrichment with the loss of iron and magnesium from the rocks overcome by migmatisation, and for this zone he coined the term "Mg-front". Backlund (1936) later showed that Fe-Mg enrichment is not confined to pelitic and semi-pelitic sediments but also affect basaltic rocks and their tuffs as the frontal zone of migmatisation advances. Dunn (1942) has reported similar association of granite and granite-gneiss with schists enriched in iron, magnesium, calcium, and soda in the Archeans of India and has correlated this enrichment with losses from zones of granitisation, and introduced the term "diabrochite" to describe the basified and felspathised schists which form the compliments of the migmatites.

The most modern developments on fronts, especially as concerned with granitisation are due to Reynolds (1943, 1944, 1946, 1947A, 1947B, 1947C, 1947D, and 1947E), who has defined a front as follows : a front occurs whereever there is a diffusion limit marked by a change in the mineral assemblage (1947C, p.211). Basic fronts are, moreover, characterised by geochemical culmination of the minor constituents such as Ti, P, and Mn. Mineralogically such culminations are made apparent by the high concentration of apatite and/or sphene. In future such concentration can be regarded as clues towards the recognition of a basic front (1947B, p.106). Associated with the development of migmatites in depth there is a concomitant basification of the sedimentary as well as basaltic rocks in the peripheral zone and the enrichment of these initial rocks in femic or cafemic materials is the expression of a basic front that proceeded in advance of one of granitisation (1947E, p.58).

The writer feels that by all the tests, as detailed above by Reynolds, it can be suggested with some confidence that a basic front of metasomatic metamorphism has moved across this area from the direction of the garnet to the chlorite zone. The evidences in favour of such a conclusion are as follows :-

(a). The chemical analyses of the epidiorites from the different metamorphic zones indicate that these are more basified compared to their assumed parent type. Bulk analysis of Rock No.208(Table 4a, p.38) is specially remarkable in this connection.

(b). There is remarkable change in mineral assemblage at the limits of each metamorphic zone involving the appearence of minerals like garnet, biotite, and chlorite respectively.

(c). The geochemical trend of the total FeO + MgO and of the sum of $TiO_2$ + $P_2O_5$ + MnO show an upward inclination with decreasing grade of metamorphism (Fig.9).

The change of composition of rocks with change in metamorphic grade has been the subject of a recent study by Lapadu-Hargues (1945). He considered rocks that were originally sedimentary and by statistical comparison of their chemical compositions in different metamorphic grades, irrespective of age, he demonstrated that Fe'' and Mg attain their maximum concentration in the lowest metamorphic grades. Ca decreases gradually with decrease in metamorphic grade. Total alkalies also decrease with decreasing metamorphic grade though in the lower grades Na shows increase and K decrease, whilst in the higher grades (granitisation) both Na and K increase. Lapadu-Hargues ascribes the variation in the concentration of the various elements in rocks of different regional metamorphic grade to the difference in mobility of the respective elements under metamorphic conditions. He finds the order of increasing mobility to be K, Ca, Na, Mg, Fe, and he correlates this order with the respective ionic radii of the elements concerned. Fe and Mg with the smallest ionic radii are the most mobile ions and in consequence they become concentrated in the lowest metamorphic grades, situated farthest from the locus of granitisation.

The writer in his investigations of the epidiorites finds it possible to agree with Lapadu-Hargues' view that Fe and Mg travel farthest and that total alkalies and CaO decrease with decreasing grade of metamorphism, as shown by the trend of the corresponding lines in Fig.9. Reynolds (1947E, p.59) holds different views about the geochemical migration of K from that of Lapadu-Hargues'. Her contention that K travels with the advancing basic front appears to be supported by the occurrence of biotite in the biotite-zone epidiorites and stilpnomelane in the chlorite-zone epidiorites.

A remarkable feature of these rocks is their poverty in total alkalies and CaO compared to their assumed parent types. Apparently these constituents have been driven out of the primary basic igneous rocks by the incoming metasomatic agents during metamorphism. There can be two possibilities as to the fate of the alkalies. Firstly that they move out of the epidiorites into the country rocks and are fixed there, or secondly that they migrate as an alkali-front ahead of the basic front and bring about alkali metasomatism further afield. Though felspathic schists and grits have been noticed in the country rocks, the investigation of the spilites further to the north may throw light as to the second possibility.

The CaO that is thrown out during metasomatism may be expected to be fixed in the country rocks due to the lesser mobility of Ca-ion as suggested by Lapadu-Hargues (1945). The disseminated nature of calcite in the country rocks, especially in the neighbourhood of epidiorite sills may be cited as evidence in favour of such a view.

3. Nature of the Metasomatic Agents and the Mechanism of their Migration.

The replacements that have been described above have evidently involved the passage through solid rocks of a stream of interchanging constituents. There is considerable difference of opinion as to the physical nature of these constituents and the manner of their migration. Read (1949, p.181) has pointed out that a distinction must be made between reaction and transport. Reaction may take place in the liquid, solid or gaseous phase.

All writers agree on the importance of water in rock metamorphism and it is generally believed that metamorphic adjustment of a mineral assemblage to imposed temperature-pressure conditions is very largely brought about by reactions taking place through the medium of aqueous pore-solutions, or their gaseous equivalents at high temperatures, the water of which is partly supplied by the rock itself, and partly is derived from magmatic source. The role of water, under certain circumstances, is somewhat comparable to that of silica in rocks containing free quartz (Turner 1948, p.51). Water, usually in the form of hydroxyl, tends to enter more abundantly into minerals that crystallise at low twmperatures than into members of high temperature assemblages.

Attention has been drawn in recent years by Eskola (1934, 1939) in particular, to the possible significance of reaction between crystalline materials in the absence of water. Recent researches into this problem has established that reaction between crystalline solids, and migration of material by diffusion through crystal lattices, are possible even in the complete absence of water or other fluids (Turner 1948, p.23). The question to be decided is to what extent the mechanism of reaction and diffusion in dry solids do actually play a part in metamorphism compared with reactions progressing through the medium of a liquid phase. Read (1949, p.181) is of opinion that in the higher levels of the crust in which fractures are developed there may be a free mobility whereas in the deeper parts diffusion may be interlattice or along grain boundaries. Not only may there be this broad depth distinction, but in the deep levels a further ionic differentiation may arise in that the small ions may go through the lattice as well as around it, whereas the larger ions may only go round.

Transport is controlled by the sizes of opening utilised. Read (1948, p.186) has again pointed out that privileged planes are usually of structural origin, but privileged bands depend on compositional and textural characters as well. If diffusion takes place, it is obvious that it must be controlled physically by the permeability and grain size of a rock and chemically by its reactivity to the incoming fluids. With supercapillary openings there is unrestricted movement of fluids and large scale replacement and deposition are possible, but when real crystals are encountered, which are mosaics bounded by sub-microscopic cracks, transportation must take place by diffusion through the solid phase along these grain boundaries and through the inter-lattice openings and the reactions may not require any liquid to be present (Read 1949, p.181). The writer is of the opinion that reactions and transport may have taken place in the solid phase in the garnet zone but there is evidence of hydrothermal alteration in the biotite and chlorite zones, where fractures offered privileged paths to the migrating solutions.

4. Episodes of Metamorphism.

The metamorphic history of this region can be divided into three episodes, each characterised by the type of physico-chemical factors operative at the time. It is suggested that the first episode of metamorphism brought about the regional schistosity and the major deformation in the area and that the emplacement of the basic igneous rocks was a phenomenon belonging to this episode. The next was an episode of meta-somatic metamorphism when garnet, biotite, and chlorite zones were formed. The third was an episode of retrogressive metamorphism. If attention is confined to the epidiorites it is observed that their parent rocks, after their emplacement and solidification, have undergone two successive episodes of metamorphism, the second and the third respectively.

First Episode.

The following sequence of events may be envisaged during the first episode in the metamorphic history of the region :-

(a) Development of regional schistosity and its deformation.

(b) Invasion of the region by sheets of a basic magma under strong compressive forces along already developed planes of schistosity, which are thus synchronous or syntectonic intrusions.

The foliated nature of the epidiorites in most localities suggest that these are syntectonic intrusions. Foliation is best developed near the margins of thick sills but it is weaker in the interior. In general the foliation strikes essentially parallel to the contacts of the sills and follows the dip of the country rocks. The foliation cannot be a flow structure produced in a solid rock by drag against the walls, for it is found throughout the body and could not have been induced on a previously massive rock (Billings 1937, p.537). Turner (1948, p.153) has pointed out that it is difficult to distinguish precisely between the igneous and the metamorphic elements in the gneissic fabric of such rocks, but in the absence of granulation, undulose extinction, or marked preferred orientation in the crystals of quartz - the mineral most sensitive to deformation - the presence and orientation of mica flakes, or prisms of hornblende may safely be interpreted as due to magmatic flow. Such an interpretation appears to be more probable in this area despite the occasional presence of undulose quartz, which in almost every case is localised in zones of later displacement. Preservation of very coarse texture in some rocks and of blastophitic and blastoporphyritic texture in others suggest that these rocks had started to crystallise after mobility had come to an end. In this connection it may be mentioned that in one rock-slide from a thin sill of epidiorite rotation of amphibole crystals have been noticed (Pl.VII,3), suggesting that thinner sills had started to crystallise earlier than thicker ones and when deformative forces were still active.

Crystallisation proceeding simultaneously with deformation has long been recognised as a most important factor in connection with the development of schistosity in sedimentary rocks. There is, however, lack of agreement as to the relative effectiveness of several mechanisms of crystallisation. Turner (1942) summarises Sander's views on this point as follows - " Sander distinguishes between two types of componental movement by which deformation is achieved in metamorphism, direct componental movements including mechanical deformation and rotation or sliding of grains, and indirect componental movements involving transport of atoms or atomic groups by such means as solution and redeposition, diffusion through pore solutions, convection governed by temperature gradients, in so far as all these movements are related to the processes of deformation." Increased temperature and velocity of movement will affect solution and redeposition of such minerals as quartz and calcite and fecilitate their formation as veins parallel to the schistosity. Similar veins have been widely noticed associated with the country rocks in this region. Holmquist (1921) stated the principle of 'lateral secretion' and Turner (1941) demonstrated 'metamorphic differentiation' in the development of similar veinites.

From petrofabric studies (Fairbairn 1942) it has been established that crystallisation commonly continues even after active deformation of the rock has ceased and while the temperature of metamorphism still remains high. Apart from change in size of the grains this post-tectonic crystallisation may affect the fabrics of the rock in any of three ways :-

(a) A type of crystallisation-schistosity may develop. The growth of crystals do not cause this schistosity but merely preserve and emphasise a set of s-planes already in existence.

(b) Post-tectonic mimetic crystallisation may develop coarse-grained schists with lattice orientation.

(c) Under other circumstances recrystallisation of a particular mineral after deformation has ceased may destroy the original lattice orientation.

Second Episode.

This was an episode of metasomatic replacement and from structural observations it appears that it started after the country rocks had attained their schistosity and the basic igneous sills had completely solidified. This episode, though post-tectonic in nature, is distinct from the post-tectonic crystallisation described above during the first episode. New and different set of chemical environments brought about the formation of minerals like garnet, biotite, and chlorite respectively in zones of decreasing temperature-pressure conditions. It is possible that physical conditions during this episode continued, to a certain extent, from the past episode and these later metasomatic changes took place while temperature-pressure conditions were still high. The production of porphyroblasts in an originally uniform rock is most likely to be accounted for by Eskola's 'concretion principle' - the piling up of an inactive mass by the rapid combination of migrating elements with elements of the host rock (Read 1948, p.192).

Third Episode.

This episode can be described broadly as the period of retrogressive metamorphism in which two distinct stages of changes can be recognised - (a) chemical and (b) mechanical. It also appears that there is a time interval between the two stages. The chemical changes during the first stage include chloritisation of biotite and garnet and saussuritisation of felspar. These changes do not appear to bear any relation to special structural features such as thrusts or faults : rather the retrograde minerals appear sporadically throughout the area and as such may be described as a phase of later hydrothermal alterations (Billings 1937, p.553). The question now remains as to whether these alterations are related to that facet of retrometamorphism described as diapthoresis by Knopf. Read (1949, p.125) holds the negative view provided no deformation is involved. The writer feels that deformation is involved in this case and that this stage can probably be correlated with the period of formation of the Cowal anticline and Loch Awe syncline in this region.

The mechanical changes during the second stage include shattering and recrystallisation of quartz and felspar crystals, twisting of mica, amphibole and felspar lamellae and development of undulose extinction in various minerals (Pl.VII,4). These features are closely related to zones of dislocation and accordingly this represents that other facet of retrometamorphism namely phyllonitisation. The scattered occurrence of pegmatitic metalliferous veins and their concentration in zones of dislocation (Fig.11) is remarkable suggesting their formation during this phase of metamorphism. These veins consist of minerals like chalcopyrite, chalcocite, cupriferous pyrites, galena, blende etc. The usual gangue minerals are quartz, calcite, siderite, barytes and felspars. In some cases gold and silver have also been reported (Special Reports on the Mineral Resources of Great Britain, Mem. Geol. Surv. Scot., Vol.17, p.74).

Now that igneous action has been invoked as the cause of metamorphism in this region, it may also be looked upon as the

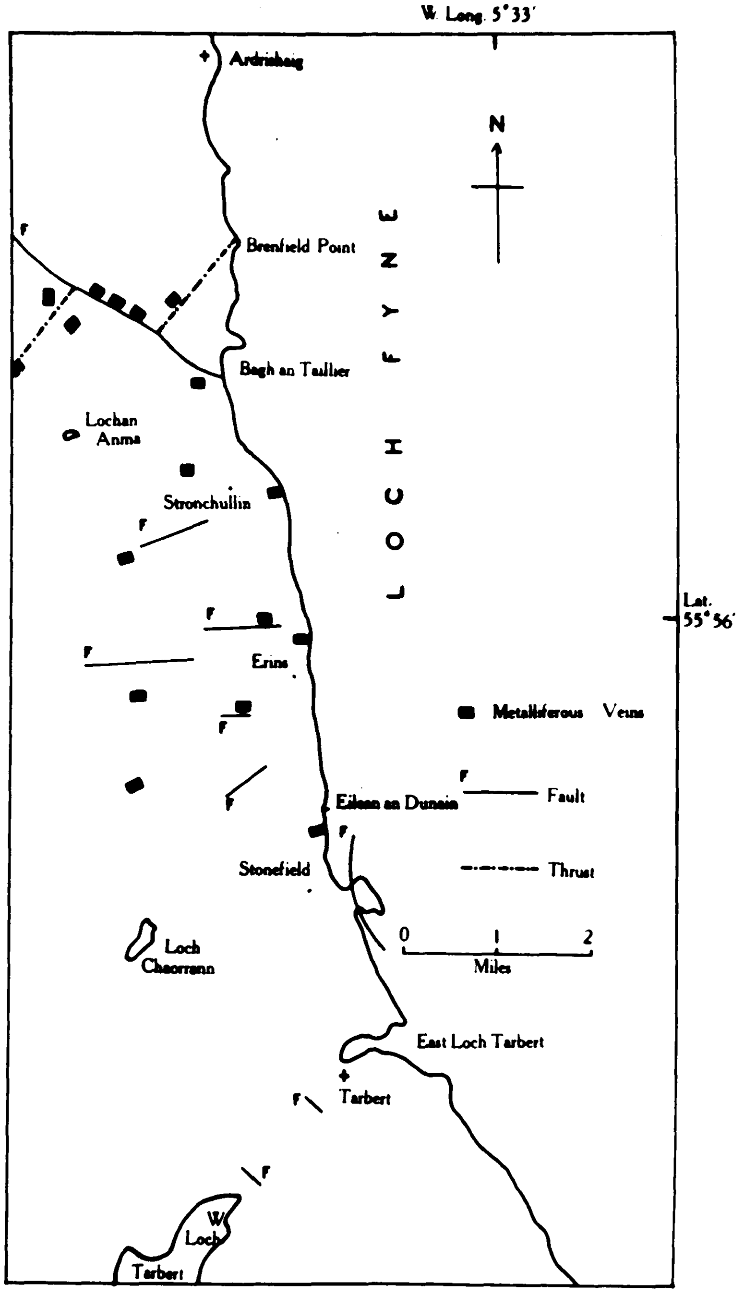



Fig. 11. Map showing the distribution of the Metalliferous Veins in the Ardrishaig – Tarbert Area.

source of the minerals in the metalliferous veins. There may be two possibilities as to the actual relation of these ores to the igneous bodies (Sullivan 1948). The first is that these are thrown-outs from sediments overcome by granitisation, thus being related to the synchronous phase of igneous activity. The second is that these are late-stage concentrations from a granitic magma, representing a subsequent phase of igneous activity (batholithic). It is not possible to draw any final conclusion without a detailed study of the ores, but the author feels that the concentration of these veins in zones of dislocation and the association of quartz and felspar in their gangue minerals appear to indicate the second of these possibilities. Holmes ( Discussion, Reynolds 1946, p.438) has pointed out that though ore-lead may be a concentration of lead that was dispersed through crustal rocks before their granitisation, partial introduction of lead from depth cannot entirely be ruled out and what is true for lead is likely to be equally true for many of the other elements geochemically associated with lead ores.

5. Relation of Metamorphism to Orogeny.

The view that metamorphism is closely related to igneous action in depth has been supported with textural, mineralogical, and chemical evidences. Now it is proposed to explore if there is any connection in this region between major orogeny and igneous action. The development of schistosity is the clue to this problem. The schists in their relationship to folds and bedding planes show three main attitudes :-

(a) Schistosity is horizontal or sub-horizontal, as near Ardrishaig.

(b) Schistosity is parallel to the axes of the containing folds and dip at angles of 15° to 40°, as near Stronchullin and Erins.

(c) Schistosity is vertical or nearly so as near Tarbert.

The question to be decided is, how much of the schistosity is of a bedding plane nature and how much originated in vertical or inclined positions i.e., associated with folding. DeLury (1941, p.57) has made an attempt to show how bedding-plane schistosity can be developed first and be later folded into vertical or inclined positions. He invokes magma in the process and his hypothesis is discussed next.

DeLury is of the opinion that deformation is caused mainly by forceful migration of more or less horizontal sheets of magma in depth and by their consequent intrusion into shallower levels. The horizontal migration in the deeper parts leads to (a) the deformation of the overlying carapace by differential frictional drag, (b) the development of foliation in the base of the carapace, and (c) the general production of sill-like apophyses from the main magma current. The velocity of the magma is obviously maximum towards the periphery of the sheets and it may be different at different places on the same front, so that there may be differential drag on different parts of the carapace. Behind may be thinning and normal faulting; further ahead plateau uplift ; and at the front folding and overthrusting. A continuous zone of horizontally foliated rocks, more or less parallel to bedding planes, is thus created and subsequently tilted at all angles. Axial-plane foliation may or may not develop depending on the amount of compressive stress in folding and on other factors. Even the compressive stress in folding is considered to have come from the forceful invasion of the magma sheets. After the invasion of the horizontal sheets, magma beds will thicken beneath anticlines and domes and the region may later be affected by another period of superficial folding.

The magma in the above hypothesis is supposed to have been generated in a region of thermal expansion, where heat is accumulating. Local thermal conditions decree that melting takes place in a thin sheet parallel to the isotherm of fusion. The great forces resulting from change of volume on fusion cause the magma sheet to spread in the plane of the isotherm, and to migrate chiefly in the direction of least resistance. Subsidence of a wide regional carapace supplies not only this force for further migration, but abundant energy as well, for conversion into frictional heat which helps to generate additional magma.

More recently Read (1948, p.190) has discussed, at length, the problem of schistosity on bedding and says, " If I had to employ magma directly in this operation, I should prefer to use DeLury's (1941) method." Later on he concludes, " I feel somewhat more comfortable in viewing horizontal schistosity, especially on bedding, as the result of frictional drag or extension rather than of orogenic compression." The frictional drag, however, is considered to be brought about by convection currents in the plastic layer below the crust, and the great authority of Vening Meinesz (1948) is mentioned in support of this view. Goguel (1943) associates such plutonic phenomena with an exceptional efflux of heat and chemical agents from the earth's interior, activated by a horizontal tension in the crust. He refers the totality of this plutonic phenomenon to a 'bouffe' (puff) ascending in a convection current. Kennedy (1948) views the metamorphic zones of the Highlands as essentially the expression of a simple pitching anticline of thermal 'surfaces'. The axis of the anticline is parallel to the main Caledonian fold-axis and it pitches to the S.W. This anticline of thermal surfaces is a direct result of uprising remolten granitic material which brings about widespread injection and migmatisation at the deeper zones of mountain chains, regional metamorphism at yet higher levels, and ultimately emplace-ment of batholithic granite.

Thus in accordance with DeLury's hypothesis , which has been supported in principle by others as mentioned above, the following sequence of events may be envisaged, " A sheet of magma is generated below the Caledonian geosyncline which starts forceful horizontal migration in a S.S.E. direction. Frictional drag exerted by the forcefully migrating sheet on the overlying carapace leads to its bodily horizontal displacement and the development of schistosity. As the process goes on Erins quartzites, Stonefield schists etc., are uplifted and folded, further ahead at the front near Tarbert and along that strike recumbent folding and overthrusting take place. Thinning takes place behind in the Loch Awe-Ardrishaig region which is invaded at the same time by a mass of basic igneous magma. It intrudes the carapace in innumerable sheets along already developed s-planes. The country rocks are thus enormously heated up and help the basic magma sheets to migrate more easily between wall-rocks. At the end of this phase magma beds thicken below anticlines and domes and are encircled by migmatitic and metamorphic zones. A period of quiet follows and broad folds like the Cowal anticline and Loch Awe syncline is developed. This is followed by a period of widespread dislocation and is possibly accompanied by the emplacement of metalliferous veins. This may be correlated to a period of intrusive igneous activity when granite with normal contact aureoles and pneumatolytic concentrations is emplaced."

The view that magma comes into place

in one continuous movement from 'depth' has been repudiated by Anderson, G.H. (1937) according to whom the available evidence appears to sustain the theory that the advance of magma takes place in a series of movements, separated by pauses (some perhaps prolonged) during which partial solidification occur, especially in the marginal portions. This aspect of time and magmatism has been discussed in detail by Read (1949, p.132). A correlation of magmatism-orogeny on the one hand and metamorphic episodes on the other is offered in Table 9, based on Read's discussion. It would appear that the series of episodes of crystallisation and deformation, though alternating and not conclusively coeval, represent parts of a unified phenomenon which has been described as Plutonism by Read (1948). The changes described belong to one self-contained act in the history of these rocks, which are therefore monometamorphic and tell the story of a single plutonic event in its different episodes.

(P.T.O.)

Table 9.

Correlation of Magmatism-Orogeny and Metamorphic Episodes.

| | Magmatism-Orogeny | Metamorphic ---- | Episodes |
|---|---|---|---|
| Prototectonic -- | Geosynclinal phase | - | - |
| Syntectonic -- | Horizontal displacement and deformation of the geosynclinal sediments due to movement of granitic magma in depth. | Development of Schistosity | First |
| | Extrusion and intrusion of a basic magma along already developed planes of schistosity. | | |
| Apotectonic -- | Concentration of magma in anticlines and domes; the volatile components of the magma are dispersed and not localised. | Migmatitic and Metamorphic zones are formed. | Second |
| | A period of relative quiet when superficial folding sets in. | Diapthoretic phase of retrometamorphism. | Third |
| | Emplacement of granite with normal contact aureoles, pneumatolytic concentrations, and possibly emplacement of metalliferous veins. | Phyllonitic phase of retrometamorphism with widespread dislocations. | |

## VII. SUMMARY AND CONCLUSIONS.

In this paper a petrological study of the epidiorites in the Ardrishaig-Tarbert area, Argyllshire, S.W.Scotland has been made to obtain information regarding the processes of metamorphism affecting this region. A study of the country rocks, mainly quartzites and schists, has also been made together with the local geological relations of the known mineral veins and disseminations. The petrological characters of the epidiorites and the country rocks from the chlorite, biotite, and garnet zones of metamorphism, as mapped by Tilley (1925) and Elles and Tilley (1930) in this part of the S.W.Highlands, have been described separately and their place in the metamorphic facies classification, given by Turner (1948), have been pointed out.

Petrographic investigations show that these epidiorites have evolved from basic igneous rocks as a result of changes in chemical and mineralogical composition and texture. These alterations include saussuritisation, albitisation, and epidotisation of the plagioclase felspars, formation of secondary amphiboles (e.g., actinolite, tremolite, and hastingsite), garnet, biotite, chlorite, ilmenite and other minerals with accompanying textural changes suggesting extensive metasomatism.

Considerable evidence has been described to support the view that there is a close connection between regional metamorphism on the one hand and igneous action on the other. From chemical considerations it appears that these epidiorites have been affected by Fe-Mg metasomatism which also has contributed minor components such as $TiO_2$, $P_2O_5$ and MnO. These mafic constituents have been regarded as driven from country rocks overcome by granitisation. The alternative view that a granitic magma could bring about the above-mentioned metasomatism has been discounted because a granitic magma, in itself, seemed unlikely to be the source of residual solutions rich in mafic constituents. It has also been suggested that a 'basic front' of metasomatic metamorphism has moved across this area from the direction of the garnet to the chlorite zone. The change of composition of the epidiorites with change of metamorphic grade has also been investigated and the results agree broadly with those obtained by Lapadu-Hargues (1945) in case of the sedimentary rocks.

Nature of the metasomatic agents and the mechanism of their migration have been discussed. The chlorite-zone epidiorites seem to have derived from basic igneous rocks by a process of selective diffusion in pore-solutions during metamorphism, in the presence of water and $CO_2$. In the biotite zone $K_2O$ was an important constituent of the metasomatic agents in addition to water and $CO_2$. Hydrothermal alterations appear to be much restricted in the garnet zone where reaction and transport may have taken place in the solid phase.

The metamorphic history of this region has been divided into three episodes, the first of which is suggested to have brought about schistosity and its major deformation, the second brought about metasomatic metamorphism when garnet, biotite, and chlorite zones were formed and the third brought about retrogressive metamorphism. Two stages in the retrogressive episode have been recognised, the first diapthoretic and the second, phyllonitic. It is suggested that during the diapthoretic stage chemical changes such as chloritisation of biotite and garnet and saussuritisation of felspars took place and that the Cowal anticline and the Loch

Awe syncline were formed. During the phyllonitic stage widespread dislocations, resulting in thrusts and faults, occured and possibly the metalliferous veins were emplaced.

The relation of metamorphism to orogeny has been explored and DeLury's hypothesis that the migration of horizontal sheets of magma, in depth, may not only bring about schistosity on bedding but also folding and overthrusting has been supported as applicable to this area. Finally a correlation of magmatism-orogeny and metamorphic episodes has been offered. It has been concluded that during the first episode horizontal displacement and deformation of the Caledonian geosynclinal sediments,due to movement of granitic magma in depth, gave rise to regional schistosity which was simultaneously deformed. Extrusion and intrusion of a basic magma was an accompanying phenomenon. During the second episode concentration of magma in anticlines and domes took place and migmatitic and metamorphic zones were formed as a result of the volatile components of the magma being dispersed. A period of relative quiet followed corresponding to the diapthoretic stage of retrometamorphism. Finally the emplacement of granite with normal contact aureoles and pneumatolytic concentrations brought about the phyllonitic stage of retrometamorphism and possibly the emplacement of the metalliferous veins. The epidiorites thus represent one self-contained act in the geological history of this region and are therefore monometamorphic and tell the story of a single plutonic event in its different episodes.

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## VIII. ACKNOWLEDGEMENTS.

I desire to record my sincere thanks to Dr.A.T.J.Dollar who supervised this work, to Professor T.N.George whose kind interest and advice during the progress of this work was very encouraging, to Dr.G.W.Tyrrell who kindly helped with the loan of a copy of one of his unpublished manuscripts and many other papers and books for purposes of reference and to Dr.B.C.King who frequently spared time to discuss some of the problems. I am also grateful to Mr.A.Fergusson and Mr.J.Keith, both of whom helped considerably with the photographic part in this work. I thank all others of the Geology Department, The University, Glasgow for their courtesy and kindness to me.

Finally I desire to express my indebtedness to the Education Department, Government of India for the award of a handsome scholarship which has entirely defrayed the expenses of this work.

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## PLATE I.

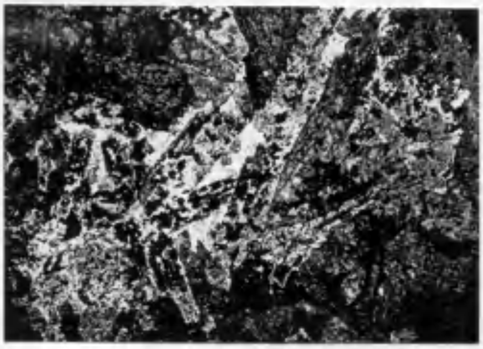
1. Blastophitic texture involving saussuritic felspar and amphibole (s.177). Chlorite zone. Ord. Light. X 10.

2. Blastopoikilitic texture - a coarse plate of amphibole completely enclosing saussuritic felspars (s.6). Chlorite zone. Ord. Light. X 10.

3. Granoblastic texture involving twinned albite and amphibole crystals (s.165). Chlorite zone. + nicols. X 20.

4. Blastoporphyritic texture involving a coarse plate of amphibole with minute inclusions of iron ore and blebs of clear albite - a few inclusions of saussuritic felspars can be recognised (s.155). Biotite zone. Ord. Light. X 10.

PLATE I.



1.

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4.

## PLATE II.

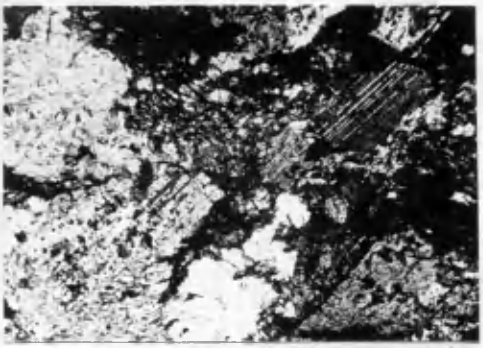
1. Cataclastic texture shown by a broken crystal of albite at the top right-hand corner.(s.2).
   Chlorite zone. + nicols. × 10.

2. Pseudo-cataclastic texture - corroded edges of the amphibole plate is remarkable (s.118).
   Chlorite zone. + nicols. × 10.

3. Micrographic texture - coarse intergrowth of quartz and albite (s.10).
   Chlorite zone. + nicols. × 40

4. Myrmekitic texture - fine intergrowth of quartz and albite.
   Chlorite zone. + nicols. × 40

# PLATE II.



1. 2.

3. 4.

## PLATE III.

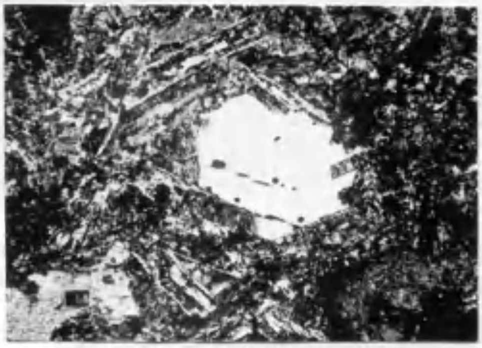
1. Crystalloblastic quartz surrounded by saussuritic felspars - inclusions of a few albite grains can be recognised (s.119).
   Chlorite zone. + nicols. × 15

2. Symplektitic texture (s.211).
   Chlorite zone. + nicols. × 10

3. Crystalloblastic albite involved with quartz in a pseudo-cataclastic texture (s.89). × 15
   Chlorite zone. Ord. Light.

4. Clouded albite (s.209).
   Chlorite zone. Ord. Light. × 15

PLATE III.



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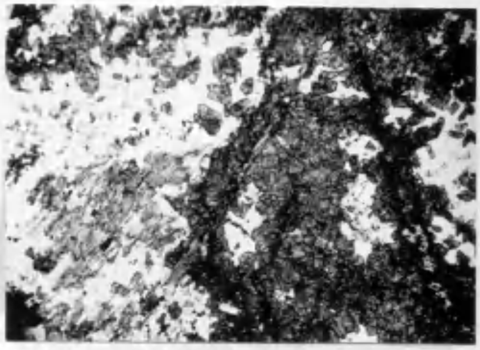

2.

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## PLATE IV.

1. Myrmekitic lace round an albite crystal (s.10).
   Chlorite zone. + nicols. x 40.

2. Chess-board albite together with clouded albite and quartz (s.31).
   Chlorite zone. + nicols. x 40.

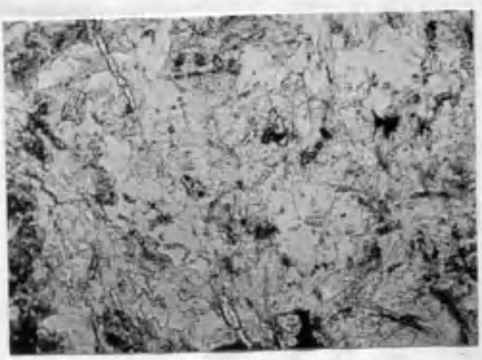
3. Inclusions of needles of rutile in quartz and felspar-grains of apatite can also be seen (s.227).
   Chlorite zone. Ord. Light. x 40.

4. Ilmenite plates replaced to sphene at the margins (s.208).
   Chlorite zone. Ord. Light. x 15.

PLATE IV.

1.

2.



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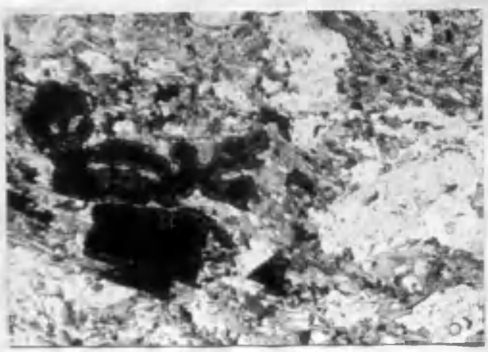


4.

PLATE V.

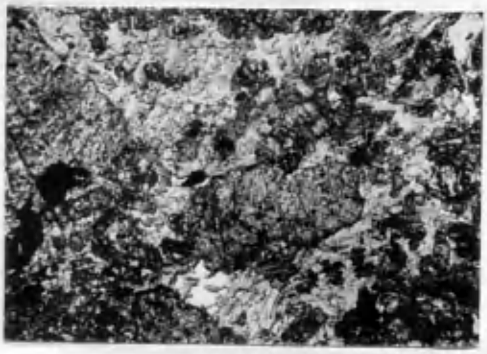
1. Sheared chlorite-epidote-albite-amphibolite (s.207).
Chlorite zone. Ord. Light. x 20.

2. Chlorite-stilpnomelane-albite-hastingsite-calcite (s.208).
Chlorite zone. Ord. Light. x 15.

3. Chlorite-albite-calcite-schist (s.178)
Chlorite zone. Ord. Light. x 15.

4. Felspathic quartzite (s.7).
Chlorite zone. + nicols. x 40.

PLATE V.



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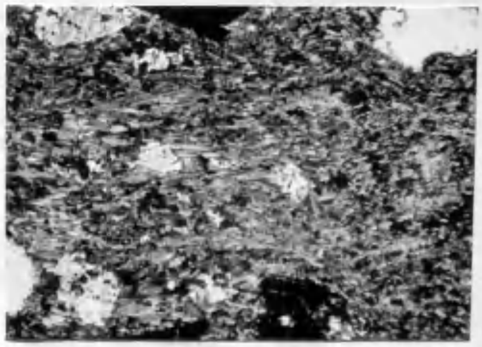

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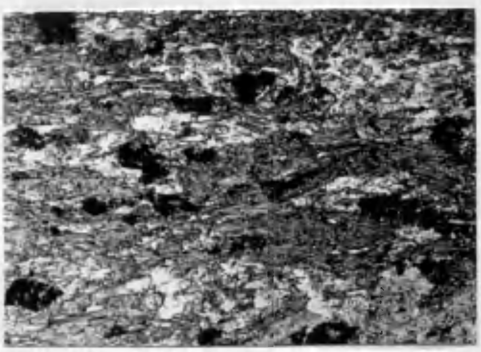

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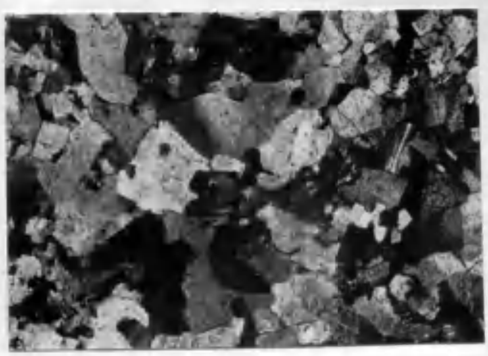


4.

PLATE VI.

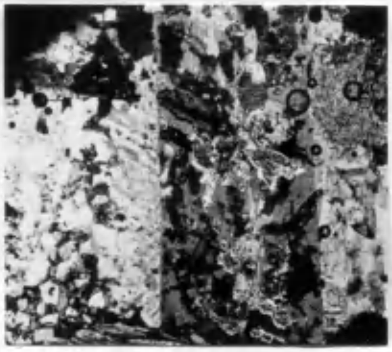
1. Linear inclusions of muscovite in albite (s.12).
Biotite zone. + nicols. x 40.

2. Biotite-chlorite-albite-hastingsite-skarn (s.81).
Biotite zone. Ord. Light. x 20.

3. Muscovite-biotite-quartzite (s.273).
Biotite zone. Ord. Light. x 20.

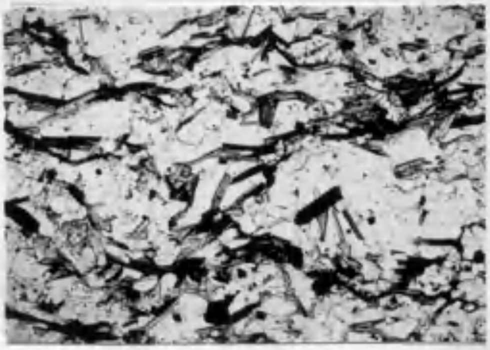
4. Garnet-hastingsite-epidote-albite-skarn (s.269).
Garnet zone. Ord. Light. x 20.

PLATE VI.



1.

2.



3.

4.

## PLATE VII.

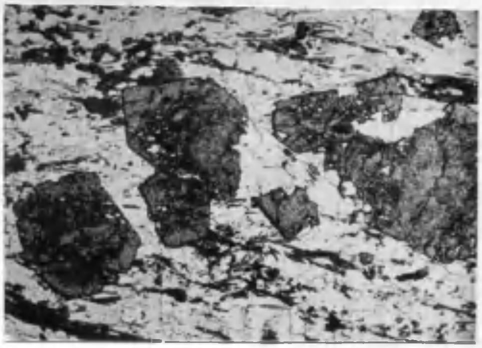
1. Garnetiferous quartzite (s.87).
   Garnet zone. Ord. Light. x 15.

2. Anorthoclase (cross-hatched twinning) at the edges of albite-plates (s.88).
   Garnet zone. + nicols. x 40.

3. Rotated crystal of amphibole (s.231).
   Chlorite zone. Ord. Light. x 40.

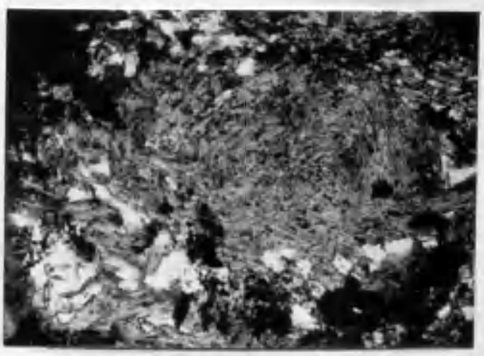
4. Bent twinned-lamellae of amphibole (s.225).
   Chlorite zone. + nicols. x 15.

PLATE VII.



1.

2.



3.

4.

PLATE VIII.

1. Distant view of an epidiorite outcrop. The elongated white patch indicates a 2 ft. scale. From near Cruach Brenfield. Chlorite zone.

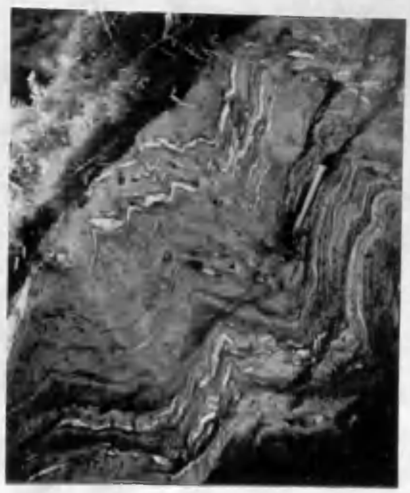
2. A thick sill of epidiorite with foliated margin. From the coast of Loch Fyne near Erins. Garnet zone.

3. Coarse-grained and massive outcrop of epidiorite. From Breac-larach. Garnet zone.

4. Folding on foliation in a bed of quartzite containing quartz-calcite veinites. The end of the hammer indicates the average direction of dip of the foliation. From near Tarbert.

# PLATE VIII.

1. 2.



3. 4.