Metamorphism and metasomatism around the Shap and Eskdale granites

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METAMORPHISM AND METASOMATISM AROUND THE SHAP AND ESKDALE GRANITES.

By

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PART I. METAMORPHISM AND METASOMATISM AROUND THE SHAP GRANITE.

CONTENTS.

I INTRODUCTION.

(a) History of Research.

The English Lake District is a well defined physiographical and geological unit. As shown in Fig.I it consists of an inlier of Lower Palaeozoic rocks bounded by Carboniferous and New Red Sandstone rocks.

Johnathan Otley, the "Father of Lakeland Geology" first recognised the three-fold division of rocks in the area. In 1820 he described the succession of "lower slates, green slates and porphyries,and upper slates,with a band of limestone at the base." This was later elaborated by Sedgwick(1842) in a series of letters published in Wordsworth's "Scenery of the Lakes of England". Furthermore, he described the main granite masses. The present research is concerned with the rocks around two of these masses, namely the Shap and Eskdale Granites intruded into south east,and western parts of the "green slates and porphyries".

The name Borrowdale Volcanic series was given to the "green slates and porphyries" by H.A.Nicholson and described by him in 1868. An official examination of these rocks was carried out under J.C.Ward's direction in the eighteen seventies and maps and memoirs were later published (Ward 1876, Aveline 1872,1888). However, Ward regarded most of the porphyritic and amygdaloidal lavas as highly metamorphosed tuffs (1875) and thus the true stratigraphy and structure was not elucidated. Geikie (1897) in an admirable account of the Borrowdale Volcanic series maintained that Ward "somewhat exaggerated the amount of fragmental material". This was confirmed by later work . Marr and Harker (1900) produced a generalised map and a stratigraphical succession. Green (1912) established a detailed sequence of lavas and tuffs in the Duddon Valley and tried to apply this succession to other areas. Detailed mapping by Mitchell (1929,1934, 1940), Hartley (1925, 1932, 1942) and Hadfield and Whiteside (1936) has shown great lateral variation and the presence of more acid flows than Green suggested. Fig. 2 shows the area mapped in detail and includes the author's and R. L. Oliver's unpublished mapping.

The petrology of the Borrowdale Volcanics has been studied by most writers on the Lake District Volcanics and detailed studies of the garnetiferous rocks have been made principally by Walker (1904), Green (1917) and Oliver (unpublished work).

The earliest studies of the Eskdale and Shap Granites were made by Marshall (1859,1862) and Nicholson (1868) who regarded these intrusions as the result of metamorphism of the surrounding "green slates and porphyries". These views were later elaborated by Ward (1875). The first detailed petrographic work on these granites was by Harker and Marr (1891) on the Shap granites and Dwerryhouse (1909) who investigated the Eskdale granite. The Shap granite was later re-examined (Grantham 1928) and the petrogenesis discussed, whilst Simpson (1934) studied the petrology of the Eskdale granite. Harker and Marr (1891 and 1893) described in detail the metamorphic aureole of the Shap granite and this work forms the basis of the present research. They discounted the possibility of widespread metasomatism and the primary object of the author's researches was to study the metasomatism of the Borrowdale Volcanic rocks around the Shap and Eskdale granites.

Apart from Harker and Marr's papers little has been published on thermally metamorphosed lavas. Harker (1894 p.331) described xenoliths of metamorphosed lavas in the Carrock Fell gabbros, whilst Walker (1904), Dwerryhouse (1909) and Simpson mentioned contact specimens from the Eskdale area. Further the western part of the Ennerdale granophyre and Eskdale granite aureoles were briefly described in the Gosforth memoir(1937)

Other relevant references to thermally metamorphosed lavas and to petrogenetic problems of thermal metamorphism, metasomatism and mineralisation are cited in the following text:

(b) Summary of the Geology of the Shap District.

The district described includes most of the country on the Ordnance Survey, Westmorland. Sheets XXI S.W. and XXI N.W. and parts of Sheets XX N.E., XXVII N.E. and XXVIII N.W. It consists largely of trackless moorland stretching westward from Shap Wells. Much of the area is covered with peat and drift covers the eastern and north-eastern part of the area. However good exposures occur on the higher parts of the fells whilst exposures of granite in the Shap granite quarries near Wasdale Head, in Shap Blue quarry and the old rhyolite quarry are excellent. The Shap Blue quarry opened for roadstone in the metamorphosed Borrowdale lavas, west of Penrith-Kendal road three miles south of Shap village, opened after Harker and Marr had completed their Shap granite researches.

The oldest rocks in the area are Skiddaw slates which outcrop near Keld. They are succeeded, apparently conformably, by mottled tuffs and porphyritic andesites of the Borrowdale Volcanic series. However, only the upper divisions of this series occur in the aureole of the Shap granite. These rocks consist of lavas and tuffs, the lavas varying in composition from basic andesites to rhyolites with andesite predominating. The Coniston limestone group, of Caradocian age, consisting of impure limestones and the Stockdale rhyolite rests unconformably on the Borrowdale Volcanic Series. Owing to faulting, the Ashgill and Stockdale shales do not outcrop in this area, though they may be seen further west. Silurian flags, siltstones, shales and occasional impure limestone occupy the ground south of Wasdale Head.

The Ordovian and Silurian rocks were subjected to pressure from the south-east in Devonian times, which resulted in folding, faulting and cleavage. It can be demonstrated that the

Shap granite was emplaced at its present level after the Lower Palaeozoic rocks had been cleaved. The granite is thus a post-tectonic intrusion and since fragments of the characteristic felspar phenocrysts from it can be found in nearby Carboniferous Basement Conglomerate, it is considered to be of Devonian age.

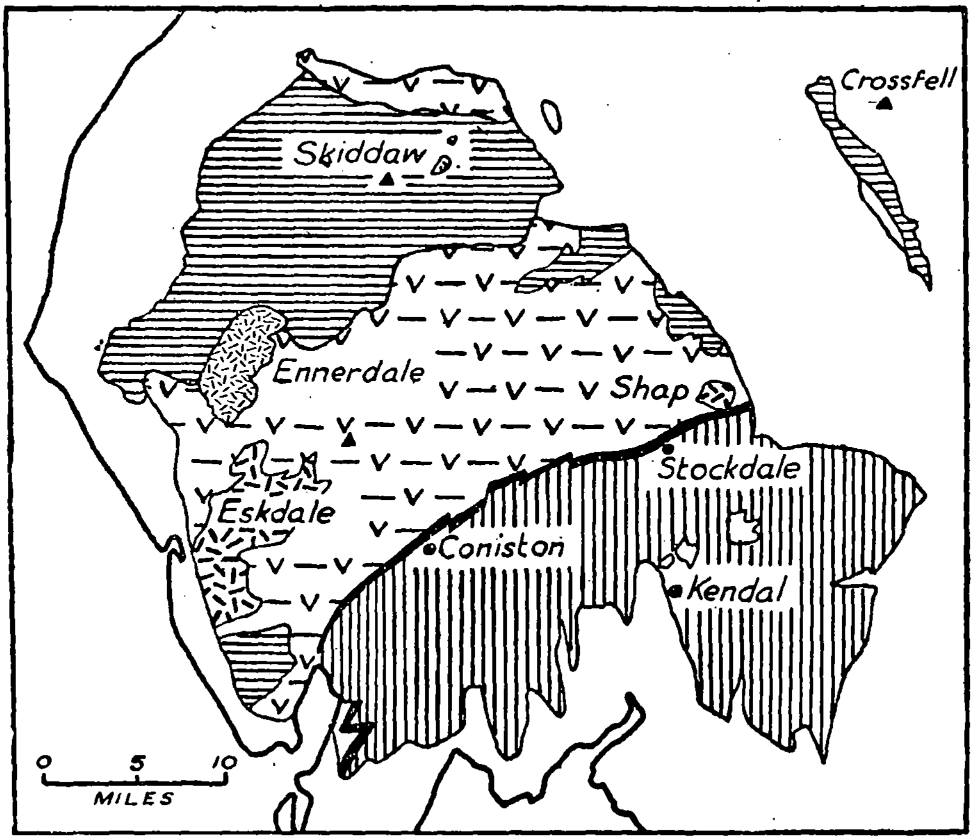


Fig.1. Sketch-map of the English Lake District, showing the major rock-groups and the more important intrusives. Ordovician horizontal ruling; Silurian vertical ruling; Borrowdale Volcanic Series, V. (After Hatch and Wells).

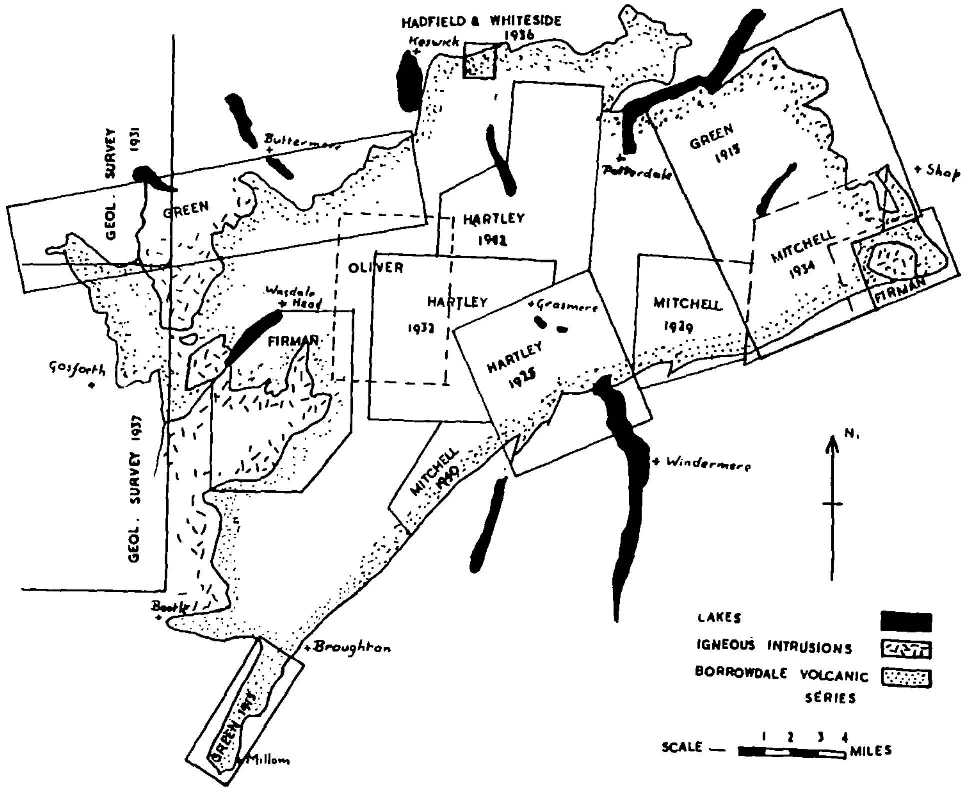


Fig. 2. Areas of the Borrowdale Volcanic Series mapped since 1910 (After Hartley 1942 with additions.)

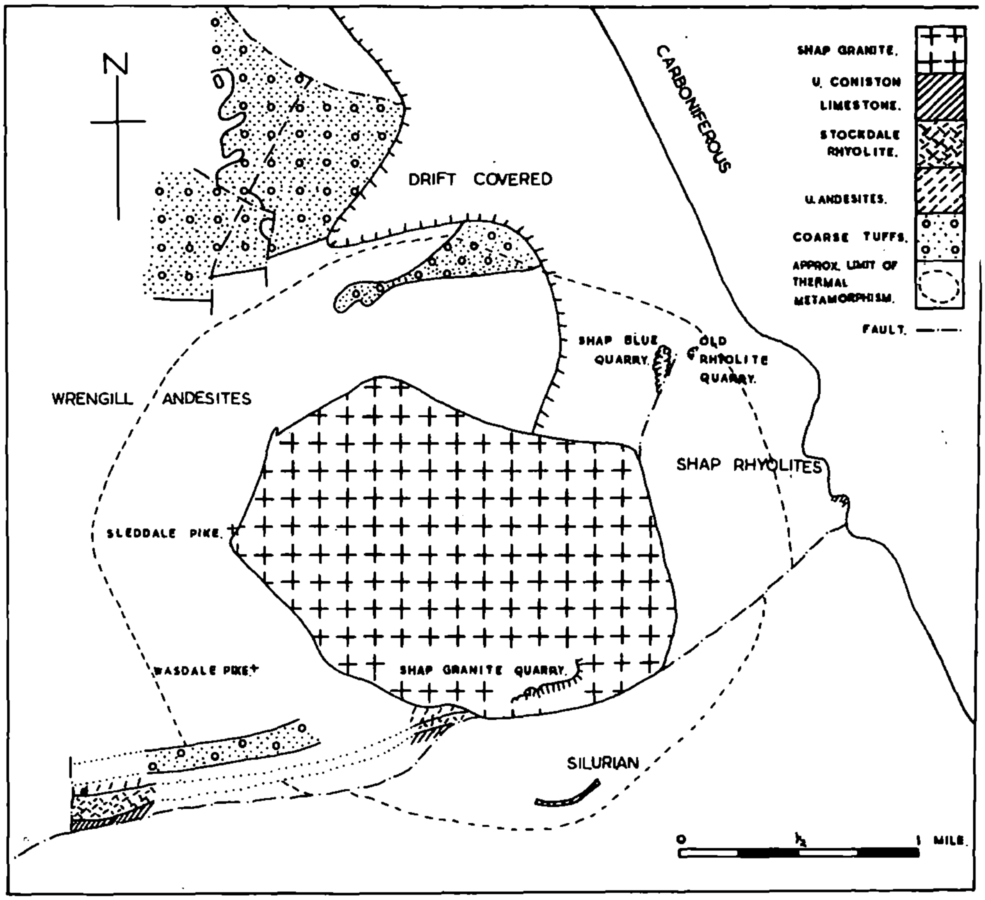


Fig.3. Sketch map of the Shap granite and surrounding rocks.

II STRATIGRAPHY.

(a). Stratigraphical Succession.

The generally accepted stratigraphical succession in this area is as follows:-

Silurian	Coniston Grits		
	Upper Coldwell	(flags)	
	Middle Coldwell	(Calc)	
	Lower Coldwell	(Grits)	
	Brathay Flags		
	Stockdale Shales - Faulted out from Red Crag to Spa Wells.		
Ordovician	Upper Coniston Limestone = Applethwaite Beds		Coniston
	Stockdale Rhyolite		Lime-
	Lower Coniston Limestone = Stile End Beds		stone
	Unconformity		Group.
	Borrowdale Volcanic Series (B.V.S.)		
	Skiddaw Slates		
	Base not seen		

The granite is in contact with the Coniston Limestone group and Brathay Flags in the south and south east respectively, but the greater part of the aureole is occupied by tuffs and lavas of the Borrowdale Volcanic Series and it is precisely in the naming of the various members of this series that there is a general lack of agreement. Three classifications have been applied to this area. Harker and Marr's (1900) classification was based on chemical and mineralogical characters, and no attempt was made to sub-divide into lavas and pyroclastic rocks. J.F.N.Green (1915) applied a lithological succession, established largely in the Duddon Valley, to the Eastern Lakes. Neither classification has proved entirely satisfactory and Mitchell's lithological classification whilst of more local application has been adopted.

The three classifications are tabulated below:-

Harker and Marr (1900)	J.N.Green (1915).	Mitchell (1934).
Shap Rhyolites	Rhyolites	(Rhyolites Kentmere only)
Shap Andesites	Upper Andesites	Upper Andesites
Scafell banded ashes and breccias = Kentmere Coniston Slate band.	Harrath Tuffs	Coarse Tuffs
Ullswater basic lava group = Eycott group	Wrengill Andesites	Wrengill andesites
Falcon Crag and Bleaberry Fell Andesites.	Middle Tuffs	Kentmere Pike Rhyolites
	Lower Borrowdale Andesites	Bedded Tuffs
	Mottled Tuffs.	Harter Fell Andesites
		Froswick Tuffs
		Nan Bield Andesites
		Haweswater Rhyolites
		Base not seen.
	Unproved succession exposed east of the Ralfland Forest faults.	(Ralfland Forest Andesites (Mottled Tuffs (Skiddaw slates (

It seems probable that Harker and Marr's Shap Rhyolites are roughly equivalent to the Upper Rhyolites (of the Kentmere district), the Upper Andesites and Coarse Tuffs of Mitchell, whilst the Shap andesites are equivalent to the Wrengill andesites. Probably the more flinty Rhyolites east of granite are equivalent to the Rhyolites of Kentmere, but it is also possible that they are lower in the succession and represent flows from an Eastern or Southern source. In the 1920's and 1930's the B.V.S. from Shap westwards to the Langdales was resurveyed by G.H.Mitchell and J. J. Hartley and, whilst it was found that many beds are impersistent, it is possible to correlate horizons in the Coniston District with those adjacent to the Shap Granite.

(b). Skiddaw slates, Mottled tuffs and Ralfland Forest andesites.

The lowest beds in the area, the Skiddaw Slates, are exposed in old workings in Thornship Gill where there are dark blue well cleaved shales gently undulating and dipping between 25° and 50° south west. These appear to be overlain unconformably by fine grained greenish tuffs with fragments of shale - the Mottled Tuffs. Similar Tuffs are found in Lowther Beck and on Slate Hill south east of Thornship Gill. Although the contact cannot be seen there is no evidence of a fault. With the succeeding porphryitic andesites the relationship is much more obscure and the feature between Keld and Thornship Gill strongly suggests erosion along a fault line. These beds and probably the tuffs and andesites near Kemphow and Crags Mill lie north and east of the Ralfland Forest fault, which throws coarse tuffs against the Ralfland Forest Andesites, and their representatives are not found within the Shap Granite aureole.

(c) Wrengill Andesites.

(i) Field Characters:- More than half the rocks outcropping in the aureole are representatives of the Wrengill Andesite Series. They outcrop in a broad arc around the granite from the Shap Blue quarry to just south of Wasdale Pike extending northward into Wet Sleddale and westward towards Mosedale. To the north of the granite the general dip is northward towards the Sleddale Syncline, whilst to the west the general dip is southward. Wet Sleddale marks the line of an eastward pitching syncline, whilst the area to the west is probably occupied by southward dipping strata with superimposed anticlinal folding. These are pre-granite structures. Owing to a thick covering of peat no clear idea of the amount of folding or thickness of the series can be obtained.

The Wrengill andesites, which are fairly well exposed outside the aureole at Tod Crags and the Widepot, consist of a number of thin flows of blue green aphanitic andesites, often vesicular, but sometimes porphyritic or massive and occasionally interbedded with tuffs. Where not greatly cleaved the more massive types are well jointed. Flow breccias are often developed and can be recognised by their characteristic honeycomb weathering or their "knotty" appearance on a fresh surface. This feature is particularly well developed within the aureole. In the stream from Tod Crags epidote is developed in association with flow brecciation. Vesicular lavas are the most common and vesicles vary from one or two mm. to several cms. in diameter and are filled with quartz, calcite or chlorite. The smaller vesicles are often quartz filled and spherical in form, whilst the larger are often ovoid. Since the long axis is usually roughly parallel with the foliation this feature is a tectonic and not an original one. Porphyritic andesites consisting of glomero-porphyritic aggregates of felspar phenocrysts and chloritic pseudo-morphs after augite set in an aphanitic ground mass have been recorded at Tod Crags, on the Widepot and nearer the granite, in Wet Sleddale at the top of the succession, and in Howe Gill. At Tod Crags a characteristic porphyritic flow has been traced about 700 yards, but no such similar flow has been found within the aureole. The dominant colour is blue-green becoming darker in colour and often purplish as the granite is approached. This is presumably due to the development of biotite resulting from thermal metamorphism, but similar purplish types outcrop outside the aureole. More leucocratic and presumably more acid types are occasionally seen.

Interbedded tuffs, usually only a few feet thick, occur sporadically. Where fine grained and highly cleaved they are often difficult to distinguish from lavas. Their greenish colour, presence of lithic fragments, absence of vesicles and tendency to be more highly cleaved than the andesites, help in field identification. Several tuff bands have been mapped, where these features were sufficiently diagnostic, and it seems certain that systematic collecting and microscopical examination would reveal others. Usually such bands are fine grained but coarser tuffs containing felsic fragments have been recorded in Wet Sleddale. Since the bulk composition of these tuffs probably corresponds to that of the andesites a similar mineral assemblage results with thermal metamorphism and tuffs are consequently very difficult to identify within the aureole. The lack of vesicles is not conclusive since non-vesicular lavas occur but it seems that the development of a schistose as opposed to a hornfelsic structure may be characteristic.

(ii) Petrography- The Wrengill Andesites in this area are usually so intensively altered and often sheared that identification of their original composition is impossible. The pyroxenes in the ground mass are always replaced by chlorite and the felspars usually sericitised.

The most characteristic texture is intersertal with an interlocking network of felspar laths (c.0.1 - 0.2mm long). Extinction varies from 0° - 10° indicating an albite-oligoclase composition and suggesting albitisation of the original felspars. The interstices are normally filled with chloritic material, granules of epidote, sphene, and magnetite, with more occasionally limonite or haematite. Apatite is the most constant accessory mineral in the ground mass occurring in minute idiomorphic prisms. Felspar phenocrysts, where present, are usually sericitised and more rarely partially replaced by epidote. Owing to the secondary products optical determination of the composition was found to be impossible. Calcite also occurs in the ground mass sometimes replacing felspars and this may be associated with later regional veins.

The most characteristic changes are the sericitisation of felspars and the development of chlorite after pyroxene. These changes are probably due to late stage dueteric effects regional metamorphism and rock weathering. Epidotisation is limited to the area around Great Saddle Crag and to flow breccias near Tod Crags.

Silicification and development of hornblende pseudo-morphs after pyroxenes, recorded in the Eskdale district, have not been observed.

Flow breccias are not infrequent and many of the features described by G.H.Mitchell (1930) are seen. Characteristically (R.F 189) angular fragments of normal andesite are set in a crypto crystalline ground which may be a devitrified glass. Often they resemble tuffs but the fragments are petrologically similar and fluidal structures may be seen.

The lavas are not vesicular throughout and massive non-vesicular types are well exposed in Shap Blue Quarry but vesicularity is a common feature. The most common minerals filling vesicles are chlorite, calcite, chalcedony and quartz.

In addition, in certain areas, the andesites have been greatly sheared and associated with this small calcite veins have developed. In areas of more intense shearing chlorite has developed along the shear planes at right angles to the maximum pressure, whilst, where regional calcite veins have developed, these tend to fill pre-existing joints. In areas where tectonic pressures were less intense chlorite normally fills most of the joints. Harker and Marr demonstrated that the Shap granite intrusion was post-tectonic and that the lavas were highly altered before being thermally metamorphosed. No evidence was found supporting Harker and Marr's contention (1893) that the lavas to the north of the granite are more basic than those further west although acid andesites do outcrop on Wasdale Pike.

Interbedded tuffs vary in grade and lithology but mostly consist of a fine grained aggregate of andesite material set in a chloritised matrix.

(d). Coarse Tuffs.

(i) Field characters.- The base of the Coarse Tuffs forms the most easily mapped horizon of the B.V.S. in the area. Coarse Tuffs outcrop in three main areas. In the south a series of coarse agglomerates about 500 feet thick has been traced to within 500 yards of the granite contact. Unfortunately peat cover prevents it being mapped with certainty nearer the granite although loose boulders have been found south east of Wasdale Pike. The coarse tuffs dip away from the hanging wall of the north-south Yarlside Crag fault until the 1500 foot contour is reached and then maintains this horizon for 500 yards. The strike changes from approximately north east-south west to east 20° north - west 20° south. A further change in horizon, probably due to faulting, is indicated by the occurrence of rhyolites and acidic andesites at 1500 feet O.D. nearer the granite. Further, boulders of Coarse Tuffs have been found at 1750 feet O.D. on Wasdale Pike.

In Wet Sleddale, near Beckside, Coarse Tuffs outcrop in the centre of the eastward pitching syncline, whilst its western and southern boundaries are well marked, the eastern and northern are obsured by drift. Similarly the eastern extent of Coarse Tuffs, north of Wet Sleddale, is obscured. This area is by far the most extensive outcrop of Coarse Tuffs in the area mapped and, since it lies almost wholly outside the aureole, shows good examples of unmetamorphosed agglomerates. This area is somewhat faulted and faulted blocks of Wrengill andesites occur. The boundary with the underlying andesites is complicated and probably best explained by generally eastward dipping rocks gently folded on east west axes (Mitchell 1934). Owing to the similarity in weathering and the fact that some of the finer tuffs are similar to those interbedded with the Wrengill andesites, difficulty was experienced in mapping in this area. There is no evidence that the Coarse Tuffs and upper Wrengills are interbedded and for general purposes the base of the Coarse Tuffs may be regarded as the most reliable datum line in the B.V.S. However, the possibility that Coarse Tuffs rest unconformably on the Wrengill Series cannot be over-looked. It may be significant that the porphyritic andesite underlying the Coarse Tuffs in Wet Sleddale south side has not been recorded elsewhere.

The Coarse Tuffs are volcanic agglomerates of coarse grade consisting of lithic angular fragments, varying greatly in size, but averaging about ½" to 1" across and more rarely up to

6": blocks of andesite up to 3 feet have also been recorded. Lithic tuffs of finer grade occur occasionally. Throughout the area the most characteristic feature is the presence of pink rhyolitic fragments and in some places, particularly north of Wet Sleddale, these are a major constituent. The source of this material is uncertain since no similar flow or intrusion has been found beneath this horizon. Other constituents discernable with the aid of a hand lens are dark green massive and amygdaloidal andesites and glassy fragments set in a paler green matrix, which appears to be composed of more or less the same material. Except where finer tuff bands occur there is no evidence of bedding and in general the agglomerates are unbedded and ill graded.

Outside the aureole the Coarse Tuffs are most easily recognised on fresh surfaces by their characteristic light green matrix with darker fragments, by the presence of pink rhyolitic material and by their characteristic weathered surfaces. The matrix is usually the least resistant to weathering and the angular fragments stand out conspicuously on the weathered surface. This is the opposite of the weathered flow breccias in the Wrengill Andesite Series, where the individual fragments are usually more easily weathered. However, weathering of a similar type does occur amongst andesites. Towards the granite the colour of the Coarse Tuffs tends to become progressively darker whilst the rock itself becomes more flinty.

Fig.4. (R.F.116) Coarse Tuff. Little Ladstones. Shap. Unmetamorphosed Coarse Tuff consisting of fragments of rhyolite andesite and felspars set in a base of chlorite and leucoxene (x 35).

(ii) Petrology- As stated, the Coarse Tuffs vary greatly in lithology and grade. They are lithic tuffs, consisting of fragments of andesitic and felsitic material. Under the microscope these angular fragments are seen to be set in a base of felspar crystals, sericite and chlorite with accessory minerals such as magnetite, ilmenite, leucoxene and limonite. The felspars are often sericitised but vary in composition from oliogase to andesine. In some areas (e.g. Great Ladstones R.F.82) the base is impregnated with haematite imparting a purplish colour to the rock.

The andesite fragments show characters similar to the Wrengill Andesites whilst the felsitic fragments resemble non-porphyritic Lake District rhyolites. They consist of a fine grained mosaic of quartz, potash felspar and albite. No similar rhyolites from beneath the Coarse Tuffs have been described from the Shap Area.

(e) Upper Andesites.

The Upper Andesites are not well exposed in the aureole. Outcrops near the Granite at Wasdale Head have been tentatively assigned to this series, but no other outcrops occur east of the Yarlside Crag Fault. Good exposures are seen in the Stockdale Beck and north of Red Crag. They consist of a succession of porphyritic and vesicular andesites with occasional interbedded tuffs. In most respects they are similar to the Wrengill Andesites but tend to be somewhat paler in colour. It should be noted here that unmetamorphosed andesites from Stockdale Beck described by Harker and Marr (1891 p.293) are from the Upper Andesite Series and cannot be correlated with andesites near the granite.

(f). Shap Rhyolite Series.

The relation of Harker and Marr's Shap Rhyolites to the under-lying rocks, must be hypothetical, since metamorphosed rhyolites and acid tuffs east of the granite either outcrop adjacent to the granite, or are faulted against Wrengill Andesites in the north, and Brathay Flags in the south. The position of leucocratic rocks on Wasdale Pike is even more obscure. Further owing to drift cover west of Shap Wells Hotel it is impossible to establish any stratigraphical succession within the series. However in Blea Beck, Coniston limestone overlies rhyolite and it appears that this series is the upper group of the B.V.S. These beds may be equivalent to the Upper Rhyolites of the Kentmere District.

In general they consist of metamorphosed fine and medium grained tuffs together with occasional rhyolite flows. Owing to the silification, the tuffs such as those in the railway cutting are hard and flinty and very difficult to distinguish from lavas.

(g) The Coniston Limestone Group.

The Coniston Limestone Group in this area consists of a lower calcareous bed, the Stockdale Rhyolite, and an upper calcareous bed with basal breccia. That this group rests unconformably on the B.V.S. has been demonstrated in other areas notably and Kentmere and Coniston Districts by G.H.Mitchell, and in the Duddon Valley by J.F.N.Green. In the Shap area the evidence for this unconformity is less clear and although the diminishing width of outcrop of the Upper Andesites suggests an overlap, there seems to be little angular discordance between the Coniston Limestone Group and the B.V.S. There is no evidence supporting the lag fault suggested by Harker and Marr.

The sedimentary rocks of the group are best exposed in Stockdale Beck and in Blea Beck near Shap Wells and are seen in a highly metamorphosed state at Wasdale Head: the Stockdale Rhyolite is well exposed from Stockdale Beck to Yarlside Crag. At Stockdale the Lower Limestone (Stile End Beds) consists of blue laminated calcareous shales with blue limestone bands and nodules. A small exposure in Blea Beck appears to be more calcareous. In Stockdale Beck the Upper Limestone (Applethwaite Beds) is represented by blue flags whereas in Blea Beck an impure limestone occurs. A breccia containing fragments of rhyolite outcrops both at Shap Wells and at Wasdale Head. Judging by the character of the calc-silicate hornfels at Wasdale Head the original rock must have been calcareous.

The Stockdale Rhyolite throughout its outcrop is a distinctive pink rhyolite. Nodular, flow banded and massive types occur but no definite order of superposition has been established. These rhyolites appear to thicken appreciably when traced westward from Wasdale Head and it has been estimated that the Stockdale rhyolites increase in thickness from 50 feet above the farm to at least 300 feet at Yarlside Crag.

(h). Silurian.

The Silurian rocks have not been mapped in detail, but appear to consist largely of argillaceous flags together with calcareous bands dipping between 50°-60° south east.

III STRUCTURE.

Both folding and faulting are important in the area, whilst the intrusion of the granite has caused some displacement of the surrounding rocks. The effects of the latter, however, are slight and the main structural features of the area were determined by the Caledonian orogenesis, the granite emplacement being post tectonic. It is unlikely that the Hercynian and Tertiary earth-movements had much effect other than uplifting and tilting the area south eastwards.

(a) Pre-Bala Movements.

Clear evidence of an overstep of the Coniston Limestone Group onto the B.V.S. is absent in this area, and most of the evidence suggests that there is little angular discordance between the two. It seems likely, however, that gentle folding on south-south-west to north-north-east axes took place and it has been suggested by G.H. Mitchell (Q.J.G.S.1934 p.435) that the widening of the outcrop of the Upper Andesites west of Crookdale suggests synclinal folding, whilst an anticlinal axes through Seat Robert would account for the Coarse Tuffs dipping away from the hill.

No faulting has been observed which can be assigned to this date.

(b) Caledonian Movements.

Evidence for folding in Devonian times rests on inferences drawn from the mapping of the Coarse Tuffs, Stockdale

Rhyolite and Silurian rocks. Peat cover and want of continuous sections prevents any detailed account of folding in the Wrengill Andesites Series, but the great width of outcrop of Wrengills west of the granite suggests that they are similarly folded to that demonstrated by G. H. Mitchell in the Haweswater tunnel area. Here a series of deep overfolds and anticlines occur. No evidence of such folding has been proved in the area mapped. However, a syncline is revealed by the outcrop of Coarse Tuff in Wet Sleddale, and gentle folding on west south west - east north east axes is suggested by the sinuous outcrop of Coarse Tuffs east of Bleak Hill. Both the Bleak Hill and Wet Sleddale outcrops pitch eastward and this may well be due to superposition of Devonian folding on earlier pre-Bala folding. Whilst evidence of a synclinal structure cannot be seen west of Sherry Gill a belt of strongly developed cleavage extends west of Tongue Rigg. Within this belt both tuffs and andesites are often well cleaved. Although the development of cleavage has been ascribed to a later date, it may have developed along the synclinal axis.

To the south the Coniston Limestone Groups and Silurians dip south and south east between 40° and 60°. As stated there is no evidence of pronounced angular unconformity and the Upper part of the Wrengills, Coarse Tuffs and Upper

Andesites dip in the same direction and inclination in this area.

(c) Faulting.

No faulting connected with Pre-Bala earth movements has been recognised and it seems that the faulting was of Devonian age although later than the folding. Some faults are filled with barytes-calcite or barytes-quartz associations and it has been shown that similar associations fill fault-breccias in the Blue quarry (p.177), faults in Sherry Gill and an unnamed gill near Tod Crags. The similarity between these pink veins and barytes veins exposed in the Shap granite quarry provides strong evidence for the assumption that this faulting is associated with the emplacement of Shap Granite. It should be noted that in the Blue quarry small normal faults will little throw transgress the garnet bearing veins. Probably these faults are associated with the intrusion of the granite but antidate hydrothermal stage.

Fault breccias ten feet or more wide are exposed in Peat Hill Gill and in an unnamed gill east of Tod Crags. They appear to be almost vertical and represent normal faults. Other faults affecting the B.V.S. have been inferred from the mapping. The most important faults in the area are (1) the fault crossing Stackhouse Brow, (2) the north-south fault east of the Blue Quarry throwing the andesites against the Shap Rhyolites, (3)north east-south west fault near Wasdale Beck throwing Shap Rhyolites against Brathay Flags, (4) Roughly east-west fault, from Wasdale Head to Borrowdale Moss throwing the Coniston Limestone against the Brathay Flags, (5) north-south fault boundary Yarlside Crag.

(1). This fault is marked by a feature on the south eastern and downthrow side formed by the Coarse Tuffs and trends southward, west of Tailbert Fell, and swings south east over Mirk Fell to Peathill Gill. Over Stackhouse Brow this feature is obscured by Drift but the presence of porphyritic andesite near Coarse Tuff suggests that the fault passes through Stack House.

(2) The north-south fault downthrown to the east and throwing andesites against the Rhyolite Group is not exposed, but its direction is inferred from the proximity of andesites and rhyolites and their difference in strike.

(3) A north east-south west fault has been mapped from near Shap Wells to the Granite contact 100 yards north of Wasdale Bridge. Owing to drift cover the exact position of this fault in unknown. A slight feature near the plantation may mark the upthrown north-west side. Brathay Flags with a constant dip of 50-55° south east outcrop in Wasdale Beck whilst boulders of metamorphosed Rhyolitic Tuff occur on Wasdale Foot. It seems

continuous with the fault from Wasdale Head to Borrowdale Moss and may like that be a thrust developed in the incompetent shales as a result of pressure from the south.

(4) The fault from Wasdale Head to Borrowdale Moss is by no means well exposed but judging by the way it swings south west after crossing Crookdale Beck it is most likely a thrust.

(5) A fault trending north 5^{o} east bounds the west side of Yarlside Crag. This is a normal fault with a throw of at least 300 feet east. By analogy with similar faults in the Kentmere district, Mitchell (1934) has suggested that it might be of Carboniferous age. The north-south direction is not typical of faults associated with Devonian movements and faults with similar trends occur further south in the Carboniferous.

(d) Minor Faulting.

Several minor faults both of the reverse and normal type are seen in the Shap Blue Quarry. Reverse faults and shatter belts often occur and one such fault accompanied by considerable shattering of the surrounding rocks is well exposed in the north end of the quarry. Most conspicuous and of later date than these reverse faults are the vertical ones which cut the garnet-bearing veins. Vertical displacement is slight, although a foot or more of breccia may be present, and it may be that these are tear faults. The general direction of these faults is parallel with the foliation east north east - west south west and they are almost always filled with barytes and quartz or calcite. They are connected with the emplacement of the granite being later than the metasomatic structures but are themselves filled with hydrothermal minerals associated with Shap granite.

(e) Cleavage.

G.H.Mitchell (1929) has shown that in the Kentmere district the inclination of the cleavage planes differs markedly from that of the axial planes of isoclinal folding and therefore ascribes the development of cleavage to a date later than the main folding and faulting. However the strike of the cleavage is coincident with the axes of folding and whilst it may be connected with later regional pressures these were in the same direction as those of the major Caledonian earth-movements.

True slaty cleavage is never developed and development of cleavage is associated with shearing. This strain slip cleavage is by no means constant in amount and whilst it is better developed in the fine tuffs, certain belts of intense cleavage occur. That in Wet Sleddale has already been mentioned. In Wet Sleddale even the massive non-vesicular andesites are well cleaved,whereas on the Saddle Crags only fine tuffs show any pronounced cleavage and the rocks tend to be well jointed. All rocks show some effects of shearing,even the Coarse Tuffs which are rarely cleaved, and it has been found that away from the granite contact the strike is fairly constant in direction an average being east 25° north. The inclination varies but it is rarely more than 15° from the vertical.

As the granite is approached the strike of the cleavage tends to become more nearly parallel with the contact and thus some idea of the displacement of the country rock by the granite may be gained.

IV SHAP GRANITE.

(a) Historical.

The characteristics of the Shap Granite were first described by H.A.Nicholson (1868) and later by Clifton Ward (1875) and J.A.Phillips (1880 & 1882) but the first comprehensive paper was given by Harker and Marr in 1891.The granite and associated dykes were described and the form of the intrusion was considered to be a "cedar-tree laccolith". The great width of the aureole was attributed to,"the passage of molten matter for a considerable period through the channel which is now filled with granite", (Harker and Marr,1891).

Grantham (1928) described the Shap granite as "a composite intrusion made up of a suite of biotite granites allied to adamellite". The earliest of these - the "early basic granite" he regarded as "a chilled peripheral, fine grained facies" characterised by a low content of porphyritic felspars and general basic character. This was later disrupted by invasions of more acid biotite-granites (Stages I and II) and now occurs only as rounded xenoliths. It was further suggested that the "early basic granite is a hybrid rock formed by the assimilation of volcanic rocks by a granitic magma. The xenoliths of country rocks and also some contact phenomena were described and a sequence of pneumatolysis and mineralisation was established. The writer's research has confirmed this sequence and it has been possible to correlate high and low temperature and hydrothermal changes in the granite with metasomatism and mineralisation around the granite.

(b) Form of the Intrusion.

The outcrop forms a rough oval 2 miles across at its widest point (west -east). The contact is poorly exposed but can be seen in Sherry Gill, on Sleddale Pike and in a small ravine behind Wasdale Head Farm. In Sherry Gill the granite is intruded along a fault or shatter-belt and a fault-breccia veined with quartz and haematite outcrops in the left bank at about 1350 O.D. Here granite occurs in the left bank and not in the right. An unfaulted contact, with a pegmatitic margin (Harker and Marr 1891. p.285) occurs a few feet above the stream and is almost horizontally overlain by veined and metamorphosed Wrengill andesites. It thus appears that a sill like mass of granite was intruded northward along the west side of a pre-existing fault.

On Sleddale Pike, granite intermingles with the country rocks and there is no evidence of the inclination of the contact. North of Wasdale Head Farm the contact is generally vertical and slightly overturned.

From the contact, therefore, there is no direct evidence of the form of the intrusion. The great width of the aureole (3/4 to 1 mile) may be considered to be due to:-

(1) The laccolithic form of the intrusion.

(2) The susceptibility of the country rocks to metamorphism.

(3) Metasomatism.

(4) The granite being superheated when intruded.

These factors are evalulated later (p. 89). Probably the excessive width of the aureole compared with the Eskdale Granite may be due to a combination of (2), (3) and (4), and it is unnecessary to invoke a laccolithic form for the intrusion. Furthermore a stock-like form is favoured since the outcrop does not tend to follow the surface contours.

(c) The Age of the Intrusion.

The Shap Granite is intruded into and metamorphoses Ordovician and Silurian rocks. Furthermore fragments of Shap Granite are abundant in the Z_1, Basal Carboniferous conglomerate at Shap Wells. The intrusion is therefore Devonian or Lower Carboniferous in age.

Its age in relation to the Caledonian earth-movements has not previously been considered in detail but it has generally been assumed to be post-tectonic. The most important lines of evidence are:-

(1) The Ordovician and Silurian rocks are strongly thermally metamorphosed.

(2) A pre-granite joint system is metamorphosed (p. 92).

(3) Biotite hornblende and epidote tend to develop along cleavage planes in the country rock.

(4) The strike of the Caledonian cleavage becomes parallel with the granite near the outcrop.

(5) Associated quartz porphyry dykes cut across the cleavage.

(6) Quartz veins, one with molybdenite, have been proved to transgress the cleavage and pre-granite joint system.

(7) Hydrothermal mineral associations filling faults and later joints can be correlated with the hydrothermal stage of the Shap granite.

The final emplacement of the Shap granite at its present level was therefore post-orogenic although the generation of the granite magma may be associated with the Caledonian orogenesis.

(d) Mode of Emplacement.

The granite was forcibly intruded to its present level and the surrounding rocks were distorted. Some stoping may have taken place but xenoliths could have been carried up with the magma.

From the petrological and field evidence of included granitic xenoliths, Grantham (1928) concluded that the intrusion was composite and a tectonic study of the country rocks supports this view. Faults, shatter belts and shear zones which transgress metasomatic replacement structures and are filled with hydrothermal minerals occur in Shap Blue quarry (p. 171). This may be associated with the emplacement of Grantham's Stage II granite (p. 36).

The amount of displacement of the country rock is difficult to estimate but a forcible intrusion has been demonstrated. No evidence of granitisation at the present level of intrusion has been found and successive magmatic intrusion is envisaged.

(d) Petrography.

(i) Introduction.- Nine tenths of the granite exposed is equivalent to Grantham's Stage II granite. Little original work has been done on the granite itself and the following account is mainly a resumé of Grantham's work (1928).

(ii) Stage I granite.- This occurs as irregular masses in later stage II granite whilst a large raft outcrops west of the granite quarry. It is characterised by a pseudo bedding structure and is recognised in the field by its grey aspect and low percentage of felspar phenocrysts. Grantham defined this type as having 13 - 17% pink felspar phenocrysts, with white margins, abundant biotite and plagioclase. It is a coarsely crystalline biotite adamellite with accessory iron ores, sphene and orthite. Most of the plagioclase is zoned and partly sericitised. Quartz is considered by Grantham to antidate some of the felspar and it is thought to have begun its crystallisation with the earliest plagioclases.

(iii) Stage II granite.- Stage II granite makes up about nine-tenths of the whole mass. Petrologically it is similar to stage I granite but contains more phenocrysts (25%), less biotite and contains large hypidiomorphic quartz crystals. Nearer the margins, particularly in the north west and west, the grain size is finer and the phenocrysts smaller.

Parallelism of felspars due to flow is a common feature and other evidence for contemporary movement includes torn and sheared felspar twisted biotite shreds and strain polarisation in felspars and quartz.

(iv) Stage III granite.- This occurs in dykes and contains more than 50% phenocrysts.

(v) Pegmatites aplites and dykes.- Pegmatites and aplites are common in the Shap Granite quarry and the latter often contain molybdenite. Drusy cavities with pegmatitic quartz, orthoclase and occasionally pink albite (W.F. Davidson, personal communication) occur. Highly biotitic schlieren have also been observed. These are usually non porphyritic but large phenocrysts of biotite occasionally occur in the pegmatites.

The dyke rocks have not been studied in detail by the writer but were fully discussed by Morrison (1919): they include granite porphyries containing pink orthoclase phenocrysts, lamprophyres and hornblende granite dykes.

(f) Xenoliths.

(i) Introduction.- Xenoliths are quite abundant in the Shap granite and are particularly well seen in the Shap granite quarry where they include hornfelsed fragments of

Coniston limestone, grits and shales, andesites and "early basic granites". The sedimentary xenoliths have not been examined in detail and will not be discussed here.

(ii) Hornfelsed Borrowdale Volcanic Rocks.- Grantham (1928) described examples of andesitic xenoliths and noted that all gradations between these and the early basic granites occur. He concluded that the early basic granite was formed by assimilation of country rock in a granite magma. Reynolds (1946) suggested that the andesite inclusions are granitised and said it would be of interest to know whether the andesitic inclusions are desilicated or basified as compared with the country rock. Changes in these inclusions are analogous to the metasomatised contact rocks, but differ in that they are completely enclosed by the granite so that there was a reciprocal exchange of material between the granite and the xenolith. Grantham's analyses show that potash, soda and silica entered the xenoliths and lime and magnesia passed out.

As with contact hornfelses, a granoblastic mosaic of quartz, albite and biotite with accessory apatite and magnetite is developed. Epidote, rutile and sphene are also common and hornblende, cordierite, tremolite and diopside also occur. These latter minerals and also occasional orthoclase phenocrysts are not characteristic of contact hornfelses, where lime, alumina and magnesia could migrate outwards into the country rocks.

(iii) Early Basic Granite.- Grantham (1928) considered the early basic granite xenoliths to be true granite inclusions. This granite contains 5% to 8% phenocrysts by volume some of which may be partly in the xenolith and partly in the surrounding granite. This suggests, together with the rounded nature of such phenocrysts, that the xenolith is being absorbed into the surrounding granite. Alternatively these phenocrysts may have developed porphyroblastically, in the solid state, by the introduction of potash into the "heathen".

The ground mass contains very abundant biotite with quartz, orthoclase and plagioclase. Sphene, magnetite, ilmenite, apatite and zircon are the chief accessories.

(g) Mineralisation in the Granite.

The pneumatolysis and mineralisation has been briefly described by Grantham (1928. pp 307-309) but the present research has, by a study of metasomatic replacement bodies and low temperature hydrothermal veins in the aureole, greatly amplified our knowledge. Grantham's time sequence has been confirmed and has been found to be generally applicable to veins in the country rocks.

One addition has to be made since a well terminated yellow crystal of <u>scheelite</u> ($CaWO_4$) has been identified by X rays from one of W.F.Davidson's specimens. It occurs in a small miarolitic cavity and is associated with quartz, orthoclase and epidote. No other tungsten bearing minerals have been found but a trace element analysis of metamorphosed andesites, west of the granite (Palframan personal communication, not for publication) shows a concentration of a 1000 p.p.m. of tungsten in metasomatised contact hornfelses, whilst the figures for lead, molybdenum and bismuth are quite low.

A modified version of Grantham's sequence of events may be quoted for reference and is later correlated with mineralisation around the granite (p. 185).

(1) Intrusion of granite stages.
(2) Intrusion of aplites and pegmatites.
(3) High temperature hydrothermal stage.
- (i) Pneumatolysis including kaolinisation.
- (ii) Deposition of molybdenite.

(4) Low temperature hydrothermal stage.
- (i) Quartz only (cemented joints)
- (ii) Quartz, calcite, bismuthinite.
- (iii) Quartz, calcite, chalcopyrite.
- (iv) Quartz, calcite, zinc-blende.
- (v) Quartz, calcite, fluorite, haematite, chlorite in open veins.
- (vi) Barite.

Although more characteristic of later stages, haematite is formed during high temperature hydrothermal alteration along joints whilst pyrite occurs at almost any stage. The barite is typically the pink cockscomb variety occurring in veins which transgress all others.

V THERMAL METAMORPHISM.

(a) Introduction.

Harker and Marr (1891 and 1893) described the thermal metamorphism of the country rocks around the Shap granite demonstrating that the rocks were folded, faulted and cleaved before the granite was intruded. They maintained that the Borrowdale Volcanic rocks were probably in the state of decomposition of the unmetamorphosed rocks before the granite was intruded. Petrographic descriptions of the changes in the amygdales of andesites and in the ground mass of lavas and tuffs were described and little petrographic detail has been added. The author is unable to agree with Harker and Marr's contention (1893) that metasomatism was limited or with the minor point that basic andesites outcrop north of the granite contact whilst more acid types outcrop west of the granite. It appears that acid andesites occur at the top of the Wrengill andesites in the Wasdale Pike area (p.16).

Although garnetiferous rocks from Low Fell, which the writer considers to be of metasomatic origin,were described (1893), Harker and Marr,found no evidence of metasomatism. On the contrary, they (1893. p. 368) argued "that thermo-metasomatism is not in general accompanied by any change in the chemical composition of the rocks affected". In considering the production of lime silicates in the amygdales they maintained that the interchange of lime and silica was limited to $\frac{1}{20}$ inch. Later Marr (1902) argued that the garnet bearing veins were thermally metamorphosed mineral veins.

The present field and petrographic investigations have proved that metasomatic changes were important near the granite contact and along veins, cleavage planes, joints and other tectonic fractures in the country rocks, and it has been shown that metamorphic differentiation was on a larger scale than Harker and Marr envisaged. Metasomatic replacement structures are best exhibited in the Shap Blue quarry where a definite time sequence of metasomatic replacement and hydrothermal mineralisation has been elucidated. Field investigation elsewhere in the aureole has suggested that metasomatism was most intense in the Blue quarry area but this may be more apparent than real owing to lack of exposures.

(b) Wrengill Andesites.

Analyses of metamorphosed basic andesites, east of the granite show that significant changes in the bulk composition took place due to introduction of silica and alkalies from the granite and to the migration of components within the rocks themselves. These changes are properly discussed when dealing with bulk metasomatism. The main petrographic details of thermal metamorphism, given below, are based on an examination of Harker and Marr's, G. H. Mitchell's and the writer's rock slices. Metasomatic changes, indicated by the petrography are commented upon but discussion of their petrogenetic significance is left over until later (p.74-88).

(i) <u>Vesicles</u>.- As emphasized by Harker and Marr (1891. p.294) changes in the vesicles are most easily recognised in the field. Vesicles originally filled with quartz or chalcedony become recrystallised into a mosaic of quartz weathering out prominently in hand specimens; calcite is similarly recrystallised whereas chlorite is usually replaced by hornblende. All these changes can be clearly seen in the field.

Petrographic examination shows that clinopyroxene and epidote, may develop as well as hornblende, and are usually associated with calcite ~~and~~ or quartz. In one instance (R.F. 149.) granular epidote apparently pseudomorphing garnet occurs. Sphene and secondary albite are also commonly developed in and around the vesicles.

Where complete replacement of chlorite by hornblende occurs, the vesicle is usually surrounded by a narrow pink "reaction zone" (1 - 2 mm.), not described by Harker and Marr, but seen clearly in all their specimens. The presence of such a zone strongly suggests a reciprocal change of material between the vesicle and country rock.

Petrographically the reaction zone is very fine grained and appears to consist of quartz and alkali felspar with occasional granules of sphene and flakes of amphibole. Biotite is always absent. Nearer the granite the reaction zone becomes more diffuse and the margins of the vesicle less well marked.

Hornblende may replace part of the ground mass.

These seem to be the normal changes due to the metamorphism in which a limited amount of metamorphic differentiation has taken place. The hornblende in most vesicles is strongly pleochroic $\alpha < \beta < \gamma$ yellow brown, yellow green and blue green. This together with the refractive indices suggests a ferriferous variety. The refractive indices determined are $\alpha = 1.628$ $\beta = 1.640$ $\gamma = 1.643$; birefringence 0.017. Possibly some irom for the formation of hornblende came from the breakdown of biotite whilst the absence of felspar, in the reaction zone, with refractive index higher than Canada balsam, suggests that some lime and alumina were added to the vesicle. But such changes were probably on the small scale and were initiated by rising temperature or heated waters, the width of the reaction zone marking the limit of ionic diffusion. This is little more than envisaged by Harker and Marr (1893).

The presence of sphene in and around the vesicles can similarly be accounted for by the combination of titania with available lime within the vesicle or reaction zone. The titania probably originates from ilmenite decomposition products, which are often collected around vesicles, in lavas outside the aureole.

Harker and Marr (1891) noted biotite and felspar in a vesicle 400 yards east of the granite contact. The re-examination of contact hornfelses has shown that generally near the contact, biotite fills vesicles. Particularly where the ground mass is rich in biotite, this necessitates the metasomatic introduction of potash. Similarly, replacement of wall rock around vesicles by epidote is best explained by metasomatic processes. (p. 99).

(ii). Phenocrysts.- Porphyritic andesites are uncommon in the Wrengill andesites and pyroxene phenocrysts have not been recognised.

Felspar phenocrysts are normally highly altered to sericite, zoizite, calcite etc., and the first observable signs of thermal metamorphism are the production of new minerals from these decomposition products. Biotite develops at the expense of sericite, and epidote may also develop (R.F.191). At about 400 yards from the contact plagioclase phenocrysts are usually recrystallised, but, as noted by Harker and Marr (1891), the original twinning can sometimes be seen vaguely. Nearer the granite the phenocryst begins to lose its original shape and a mosaic of quartz, plagioclase and some biotite is formed. At the contact, in high temperature conditions, the original felspar phenocrysts are indicated only by areas of relatively little biotite (R.F.183) and by the occasional twinned plagioclase grain compared with the water clear albite of the ground mass. In these conditions the rock is normally an equigranular mosaic of quartz, felspar and biotite but the presence of both albite and a more calcic plagioclase (usually andesine) demonstrates that complete chemical equilibrium was not achieved.

As observed at Eskdale, the felspar phenocrysts are less susceptible to thermal metamorphism than the ground mass felspars, but in contrast to Eskdale they are usually completely recrystallised. The peculiar clouded felspars (MacGregor 1937) have not been recorded at Shap.

(iii). <u>Ground Mass</u>.- The ground mass of the lavas is usually highly altered to chlorite, calcite, sericite, limonite,leucoxene etc., but the original intersertal or ophitic texture is usually indicated by the interlocking network of felspars. This texture is often observable in all but the contact hornfelses.

The first petrological changes in low grade metamorphism are the development of new minerals from the decomposition products. Scaly biotite replaces sericite, wisps of amphibole replace chlorite and minute octrahedra of magnetite usually develop in the ground mass. Associated with this stage granules of sphene may develop from leucoxene and some granular epidote at the expense of the felspar. Usually at this stage (e.g.R.F.190) the felspars are relatively unaltered and sphene develops only in the presence of excess lime. These changes are indicated in the field by a general hardening and darker colour of the rocks. The first signs of thermal metamorphism are usually shown by the development of dark patches and are generally seen at about 1500 yards from the granite.

Nearer the granite the biotite flakes assume a more definite form whilst the iron ores are partly resorbed. If the ground mass is rich in lime, hornblende may form instead of biotite. At this stage (700 - 900 yards from the contact) the ground mass felspars begin to recrystallise, being replaced by granular epidote, quartz, and sodic plagioclase. At about 200 - 300 yards from the contact complete recrystallisation has taken place. Usually, at this stage, the irom ore granules have been completely resorbed, most of the iron having gone into biotite so that the only accessory minerals present are sphene and apatite. Hornblende may be present in the ground mass but is more often replaced by biotite.

Contact rocks usually develop a granoblastic texture, with an average grain size of 0.2 to 0.5 mm, consisting essentially of quartz, albite and biotite. Sillimanite is sometimes developed, particularly in the more acid rocks, whilst cordierite has been recorded from a contact hornfels (possibly a tuff) north of the granite. Cordierite spots in hornfelses from the Blue quarry are thought to be metasomatic. All the ground mass felspar in contact hornfelses has a refractive index lower than Canada balsam and it seems that complete albitisation has occurred also the high proportion of quartz and biotite suggests the introduction of silica and potash. The similarity of quartz and "water clear" untwinned albite makes a modal analysis, both difficult and tedious, but examination of several contact specimens shows a high proportion of quartz. No accessory iron ores are usually present and variations in the biotites may reflect the original percentage of iron in the parent rock. Lepidomelane is well developed in contact hornfelses in Sherry Gill whilst a foxy-red variety has been recorded from Sleddale Pike.

(iv) Flow Breccias.- Flow breccias have not been recognised with certainty within the aureole of the Shap granite. Possibly the metamorphism of broken lava fragments is much the same as the matrix and the structure tends to become obscured in an analagous manner to the coarse tuffs. However, a curious spheroidal structure (R.F.76) and R.F. 83 has been attributed to metamorphosed flow breccias.

R.F.76 was collected from near Tongue Regg 700 yards west 10° north of the granite contact in Sherry Gill; stratigraphically it appeared to be the top of a lava flow and was mapped as a flow breccia. In hand specimen it is a melanocratic rock with a spheroidal structure which consists of a number of rounded blobs averaging $\frac{1}{8} - \frac{1}{4}$" in diameter set in a lighter grey ground mass. Mitchell (1930) stated that in some Upper Andesites, in the Kentmere area "resorption of the crust by the liquid lava has taken place, resulting in rounded and ill defined patches of earlier and darker material in a lighter matrix". These appear to be very similar to R.F.76.

Petrographically the lighter patches are micro-crystalline aggregates of quartz, albite, octrahedra of magnetite and some sericite; amphiboles occur occasionally. "Foliation" is indicated by a linear parallism of felspar and sericite but the orientation of the "foliation" is different in each patch as if later brecciation had taken place. Possibly this foliation represents the original flow structure of the surface of a lava brecciated by later, more fluid, lava. The interstices between the patches are replaced by decussately arranged biotite. A similar structure is seen in R.F.83, collected from a loose block 200 yards west of the granite contact in Sherry Gill, but here complete recrystallisation has taken place and the leucocratic patches have partly lost their identity.

(v). Joints.- Joints and shear planes outside the aureole are normally filled with chlorite or more rarely calcite. Regional calcite veins have not been found and quartz veins are thought to be associated with the intrusion of the Shap granite. Joint fillings are thus analogous to the amygdales and the same mineralogical changes took place.

Hornblende replaces chlorite and as in the vesicles clinopyroxene, epidote, calcite and quartz may also be developed. However, these joints formed convenient channels for high temperature hydrothermal solutions and consequently metasomatisation of the wall rocks was more intense than that around the vesicles.

At or near the contact there is no sign of these joints and it seems that when complete recrystallisation occurred the original structures were destroyed. In contrast the vesicles and phenocrysts are often vaguely indicated. Possibly chemical equilibrium was established more easily along the joints, where diffusion was facilitated by open fissures, than in the country rock around vesicles.

(vi) Interbedded tuffs.- Interbedded tuffs are more susceptible to thermal metamorphism, than the lavas, since they are usually more highly altered. The mineralogical transformations are very similar to those in the ground mass of lavas, but in addition sericite often develops. In contact specimens the original bedding may be indicated by an inequigranular texture. Cordierite has been recorded in one instance (R.F.93. Fig.6 .).

(c) Coarse Tuffs.

Only the outcrops in Wet Sleddale and east of Great Yarlside fall within the aureole but some of the acid tuffs east of the granite may be partly Coarse Tuffs. Peat and drift cover prevents any continuous section to the granite contact being examined.

Fig.5.(R.F.30) Metamorphosed vesicular andesite
Shap Blue Quarry.
Hornblende developed in the vesicles
surrounded by a reaction zone.
Ground mass a biotite, quartz, albite hornfels (x 35).

Fig.6.(R.J.93) Contact hornfels. North of the granite.
A cordierite-quartz-albite-biotite hornfels.
Probably a metamorphosed tuff. (x 35).

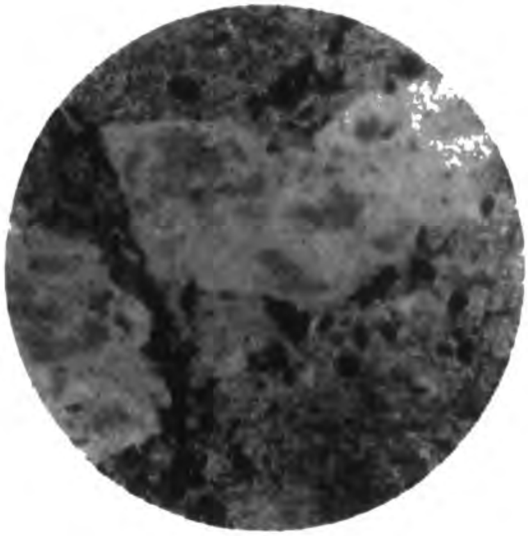


Fig.7. (R.F.190.) Porphyritic andesite.
Widepot, Shap Fells. 1,500 yards west of the granite contact.
Phenocrysts relatively unaltered, some chlorite developed. Magnetite and leucoxene abundant in the ground mass. (x 35).

Fig.8. (R.F.191.) Metamorphosed porphyritic andesite.
Saddlecrags gill, $\frac{1}{2}$ mile west of the granite contact.
Felspar phenocrysts relatively unaltered - a few amphibole flakes have developed from the alteration products.
Scaly biotite developed in the ground mass. (x 35).

Fig.9.(R.F.182.A.) Metamorphosed porphyritic andesite.
Tongue Rigg gill $\frac{1}{4}$ mile west of the granite contact at Sleddale Pike.
Ground mass completely recrystallised with the development of biotite, quartz, albite and octahedra of magnetite Felspar phenocrysts partly replaced by biotite, quartz and clear felspar.

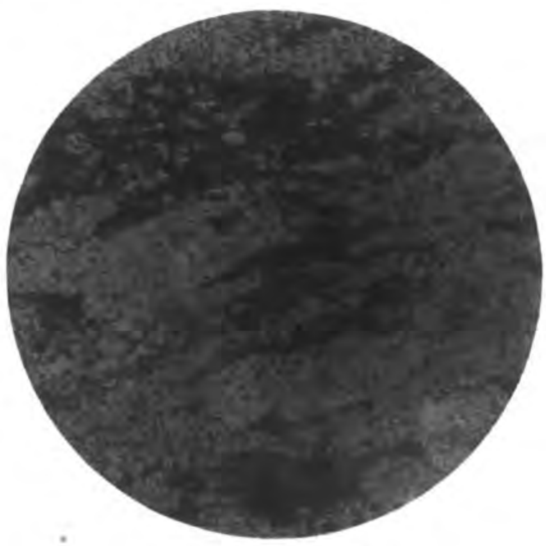


Fig.10.(R.F.183.) Contact hornfels, Sherry gill, Shap.
Metamorphosed porphyritic andesite.
Ground mass and phenocrysts completely recrystallised.
Ground mass consists of a mosaic of quartz albite and biotite.

In the field the Coarse Tuffs are most easily recognised by their angular fragments of andesite and pink rhyolite contrasting with the pale green matrix; but with progressively higher grades of thermal metamorphism angular fragments tend to become more and more rounded and assume the texture and mineralogy of the matrix until, as in Wet Sleddale, only the rhyolite fragments can be distinguished. The matrix may become flinty and aphanitic or fairly coarsely crystalline, as in Wet Sleddale, depending on the initial composition and subsequent silicification.

Metamorphism of the individual fragments is much the same as described above. Hornblende may be seen developing from chlorite in vesicles of the andesite fragments whilst rhyolite usually recrystallises into a mosaic of quartz and felspar. The changes in the matrix are similar to those in the altered ground mass of Wrengill Andesites but sericite and muscovite often develop secondarily. Abundant biotite is developed particularly around the fragments. With higher grades of thermal metamorphism there is a tendency for an equigranular texture to develop, but in some of the finer cleaved tuffs a schistose texture is formed.

(d) Upper Andesites.

Biotite hornfelses 450 yards north-west of Wasdale Head Farm are thought to be of this horizon, as are the contact hornfelses in a small ravine north of the farm. A specimen from the contact shows the hornfelses to be little different from those of the Wrengill Andesites. It is a medium grained (average 0.1 mm.) quartz-alkali felspar-biotite hornfels with accessory pyrite, apatite and minute needles of sillimanite. The biotite is strongly pleochroic in straw yellow and greens. Sillimanite suggests an aluminous parent rock. A rock slice of a bedded tuff 200 yards west of Wasdale Head Farm and 150 yards from the granite contact shows recrystallisation with the development of quartz, sericite and colourless idioblastic epidote of low birefringence.

(e) Shap Rhyolite Series.

The thermal metamorphism of the Shap Rhyolite Series has been exhaustively described by Harker and Marr (1891). An examination of the original rock slices has shown no new facts and only one correction has to be made - the "kyanite" identified by Harker and Marr is an aggregate of andalucite and sillimanite needles. The metasomatism appears to have been limited and only one example of fissure metasomatism has been found.

The Shap Rhyolite Series is thought to be equivalent to the Coarse Tuffs, Upper Andesites and Upper Rhyolites and the metamorphism of the tuffs and intermediate lavas is similar to that already described. Pyrite, however, is a more important constituent of the acid tuffs than is usual in the Coarse Tuffs. Also silicification is common but it is uncertain whether this is due to the metasomatic introduction of silica.

Since Harker and Marr have so fully described the petrographic details it is not proposed to repeat them but their views may be usefully summarised.

(i) Lavas.

(1) Evidence is given (Harker and Marr 1891) that the rhyolites were devitrified and silicified before the intrusion of the granite. Traces of perlitic cracks in a crystalline ground mass seems sound evidence of devitrification but replacement of phenocrysts by mosaics of quartz may equally well be due to thermal metamorphism as to deuteric changes or regional metamorphism. Although similar changes have occurred in rhyolites remote from igneous intrusions the same changes could be facilitated by hot watery solutions containing silica from the granite.

(2) As with the Wrengill andesites, the effects of thermal metamorphism (apart, possibly from silicification) are seen in decomposition products in the ground mass. Usually a mosaic of quartz, albite, and orthoclase is developed together with both biotite and muscovite. Amphiboles have not been recorded, presumably because of lime deficiency. Secondary albite has been observed along cracks.

(3) At the granite contact a granoblastic texture is developed and minute sillimanite needles are often developed.

(ii) Tuffs.- Thermal metamorphism of the tuffs is very similar to the Coarse Tuffs but muscovite more often occurs. Andalusite and sillimanite (Harker and Marr's Kyanite) is developed in tuffs about 400 yards from the granite contact whilst sillimanite is common at the contact but cordierite has not been recorded.

There is, therefore, little petrographic evidence of metasomatism although the silicification may indicate introduction of silica. Two analyses of Stockdale Rhyolite by Garwood (quoted Harker and Marr 1891. p.302.) show an increase of 1.0 % SiO_2 and 0.8 % CaO compared with an unmetamorphosed spherulite rhyolite from Stockdale. Lime and silica are probably reliable but in all other respects these two analyses are untrustworthy; ferrous iron, phosphorous pentoxide and water were not determined and total alkalies were determined by difference. No idea of the metasomatism can be gained from these analyses.

VI METASOMATISM.

(a) Introduction.

Harker (1939) defined thermal metamorphism as a change in form, consequent upon a rise or fall in temperature, in which the bulk composition of a rock remains unchanged. Metasomatism involves, not only changes in mineralogical but also in chemical composition. These changes may be initiated by the diffusion of solutions from a granite, or, if the granitisation school of thought is followed, by emanations which caused metasomatic changes leading to the formation of the granite itself. Whichever view is adopted metasomatism entails not only addition of material but also complementary subtraction leading to outward diffusion from the metasomatised rocks themselves.

Modifications of this kind have been cited as evidence of "geochemical changes leading to granitisation" (Reynolds 1946) but they could equally well have been caused by fluids derived from a granite magma. No agreement exists on chemical or petrographic criteria for distinguishing "magmatic granites from metasomatic granites" and in the absence of such agreement, field evidence seems the only reliable guide.

At Shap it has been demonstrated that the final emplacement of the granite was post-tectonic and that it caused some distortion of the country rocks. Dykes and sills are associated with the granite and Grantham (1928) found evidence of flow structures in Stage II granite. Therefore it seems most reasonable to assume that, when intruded at its present level, the granite consolidated from an acid magma ✓ Low temperature hydrothermal mineral veins which fill deformation structures associated with the granite's emplacement most probably were precipitated from the late granite residium, percolating outwards into the country rocks. The possibility remains that the high temperature fluids, which caused the bulk metasomatism, may have preceded the intrusion of the granite. Some high temperature metasomatism took place before the final emplacement of Stage II granite but the geochemical similarities of high and low temperature solutions suggest that both were derived from a granite magma. The fundamental premise of this thesis is, therefore, that the metasomatising fluids were derived from a cooling granite magma and not from emanations preceding the formation of the granite.

Field and petrographical investigations suggest that these metasomatising solutions percolated through the pore spaces in the country rocks and along open fissures. This has given rise to two distinct though inter-related types of metasomatism which it has been found convenient to consider separately. The classification adopted is similarly that suggested by Korzhinsky (1950. B.) and is as follows.

A. Bulk Metasomatism involving changes in bulk

✓ An acid magma is considered to be a plastic mass including liquids and crystals and the granite may have been intruded as a crystal mush. (see Shand 1947, p.4).

composition of the country rocks due to fluids percolating or diffusing through the aureole as a whole.

B. Fissure Metasomatism.- Limited to alteration of wall rock along fissures, and thus much more localised. Near the granite contact, in high temperature conditions, fissure metasomatism was not important since equilibrium conditions were more nearly established but where there was a significant temperature gradient between the metasomatising fluids and the wall rock, fissure metasomatism took place on a large scale.

(b) Petrographic Calculations.

In studying metasomatic phenomena it is desirable to be able to relate mineralogical changes to variations in the chemical composition. No wholly satisfactory method of petrographic calculation has been devised to do this. The "classical" weight, or standard, norm is unsatisfactory when applied to metamorphic rocks, but it has been retained for comparison with other analyses in the literature. Similarly, Niggli values have been quoted. Both methods of recalculation are useful in emphasizing certain chemical characteristics not brought out by the weight percentages.

Comparison of the weight percentages does not give a true picture of variations in bulk composition, not only because molecular percentages are not comparable amongst themselves, but also because of the number of variables involved. In igneous petrology it is often expedient to plot the molecular percentages of oxides against SiO_2 which is known to vary constantly in crystal fractionation of a basaltic magma, but no such constant has been used successfully to study metasomatism. Lapadu-Hargues (1945) suggested that aluminium and silicon remain constant but these components certainly vary in the Shap area.

More recently, however, Barth (1948) has suggested that oxygen may be used as a basis for petrographic calculation. He argued that since, in most rocks, oxygen makes up about 92% by volume, "the number of oxygen ions is of utmost importance for the volume relationships in rocks". The packing index and the size of constituent cations are considered to be of secondary importance. Most metasomatic changes involve no change in volume and Barth therefore believes the oxygen ions act as "solvents" for the mobile cations. The oxygen ions are also mobile, acting as "carriers" for many cations, but, owing to their great preponderance, oxygen ions may be regarded as statistically stationary.

Barth has demonstrated that near-surface rocks contain very nearly 100 cations to 160 oxygen ions. He, therefore, suggests that for comparison chemical analyses may be recalculated on the basis of 160 oxygen atoms, giving the so called "standard cell" of a rock. Comparing the standard cell of the parent rock with that of a metasomatised example we can calculate the number of cations which were added to or subtracted per 160 oxygen ions, in metasomatism. As in ionic substitution in isomorphous minerals, the charge relationships must be satisfied over the structure as a whole; therefore, within the limits of experimental error, the valences represented by ions added should counter balance those subtracted. This method is therefore very useful, not only in illustrating chemical changes, but in establishing the parentage of metasomatised rocks.

Criticisms of the Barth method (Rosenquist 1949) arise from a misconception of Barth's paper. It should be emphasized that this method of calculation is inapplicable where:-

(1) Metasomatic changes do not obey the "Law of Equal Volumes".

(2) The oxygen content varies significantly (e.g. in replacement by sulphides).

(3) The packing index is more important than the number of oxygen ions (e.g.in dynamic metamorphism).

The fact that oxygen is determined by difference,and is likely to be one of the most inaccurate elements in a chemical analysis, is a valid argument, but it may be noted that recalculation on a basis of 160 oxygen ions is a useful means of checking an analysis. Since the constituent minerals are in ionic equilibrium the valences represented by the cations in a standard cell should equal 320.

The Barth method of petrographic calculation has been used throughout this thesis.

B. BULK METASOMATISM.

(a) Introduction.

A petrographic study of the thermal metamorphism around the Shap granite has suggested that potash, soda and silica have been introduced from the granite. To confirm this, and to test the nature and extent of metasomatism five analyses were made of a porphyritic lava flow, traced from the granite contact, in Sherry Gill to a point I mile west, near the Widepot.

Drift and peat cover prevent the mapping of individual flows, with certainty, in the Shap area, but it is known that the strike of lavas, west of the granite, is approximately at right angles to the contact. In tracing a slightly porphyritic andesite along the escarpment of the Widepot to Saddlecrags Gill and from here along the 1500 feet contour, the writer is fairly confident that specimens were collected from the same lava flow, or, at the worst, from a group of lava flows with similar characters. This was confirmed by the petrography although R.F.189 (1 mile from the contact) shows some flow brecciation; probably this was near the top of the flow. It seems likely that these rocks originally had about the same composition as R.F.189 which is not affected by thermal metamorphism.

Although porphyritic andesites are not representative of the Wrengill andesites, it is considered that the analyses (Tables I - V.pp.65-69) will illustrate adequately the metasomatic changes in the lavas around the Shap granite.

TABLE I

	Wt. %	Mol.Prop.	Wt.Norm (C.I.P.W.)		Niggli Values	
SiO_2	57.82	964	Quartz	26.16	si	216
TiO_2	1.50	19	Orthoclase	15.01	al	37
Al_2O_3	16.19	159	Albite	25.15	fm	34
Fe_2O_3	3.60	23	Anorthite	Nil	c	11
FeO	3.92	55	Corundum	9.59	alk	17
MgO	2.74	64	Hypersthene	8.24		
CaO	2.88	51	$MgO.SiO_2$ 6.40			
Na_2O	3.01	48	$FeO.SiO_2$ 1.84		ti	4.2
K_2O	2.54	27	Magnetite	5.34	p	0.9
H_2O+	3.04	-	Ilmenite	2.89	k	0.34
H_2O-	0.13	-	Apatite	3.80	mg	0.42
P_2O_5	0.57	4			c/fm	0.33
MnO	0.13	1				
CO_2	2.23	50				
	100.30					

R.F. 189 Porphyritic andesite Widepot. Shap.

TABLE II

	Wt.%	Mol. Prop. x 1000.	Wt. Norm. (C.I.P.W.)		Niggli Values	
SiO_2	52.49	875	Quartz	9.66	si	159
TiO_2	1.72	21	Orthoclase	16.68	al	34
Al_2O_3	19.25	188	Albite	36.15	fm	33
Fe_2O_3	5.07	36	Anorthite	8.34	c	15
FeO	3.51	49	Corundum	6.02	alk	18
MgO	2.43	61	Hypersthene ($MgOSiO_2$)	6.20	ti	3.8
CaO	4.59	82	Magnetite	6.50	p	1.8
			Haematite	1.28		
Na_2O	4.30	69	Ilmenite	3.19	k	0.30
K_2O	2.75	30	Apatite	3.36	mg	0.33
H_2O+	1.45	-	Calcite	1.80	c/fm	0.22
H_2O-	0.08	-				
MnO	0.06	1				
P_2O_5	1.28	10	Normative plagioclase			
CO_2	0.78	18	$= Ab_{70} An_{30}$			
	99.76					

R.F. 190. Porphyritic andesite. Widepot, Shap.
1500 yards west of the granite contact.

TABLE II1

	Wt. %	Mol. Prop. x 1000	Wt. Norm. (C.I.P.W.)		Niggli Values	
SiO_2	60.86	1013	Quartz	20.82	si	220
TiO_2	1.42	18	Orthoclase	18.35	al	30
Al_2O_3	15.12	148	Albite	33.54	fm	37
Fe_2O_3	3.49	22	Anorthite	13.07	c	13
FeO	4.77	68	Corundum	0.41	alk	20
MgO	2.13	58	Hypersthene	9.89	ti	3.7
CaO	3.61	64	$MgO.SiO_2 = 5.80$		p	0.82
Na_2O	3.96	64	$FeO.SiO_2 = 4.90$		k	0.34
K_2O	3.10	33	Magnetite	5.10	mg	0.33
H_2O+	0.61	-	Ilmenite	2.88	c/fm	0.26
H_2O-	0.03	-	Apatite	1.34		
MnO	0.17	3	Calcite	0.40		
P_2O_5	0.53	4				
CO_2	0.17	4	Normative plagioclase			
	99.97		$= Ab_{57}\ An_{43}$			

R.F. 191 Metamorphosed porphyritic andesite Saddletrags gill, Shap. Half mile west of the granite contact.

TABLE IV

	Wt. %	Mol. Prop. x 1000	Wt. Norm (C.I.P.W.)			Niggli Values	
SiO_2	63.40	1057	Quartz		22.56	si	240
TiO_2	1.40	18	Orthoclase		17.24	al	30
Al_2O_3	13.75	134	Albite		23.06	fm	41
Fe_2O_3	0.64	4	Anorthite		8.30	c	12
FeO	6.28	88	Corundum		2.96	alk	17
MgO	3.56	89	Hypersthene		19.72	ti	4.1
CaO	2.98	54	$MgO.SiO_2$	8.90		p	0.68
Na_2O	2.71	44	$FeO.SiO_2$	10.82		k	0.41
K_2O	2.93	31	Magnetite		0.93	mg	0.40
H_2O+	1.37	-	Ilmenite		2.74	c/fm	0.23
H_2O-	0.10	-	Apatite		1.01		
MnO	0.10	1	Calcite		1.40		
P_2O_5	0.43	3					
CO_2	0.60	14	Normative plagioclase				
	100.25		$= Ab_{59}\ An_{41}$				

R.F. 182. Porphyritic andesite. Tongue Rigg Gill, Shap ¼ mile west of the granite contact.

TABLE V

	Wt.%	Mol. Prop x 1000	Wt. Norm. (C.I.P.W.)			Niggli Values	
SiO_2	62.25	1038	Quartz		15.90	Si	234
TiO_2	1.79	23	Orthoclase		23.91	al	29
Al_2O_3	13.18	129	Albite		27.77	fm	35
Fe_2O_3	1.18	8	Anorthite		9.17	c	14
FeO	5.62	78	Diopside		3.22	alk	22
MgO	2.48	62	$CaO.SiO_2$	1.63		ti	5.2
CaO	3.45	62	$MgO.SiO_2$	0.80		p	0.90
Na_2O	3.28	53	$FeO.SiO_2$	0.79		k	0.45
K_2O	4.00	43	Hypersthene		5.36	mg	0.39
H_2O+	1.76	-	$MgO.SiO_2$	1.86		c/fm	0.39
H_2O-	0.07	-	$FeO.SiO_2$	3.50			
MnO	0.12	1	Magnetite		3.50		
P_2O_5	0.49	4	Apatite		1.34		
CO_2	0.11	2	Calcite		.20		
	99.78						

Normative plagioclase

$= Ab_{62}\ An_{38}$

R.F. 183. Contact hornfels. Sherry Gill, Shap

(b) Discussion of the Analyses.

(i) Character of the Analysed Rocks.- The petrographic character of the analysed metamorphosed rocks has been described: nevertheless it is necessary to relate the mineralogy to the petrography.

R.F.189. was collected about a mile west of the granite contact. Difficulty was found in obtaining fresh samples owing to the poor exposures and deep weathering. The rocks here are strongly cleaved and chloritised with many small calcite veins, filling joints and irregular cracks cutting across the cleavage. Phenocrysts can be seen occasionally but are difficult to distinguish from the pale green chloritised ground mass.

Petrographically the rock is a somewhat flow brecciated, fine grained, slightly porphyritic, andesite. Phenocrysts occur in glomero porphyritic aggregates or more occasionally as single crystals. They are usually completely replaced by sericite and epidote. The ground mass felspar laths are partly altered to sericite but show straight extinction and are probably oligoclases. Chloritisation is almost complete the ferromagnesian minerals being replaced by chlorite and magnetite granules. Calcite veinlets and chlorite are abundant.

Chemically this flow is similar to the Wrengill Andesite from Ullstone Gill, Kentmere, analysed by Mitchell (1930). The differences are indicated by comparing Niggli Values as shown below:-

	si	al	fm	c	alk	k	mg
R.F.189:-	216	37	34	11	17	0.34	0.42
Mitchell:- 585.	207	35	40	11	14	0.41	0.40

The most significant differences are that R.F.189 contains less ferrics, chiefly ferrous iron and more alkalies, principally soda. The agreement is surprising in view of the highly altered state of both rocks (both contain about 2% CO_2 and 3% H_2O) and this coupled with the unusually low lime content suggests that only water and CO_2 were introduced during the period of low grade regional metamorphism. Albitisation of the felspars is characteristic of many andesites and may be a deuteric effect but was presumably also effected by the introduction of CO_2.

Most of the andesites in the area are highly chloritised and most of the original lime has combined with CO_2 to give calcite. Although the proportions of CO_2 and H_2O may vary chemically R.F.189 is thought to be representative of Wrengill andesites in the area and the parent of the analysed metasomatised rocks. In the vesicular types calcite often fills amygdales and the lime content is higher.

R.F.190.- R.F.190 was collected from the top of the Widepot escarpment,1500 yards west of the granite, where dark blue indurated porphyritic andesites showing patchy metamorphism with occasional traces of calcite, epidote, pyrite, and malachite. Petrographically it appears to be little affected by metamorphism although it contains more iron ore and epidote granules than R.F.189. The felspars are similarly albitised as illustrated by the normative plagioclase (Ab_{70} An_{30}) and altered to sericite and epidote but metamorphic minerals have developed. The chemical analysis shows that the bulk composition is very different from R.F.189; not only was much of the water and CO_2 driven off by increasing temperatures but it appears that silica was subtracted and alumina lime and soda were added. Metasomatic effects must have extended to the margin of the aureole.

R.F.191.- Collected in Saddlecrags Gill about half a mile from the contact, R.F.191 is darker and more flinty than the other analysed specimens. It shows the typical metamorphic changes already described (p. 48.) but recrystallisation is not complete. Biotite has developed in the ground mass together with quartz and secondary albite but the felspars are relatively unaltered. Pyrite veins and the presence of biotite in vesicles suggest the metasomatic introduction of S and K.

The chemical analysis illustrates these changes and it is significant that as in R.F.182 and R.F.183 the ratios of potash to total alkalies and ferrous to total tends to increase with increasing amounts of biotite whilst the Niggli value

$$mg \left(\frac{\text{magnesia}}{\text{total ferrics}}\right)$$

increases. These ratios are plotted on Fig.11 A and it may be noted that the high ratios in R.F.189 are related to the abundant chlorite and subordinate sericite in the mode.

R.F.182.- R.F.182 was collected from Tongue Rigg Gill a quarter mile west of the contact on Sherry Pike. Complete recrystallisation has taken place but the original phenocrysts and vesicles can be seen.

R.F.183.- R.F.183 is the contact specimen described on p. 46-48 and as shown by the analyses shows many chemical differences from R.F.182. Both, however, appear to consist of quartz, albite and biotite with accessory iron ores, sphene, apatite etc., and the chemical differences are attributable to the relative proportions of these minerals. These metasomatic changes are discussed below.

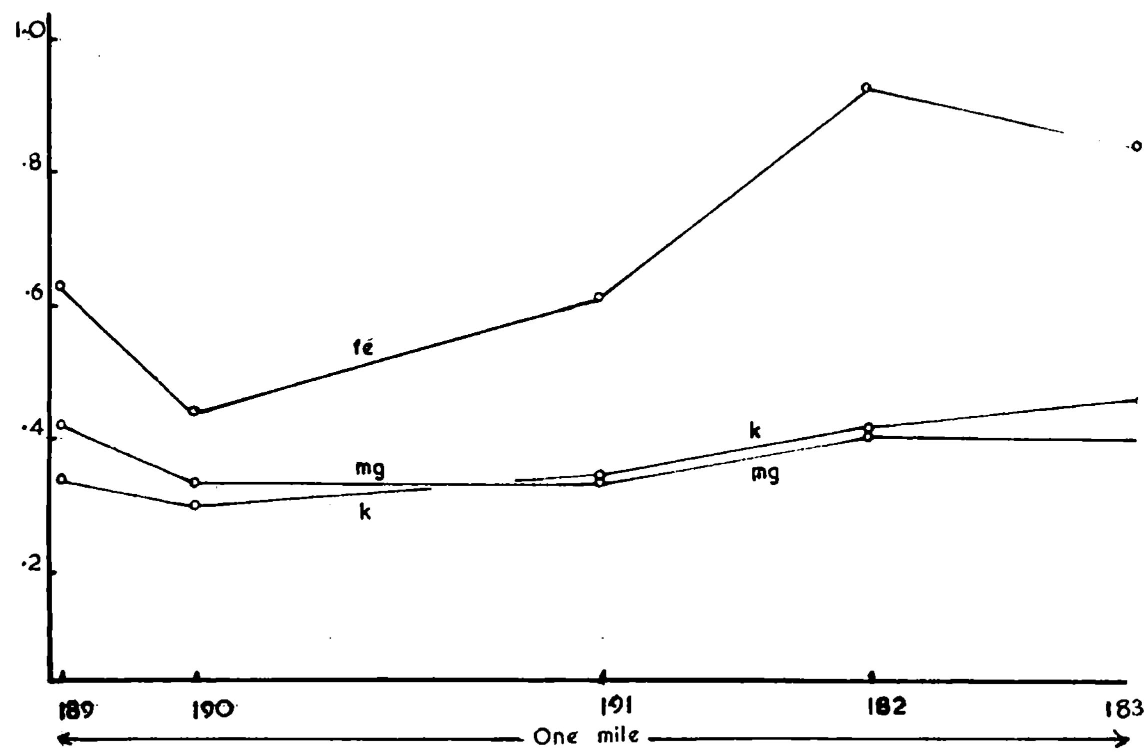


Fig. 11 A. Variation diagram $K = \frac{K_2O}{K_2O + Na_2O}$ $mg = \frac{MgO}{FeO + Fe_2O_3 + MgO}$

$$fe = \frac{FeO}{FeO + Fe_2O_3}$$

(ii) Geochemistry.- In an attempt to get a clearer idea of the geochemical changes involved in bulk metasomatism, the five analyses were recalculated on the basis of 160 oxygen atoms and the number of cations plotted on the variation diagram Fig.11 B, which gives a truer idea than plotting the weight percentages (Fig.11 C). Whether variations in ratios (Fig.11 A) weight percentages or number of cations per 160 oxygen ions are considered discontinuities in the curves exist between R.F.189 and R.F.190 at the edge of the thermal aureole and between the contact specimen R.F.183 and that collected quarter mile from the contact. The former is best explained by assuming that metasomatic effects extended to the margin of the thermal aureole, but the latter phenomena has two possible explanations:-

(1) That two periods of metasomatism, possibly associated with the intrusion of different granite stages, are superimposed. The later metasomatism was limited to the immediate contact hornfelses.

(2) Local enrichment in material added from the granite was restricted to a zone near the granite contact whilst other components displaced from the country rocks themselves, diffused outwards through the aureole as a whole.

Probably both processes took place and were facilitated by a diffusing pore solution of heated water and volatiles.

The geochemical changes are best discussed by comparing the standard cells with that of the parent rock. The "rock formulae" are given below.

R.F.189.

$K_{3.6}Na_{5.0}Ca_{2.6}Mg_{3.4}Fe_{5.3}Al_{16.7}Ti_{1.0}Si_{50.6}P_{0.3}C_{2.6}\left[O_{142.5}(OH)_{17.5}\right]^{160}$

R.F.190

$K_{3.3}Na_{7.5}Ca_{4.4}Mg_{3.4}Fe_{6.8}Al_{20.5}Ti_{1.0}Si_{47.8}\ P_{1.1}.C_{1.0}\left[O_{151.3}(OH)_{8.7}\right]^{160}$

R.F.191.

$K_{3.6}Na_{6.8}Ca_{3.5}Mg_{3.1}Fe_{6.3}Al_{16.2}Ti_{1.0}Si_{55.6}\ P_{0.4}C_{0.2}\left[O_{156.4}(OH)_{3.6}\right]^{160}$

R.F.182

$K_{3.3}Na_{4.7}Ca_{2.9}Mg_{4.8}Fe_{5.2}Al_{14.3}Ti_{1.0}Si_{56.3}\ P_{0.4}C_{0.7}\left[O_{151.7}(OH)_{8.3}\right]^{160}$

R.F.183.

$K_{4.5}Na_{5.7}Ca_{3.4}Mg_{3.4}Fe_{4.9}Al_{13.9}Ti_{1.2}Si_{56.2}\ P_{0.4}C_{0.1}\left[O_{148.8}(OH)_{11.2}\right]^{160}$

Comparing the standard cell of the parent rock (R.F.189) with the metasomatised contact hornfels (R.F.183) an estimate of the material added from the granite may be made.

The standard cell R.F.189 passes into the standard cell R.F.183 by:-

Adding.		Subtracting.	
5.6	Si-ions	2.8	Al-ions
0.2	Ti-ions	1.5	Fe^{+++}-ions
1.1	Fe^{++}-ions	6.3	H-ions
0.8	Ca-ions	2.5	C-ions
0.7	Na-ions		
1.9	K-ions		
0.1	P-ions		
Total: 9.4	cations	13.1	cations
representing 30 valences.		representing 30 valences.	

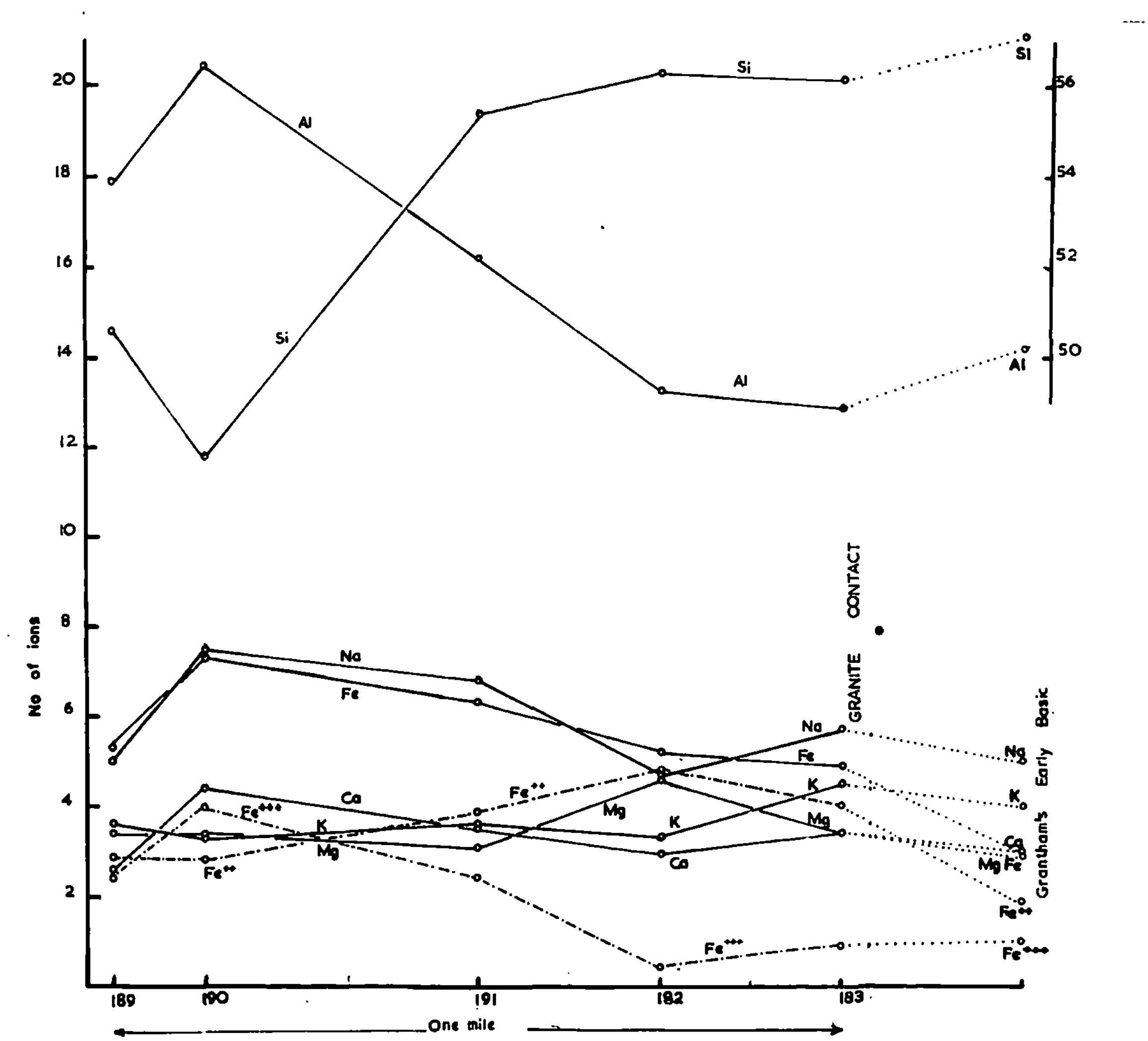


Fig.II B. Variation diagram based on the number of cations per 160 oxygen ions.

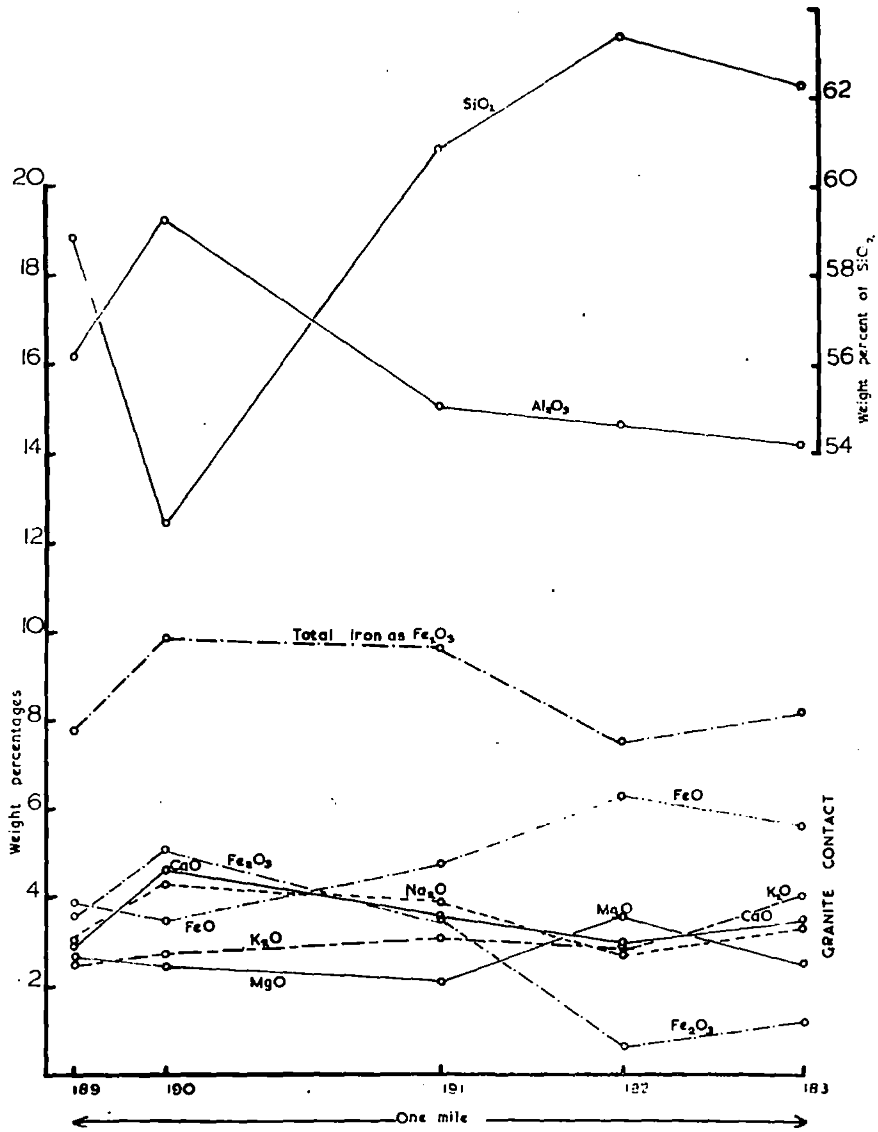


Fig. II C. Variation diagram based on weight percentages.

The Barth system shows that 1.1 -ions of Fe^{++} were added and 1.5 ions of Fe^{+++} subtracted. More probably the metasomatising solutions reduce most of the ferric iron to ferrous and some ferric iron was carried away in solution. Since these reactions involve oxygen they cannot be adequately expressed by the Barth method.

The above table shows that the solutions from the granite were probably siliceous fluids containing lime, soda and potash. The chemical analyses show that some Ti and P were added, but the quantities involved are hardly significant. Mineralogical changes caused the removal of excess alumina probably derived from the albitisation of plagioclases and from the formation of biotite from aluminium-silicates such as hornblende and sericite; ferric iron removed was probably derived from the breakdown of magnetite, the ferrous iron contributing to biotite formation. The high temperature conditions would tend to drive off the carbon-dioxide and most of the water, but the initial metasomatising fluids were probably watery and contained CO_2 from the granite. Most of the original CO_2 and water in the parent rock would be driven off by rising temperature before the solutions were added.

The possibility of reciprocal exchange between the granite and contact rocks has not been investigated but the field evidence suggests that such changes were limited to a few inches. R.F.183 was collected about 3 feet from the contact and is unlikely to have been affected in this way.

The standard cells of other rocks may similarly be compared with the parent rock. The results are tabulated below and plotted on the graph (Fig. 11 D).

R.F.189 ⟶ R.F.182

Adding.		Subtracting.	
5.7	Si-ions	2.2	Al-ions
1.9	Fe^{++}-ions	2.0	Fe^{+++}-ions
1.4	Mg-ions	0.3	Na-ions
.3	Ca-ions	0.3	K -ions
		9.2	H -ions
		1.9	C -ions
9.3	cations representing 31 valences.	15.9	cations representing 31 valences.

R.F.189 ⟶ R.F.191

Adding.		Subtracting.	
4.8	Si-ions	0.5	Al-ions
1.0	Fe^{++}-ions	.3	Mg-ions
.9	Ca-ions	13.9	H-ions
1.8	Na-ions	2.4	C-ions
8.5	cations representing 25 valences.	17.1	cations representing 25 valences.

R.F.189 ⟶ R.F.190

Adding.		Subtracting.	
3.7	Al-ions	2.8	Si-ions
1.6	Fe^{+++}-ions	0.1	Fe^{++}-ions
1.8	Ca-ions	0.3	K-ions
2.5	Na-ions	8.8	H-ions
0.8	P-ions	1.7	C-ions
10.4	cations representing 28 valences.	13.6	cations representing 27 valences.

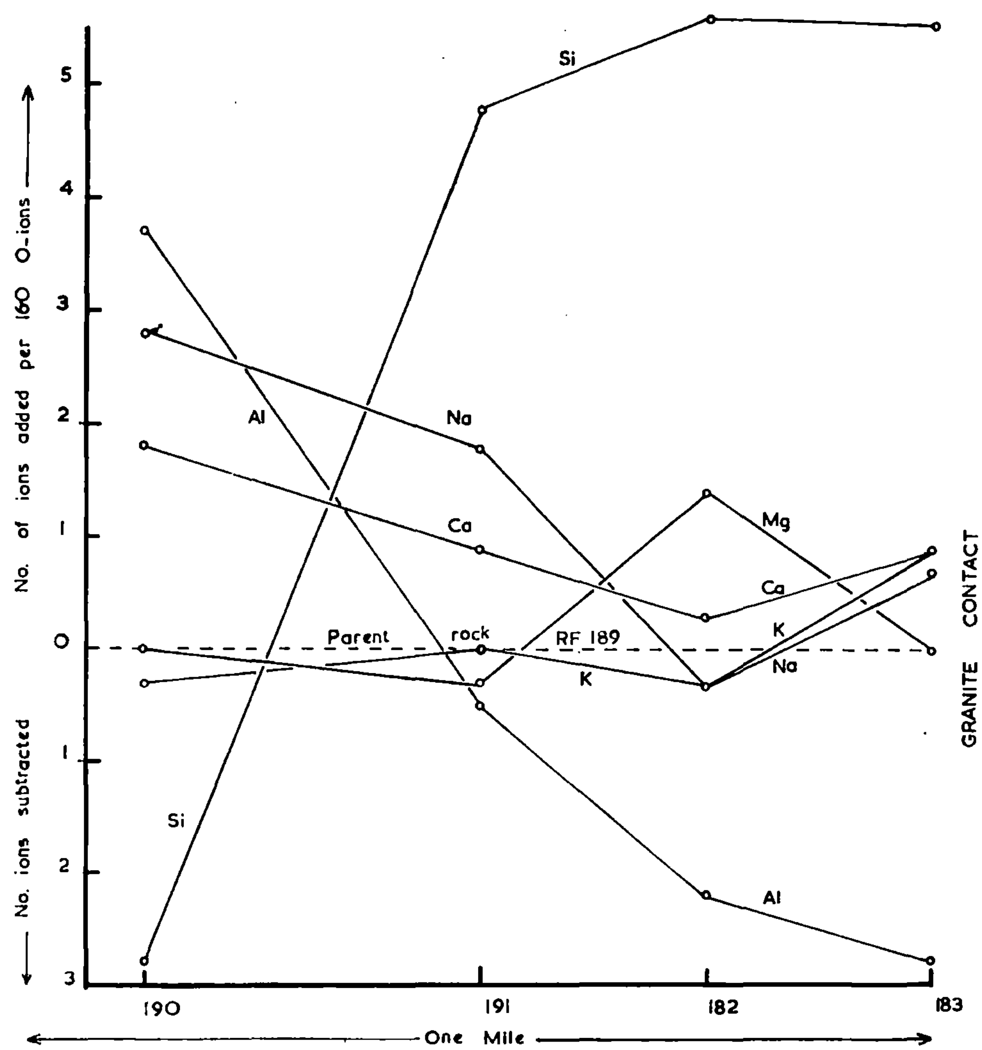


Fig. 11 D. Variation diagram showing the number of cations added to or subtracted from the standard cell of the parent rock R.F.189.

Exact valency agreement was not found and the valences are expressed to the nearest whole. But the measure of agreement is sufficient to show that a rock of the composition of R.F.189 is the parent rock. Valency discrepancies fall within the limits of experimental error (2%) in all but the case of R.F.190 but a slight variation in the original CO_2 content of the parent rock would account for these discrepancies.

The tables and graph (Fig.11 D.) show that only about 5% of the metal ions need migrate from the rock to effect significant metasomatic changes.

The distribution and migration of the ions are best discussed by dealing with the individual elements before attempting a synthesis.

Carbon.- Carbon-dioxide was probably expelled from the parent rock near the contact in high temperature condition. Carbon enters into no other minerals than calcite which occurs in veins and vesicles,particularly in the outer part of the aureole. Geochemical changes associated with fissure metasomatism suggest that CO_2 was an important volatile component of solutions percolating along joints. Similarly CO_2 both from the granite and the country rocks was probably important as a "carrier" for lime, in bulk metasomatism.

Hydrogen.- As with carbon-dioxide the parent rocks contained more water than the metasomatised types. The presence of hydroxyl bearing minerals such as biotite, hornblende and epidote testifies to the activity of water in metasomatism. Although ionic diffusion in the solid state is a possible mechanism, such reactions are greatly accelerated in the presence of water. Intergranular water is therefore considered to have acted as the solvent for the metasomatic components whose mobility consequently depended on their solubility coefficients. The metasomatising fluids are regarded as aqueous solutions and the circulation of these weak solutions as the prime metasomatising agents.

<u>Silicon</u>.- The Barth system shows that, up to $\frac{1}{2}$ mile from the contact, about 60% of the ions added are Si. A similar increase in SiO_2 is shown by the weight percentages. Silicification is thus of major importance in bulk metasomatism and the introduction of soda in the presence of excess silica may have facilitated the formation of albite in the ground mass. In contrast, silica has been subtracted from R.F.190 at the margin of the aureole, and was probably carried off in solution being deposited in quartz veins beyond the aureole.

Na Ca and Al have been added leading to the formation of epidote with the associated albitisation of the ground mass plagioclases. A similar enrichment in lime, alumina and alkalies and deficiency in silica is shown by an analysis of a porphyritic andesite from Shap Blue quarry (R.F.153. p.140) but this may have been a more basic rock.

<u>Aluminium</u>.- Associated with the silification, excess alumina has been expelled from the contact hornfelses migrating out into

the country rocks and becoming concentrated in the outer part of the aureole. Aluminium shows a higher mobility in the higher temperature conditions near the contact but it was also introduced into the wall rocks, during the formation of pyrite replacement bodies in fissure metasomatism (p160-179) and here, in lower temperature conditions, pH was probably the controlling factor. Possibly circulating solutions near the granite contact were acidic but in the outer part of the aureole cooler weaker solutions carried less aluminium (either as discrete ions or as the hydroxide). The most probable explanation of the migration of Al is that in high temperature acid conditions with the introduction of alkalies in the presence of excess silica, Al and Ca are driven off during the albitisation of plagioclases and Al in formation of biotite from chlorite and sericite but in lower temperature conditions Al and Ca are relatively immobile and become concentrated forming lime alumino-silicates such as epidote. Albitisation, due to the introduction of Na^{+} has taken place both in the contact and at the extremity of the aureole, but in the latter case Al^{+++} has remained relatively immobile and becomes concentrated by the addition of Al^{+++} diffusing outwards from the contact hornfelses. An analogous process, has taken place around the Eskdale granite where an outer zone of epidotised andesites has formed. Similar processes were effective on a small scale in the formation of epidote replacement bodies adjacent to open fissures.

Calcium.- Particularly where CO_2 acts as a "carrier" Ca is more mobile than Al but the geochemical distribution of both is similar. Lime is subtracted in the formation of quartz-albite-biotite hornfels and migrates outwards becoming concentrated in the outmost part of the aureole and also as calcite in low temperature veins beyond the thermal aureole. Some lime was added from the granite and that migrating in the aureole is considered to be from these two sources. The ratio of Na to Ca is critical in determining the composition of ground mass felspars but epidote was formed in the outer part of the aureole.

Iron.- Two complementary processes have taken place; namely the reduction of ferric iron in the formation of biotite and the removal of excess in solution. There is no evidence that ferric iron was derived from the granite, particularly since the initial metasomatising solutions tended to reduce most of the ferric iron. Magnetite in the garnet bearing veins (p. 128.) is thought to have come from the granite but this may have been at a later stage and the solution percolated exclusively along fissures.

Magnesium.- The Barth calculation shows that Mg has an anomalous distribution. R.F.182. ¼ mile from the granite contact shows a significant addition, but the others show little change in comparison with the parent rock. Possibly magnesia was introduced from the granite and contributed to the formation of biotite. Rocks in the Blue Quarry occasionally contain incipient cordierite which might be due to the metasomatic introduction of magnesia.

Sodium.- The geochemical distribution of Na in the Shap granite aureole is puzzling. Na is introduced at the contact but a ¼ mile further west (R.F.182) analyses show no appreciable difference to the country rock. Further away from the granite a significant increase in soda is shown. This is best interpreted by assuming an earlier soda metasomatism which extended as far as the thermal effects; later introduction of soda was limited to an area near the contact, but no accurate estimate of the extent of this metasomatism can be made.

Introduction of Na at the contact and in the outer part of the aureole also caused albitisation but the processes are different. In the high temperature contact conditions both soda and silica were introduced and the reaction may be similar to that demonstrated experimentally by Eskola, Vuoristo, and Rankama (1937).

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_8} + Na_2CO_3 + 4SiO_2 \longrightarrow \underset{\text{Albite}}{2NaAlSi_3O_8} + CaCO_3$$

Heated under pressure in the presence of excess CO_2 this reaction takes place readily at temperatures ranging from 310°C to 330°C. In the higher temperatures at the contact $CaCO_3$ would be removed in solution. But the reactions are more complicated since analyses show that alumina removed and a reaction involving no volume change such as that suggested by Turner (1948) is more likely

$$2CaAl_2Si_2O_8 + Na_2O + 2SiO_2 \longrightarrow 2NaAlSi_3O_8 + CaO + Al_2O_3$$

Anorthite Albite

At the contact slight enrichment in lime has occurred but further away lime and alumina are carried off in solution contributing to the formation of epidote. In the outer part of the aureole albite seems to have formed secondarily from the breakdown of calcic felspars in forming epidote and as a result of the addition of soda and alumina. This formation shows that the addition of silica is not necessary in this environment.

Potassium.- A significant increase in K^n is shown only at the contact and it seems that potash metasomatism is limited to the rocks in which biotite replaces hornblende in the vesicles (i.e. up to about 400 yards from the granite contact).

Titanium.- Grantham (1928) recorded an increase in the weight per cent of titania in hornfelsed Borrowdale lava inclusions compared with the average in metamorphosed andesites. A slight increase in Ti is shown at the contact but this is hardly significant.

Phosphorous.- Little change in the amount of phosphorous occurs except at the margin of the aureole where a significant increase has been recorded. Similarly an aluminous hornfels from Shap Blue quarry (R.F.153) has a high phosphorous content. The geochemical significance of this is uncertain.

<u>Trace Elements</u>.- Research into the trace element distribution in and around the Shap granite is being undertaken by J.Palfreman. Preliminary investigations show a significant concentration of tungsten (1000 p.p.m.) in the contact hornfelses R.F.183 and R.F.182. Further from the granite the concentration diminishes to 500 p.p.m.

(c) Summary and Conclusions.

The hypotheses put forward are based on five analyses and further chemical work may modify these ideas.

The most important geochemical changes are the addition of silica from the granite and displacement and outward migration of alumina. Compared with the parent the rocks at the edge of the thermal aureole are enriched in alumina, lime, soda and iron and deficient in silica. The outward migration of material and its fixation in an outer zone is partly accounted for by the expulsion of CO_2 and water. The width of the aureole is probably due to the country rocks being very susceptible to thermal metamorphism and to the relatively wide extent of metasomatism.

The chief processes are considered to be:-

(1) Early introduction Na which migrated to the margin of the thermal aureole.

(2) Introduction SiCaNa and K: the effects of the alkalies were limited to the contact zone but silica enrichment was important more than ½ mile from the contact.

(3) This (2) caused the formation of quartz-albite-biotite hornfelses and the reduction of ferric iron to ferrous in the formation of biotite.

(4) The outward migration of AlCaFe and (?)P following the driving off of CO_2 and removal of silica in solution from the outer part of the aureole.

(d) A note on the formation of xenoliths.

Grantham (1928) has described the dark inclusions in the Shap granite which had previously been regarded as "basic segregations". Although he found xenoliths convergent in character between the "early basic" and "andesitic" types, Grantham regarded the former as true granitic inclusions resulting from the disruption of an earlier intrusion. To test the validity of these conclusions the writer recalculated Grantham's analyses on the basis of 160 oxygen ions. Comparing the "rock formulae" with R.F.189, a valency discrepancy of 30% suggested that the basic granite and andesitic inclusions cannot be derived directly from andesites of the composition of R.F.189. Similarly comparison of the standard cells of both types of xenoliths shows that they must have formed by differing processes. The higher percentage of magnesia and lime than in any analysed Wrengill Andesite indicates that they were derived from more basic rocks. These might have come from lower in the Borrowdale Volcanic Series, being carried up by the granite magma (or crystal mush).

The environment of a xenolith is different from that of the contact hornfelses in that the xenolith is enclosed by granite and reciprocal chemical exchanges take place, whereas the hornfelses are subject to bulk metasomatism in which material migrated outwards from the granite. Similar changes to those shown in the xenoliths may be expected at the granite contact; indeed Grantham has recorded porphyritic orthoclases in a metasomatised andesite adjacent to a hornblende-granite dyke. No special study of this type of metasomatism has been made in the present thesis. Grantham's evidence suggests that orthoclase phenocrysts may develop porphyroblastically and, whilst his analysis of the basic granite shows no more potash than the "andesitic" inclusion, the ratio of K_2O to total iron is much higher. It is considered, from this evidence, that orthoclase will form only at fairly high temperatures in the absence of excess iron. In the contact hornfelses iron is not very mobile and with the reduction of ferric to ferrous iron biotite is formed in preference to orthoclase. However when enclosed by a liquid of low iron concentration Fe tends to migrate, together with Ca, Mg and Al, from the xenolith. Inclusions containing phenocrysts might have originated in this way and the early basic granite, which has been shown by Grantham to be fluidal, may itself be a hybrid.

In the absence of further detailed geochemical evidence, it is thought that the xenoliths are formed by the addition of Si, Na and K to and the subtraction of Fe, Ca, Mg and Al from fragments of Borrowdale lavas more basic than the Wrengill Andesites analysed. These may have originally been rich in titania so that Grantham's evidence of addition of titania to the xenoliths is unconfirmed.

B. FISSURE METASOMATISM.

(a) Introduction.

Fissure metasomatism is here taken to include all replacements which have probably resulted from the reaction between solutions migrating along joints, cleavage planes and irregular fractures in the country rocks, and the wall rock. Such structures are best exposed in the Shap Blue quarry where thermally metamorphosed andesites are quarried for road metal. The following is largely an account of fissure metasomatism in this quarry.

(i) The Shap Blue quarry:- The south end of this quarry lies 400 yards north of the granite contact (Fig.3.). The rocks consist predominantly of thermally metamorphosed, non porphyritic, or slightly porphyritic andesites. Amygdaloidal types are common but no inter-bedded tuffs have been definitely identified. The lavas have been strongly metamorphosed with the consequent development of biotite in the ground mass and hornblende in vesicles and along joints. Some lavas at the south end have developed cordierite spots and were presumably metasomatised.

(ii). Structure.- Mapping on Low Fell and in Howe Gill, west of the quarry, has revealed that bedded tuffs dip at 70^{o}, north 25^{o} west and a consideration of the alignment of vesicles in vesicular flow suggests a similar dip in the Blue quarry. Cleavage is not well developed in these jointed andesites. Strain slip cleavages are sometimes seen on weathered surfaces but are more often shown by the development of epidote and hornblende along the cleavage planes giving the rock a characteristically streaky appearance: this false cleavage varies in inclination from vertical to 75° north but the strike remains constant (east 25° north - west 25° south).

The rocks are well jointed and a pre-granite (Caledonian) joint system and deformation structures associated with the emplacement of granite have been elucidated. The deformational structures (p. 172) may be further sub-divided into:-

(1) <u>Compressional structures</u>.- Shear joints, faults and shatter belts.

(2) <u>Tension joints</u>.- Conjugate rhomboid joints.

Walls of the pre-granite joint system have been metasomatised and the deformation structures are often filled with low temperature hydrothermal minerals associated with the Shap granite. Apparently deformation of the country rocks took place after the period of fissure metasomatism but before the low temperature hydrothermal stage.

The structural relationships between the metasomatised pre-granite joint system and the tension joints is shown diagrammatically in Fig. 12 p. 96 amd the chief structural trends are tabulated (p. 95.).

Both the pre-granite and later tension joints are rhomboidal (Hartley 1925) and a study of the garnet bearing veins strongly suggests that these are metasomatised wall rocks of low angle joints of the pre-granite joint system whilst the epidote veins represent the high angle joint system.

Structure.	Strike.	Dip.	Mineralisation.
I Pre-granite joints.			
(a) High angle.	E.3-14°N.	N.	Hornblende-epidote veins
(b) " "	E.17-34°N	S.E.	" " "
(c) Impersistent high angle.	E.34-40°S.	?	" " "
(d) Low angle(<66°)	E.17-19°N.	40°-60° S.E.	Garnet bearing veins.
II Deformation Structures.			
(a) Faults and Shatter belts.	Approx. E - W+S - N		Low temperature hydrothermal minerals.
(b) Shear joints	Irregular.		"
(c) Tension joints.			
(i) High angle.	N.20°W(average)	W	"
(ii) " "	E.33°S(")	S.W.	"
(iii) " "	N.40°E(")	N	"
(iv) Low angle.	N.20°W(")	30-68°W	"
(v) " "	N.20°W(")	40-60°E	"
(vi) " "	N.25°E(")	36-50°W	"

Table of joints exposed in Shap Blue quarry based on 80 measurements.

Sufficient number of tension joints has not been measured to make a complete statistical analysis but it has been observed that the low angle joints are often curved and the westward inclined joints predominate.

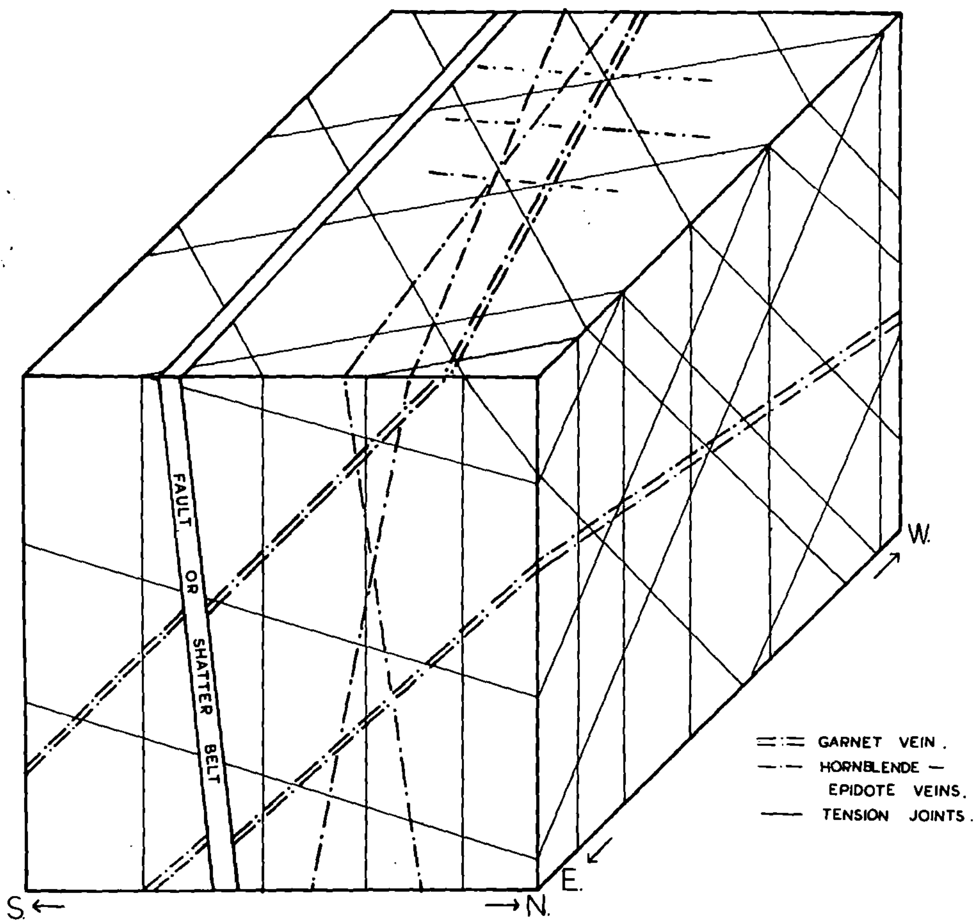


Fig.12. An axonometric projection showing the relation between the metasomatised pre-granite joint system and the later tension joints.

(b) Replacement Structures.

A definite time sequence of metasomatic replacement and mineralisation has been established in the Blue quarry and has proved to be applicable elsewhere in the aureole. In the Blue quarry area replacement was controlled by fractures such as joints, cleavage planes and faults and was probably due to percolating solutions.

The following sequence was proven in the field by transecting veins and replacement bodies and was later confirmed and amplified by microscopic examination.

(i) Replacement of the country rocks around vesicles and along cleavage planes.

(ii) Replacement of wall rock along low angle joints.- the garnet bearing veins.

(iii) Replacement of wall rock along high angle joints.- the hornblende-epidote veins.

(iv) Late stage veining in garnet bearing veins.

(v) The pyrite veins and associated metasomatism.

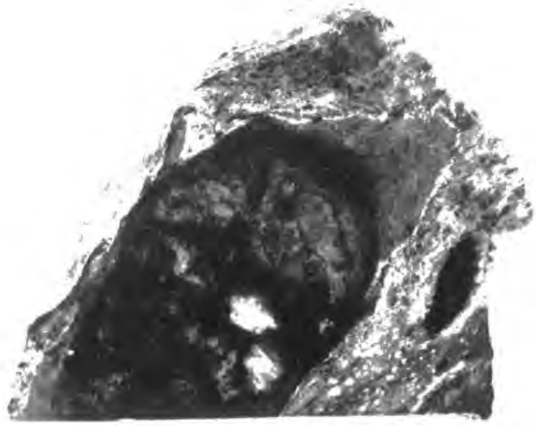
(vi) Low temperature hydrothermal veins. The metasomatism of the high and low angle joints was probably simultaneous whilst the formation of pyrite veins probably coincided with iv.

This metasomatism and mineralisation may be correlated with the late stage processes in the Shap granite. However fluorite, bismuthinite and molybdenite, common in veins in the

Shap granite, have not been recorded from the Blue quarry although a quartz-molybdenite vein outcrops west of the granite.

(i) Replacement of the country rocks around vesicles and along cleavage planes.- Epidote is often developed in irregular patches in the ground mass, along cleavage planes, and around the larger vesicles (R.F.205. Fig.10). Usually this is bounded by a pink silicified reaction zone 1 - 3m.m. wide. In rocks where epidote has developed along cleavage planes this gives rise to a characteristic "streaky" appearance in greens and pinks.

Epidote is normally granular brown or greenish-brown and in this occurrence is more usually associated with quartz than calcite. Hornblende is rarely developed. The reaction zone is usually too fine grained for individual minerals to be distinguished but appears to consist principally of quartz, albite and occasional granules of epidote and sphene. Magnetite and sphene often tend to be concentrated more at the edge of the zone.



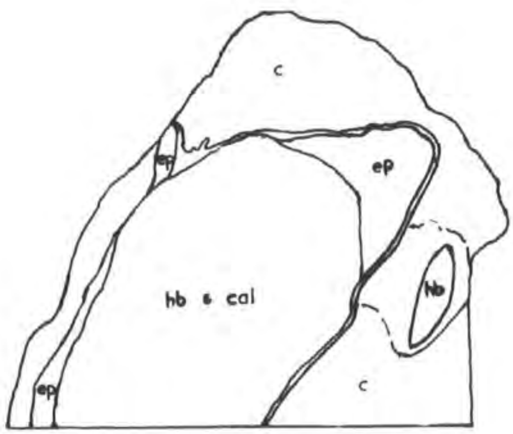


Fig.13.(R.F.205.) Vesicular andesite. Shap Blue Quarry.
c = country rock (biotite hornfels), ep = epidote,
hb = hornblende, cal = calcite.

(ii) Wall rock alteration along low angle joints, the garnet bearing veins.- These are unique in the aureole, being exposed only in Shap Blue quarry and in the old Rhyolite quarry east of the Penrith-Kendal road. They show a constancy of strike and inclination which suggests tectonic control, and their irregular boundaries and petrography prove they are replacement structures, probably due to metasomatic replacement of wall rock by solutions percolating along low-angle pre-granite joints.

These veins are particularly well exposed on the east face of the quarry and in the south-western corner (Fig.14). They vary in width from one inch to more than one foot and often have irregular boundaries and subsidiary veins. Their strike roughly corresponds with that of the cleavage whilst they are usually inclined at angles of 45^{o}-60^{o} south south east. Steeper veins have been recorded from the south western part of the quarry; these probably represent metasomatised high angle joints in which garnet has developed.

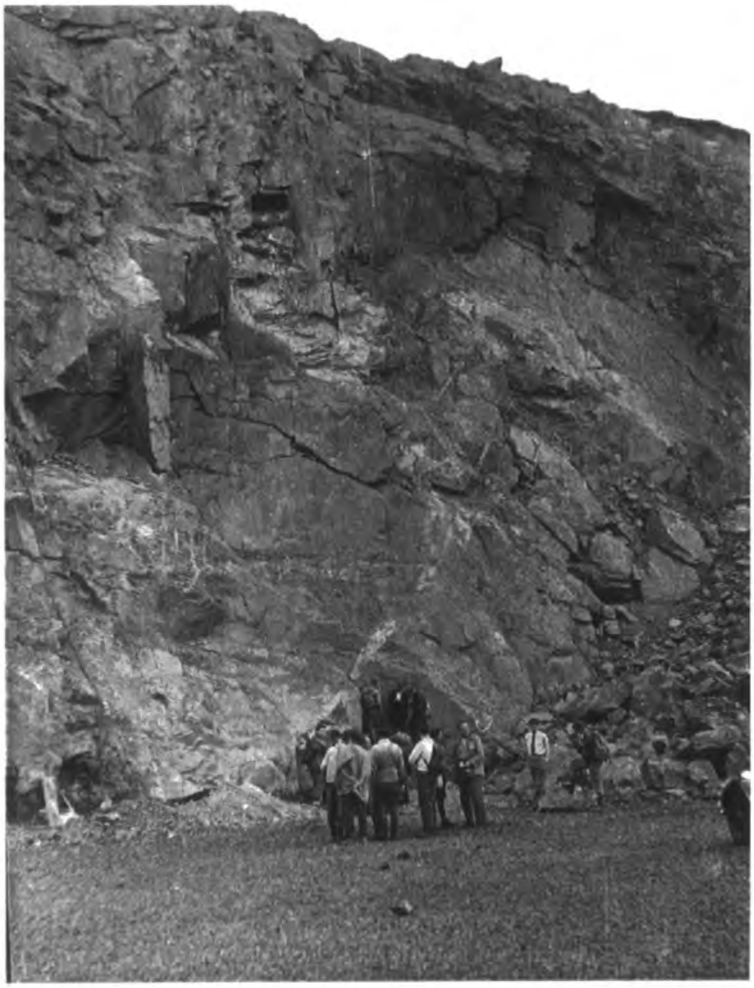


Fig.14. Garnet bearing veins. South end of Shap Blue quarry. (Photographer, J. Kenworthy.18.5.52.).

Fig.15. Garnet bearing vein. South end of Shap Blue quarry. Vein is cut by a later barytes vein and affected by post-granite shear joints. (Photographer J. Kenworthy. 18.5.53.)

A study of the hornblende-epidote veins (p. 95.) strongly suggests that the garnet bearing veins follow the low angle joints of the pre-granite joint system. Offshoots from these veins sometimes fill the vertical joints and occasionally irregular garnetiferous patches are developed in nearby country rocks. Also some of the epidote hornblende veins contain garnets. The garnet bearing veins almost invariably contain later low temperature hydrothermal minerals although sometimes the cracks are not completely filled. Probably tangential pressures set up when the granite was intruded opened the low angle joints so that they were open fissures along which both high and low temperature mineralising solutions flowed easily. In contrast the same pressures would tend to close the steeper joints; fissure metasomatism was limited and the epidote-hornblende veins are rarely affected by low temperature hydrothermal solutions.

The garnet bearing vein in the Old Rhyolite quarry has the same general strike and inclination as those in the Blue quarry and probably has the same genesis but similar veins have not been found elsewhere in the aureole.

The characteristic mineral assemblage is hornblende, epidote, garnet, quartz and calcite. Microscopic examination has shown that the quartz and calcite are later than the formation of the garnets and it seems that the garnet veins formed channels for hydrothermal solutions which precipitated quartz and calcite together with pyrite and more rarely magnetite, chalcopyrite, haematite, galena, sphalerite, and laumontite. The presence of this latter zeolite in intimate association with calcite suggests that the calcite was formed under low temperature conditions in contrast to the metallic minerals. Furthermore, the fact that the metallic minerals are later in origin than the garnets disproves Marr's theory (1902. p. lxxi) that the garnet bearing veins are thermally metamorphosed metalliferous mineral veins.

In the field the veins show a rude zonation represented diagrammatically in Fig.16. The texture is usually coarse. In the open veins needles of hornblende and well terminated crystals of epidote are often developed although the epidote isusually corroded. Similarly in open fissures the garnets may be completely corroded leaving only the quartz matrix.

<u>Zone I</u> <u>Hornblende zone.</u>

Rarely more than 2 mm. thick and sometimes absent. Often the hornblende is chloritised and may be replaced by calcite (R.F.43. Fig. 22.). The hornblende zone when present represents the true edge of the vein and may represent metamorphosed joint fillings (e.g. chlorite). Often metasomatic replácement of the wall rock by epidote has occurred beyond the hornblende zone.

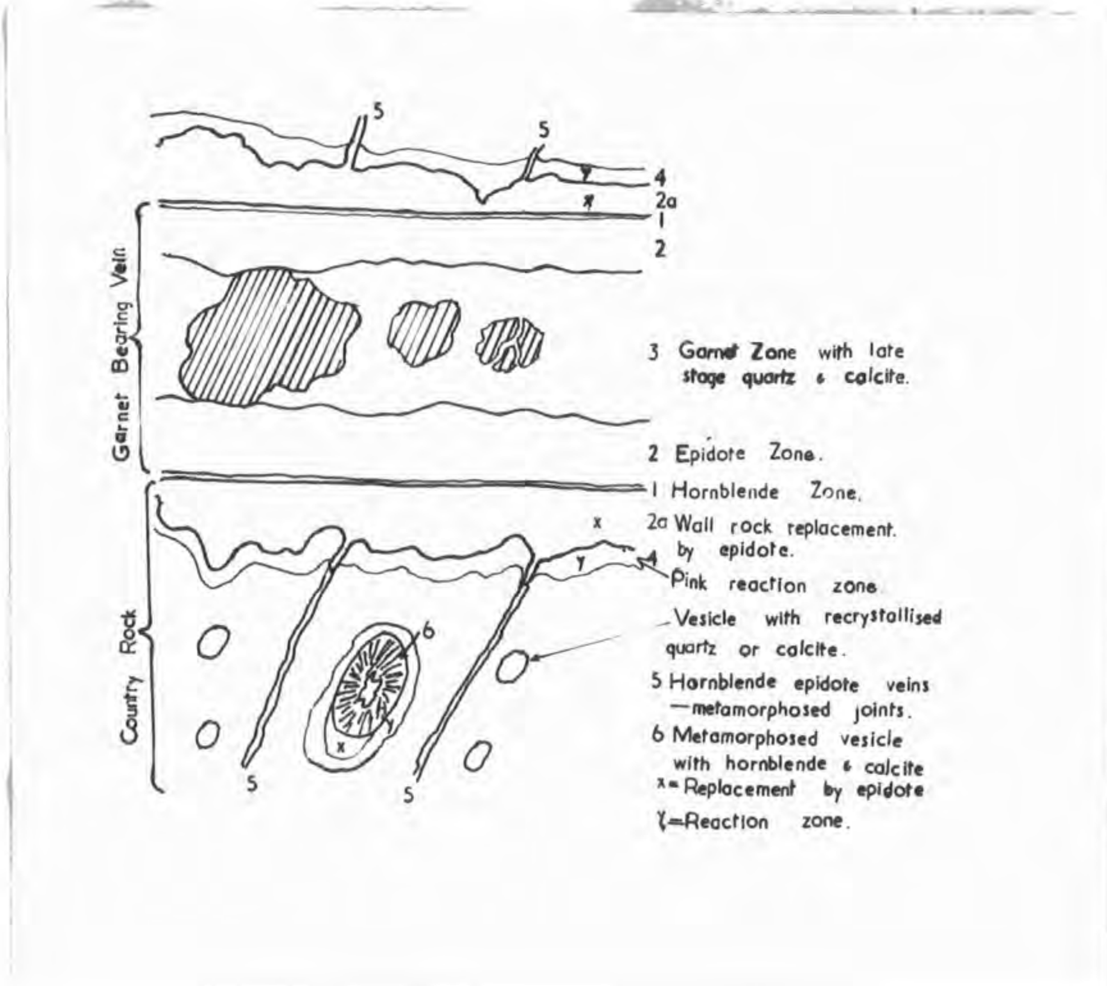


Fig.16. Diagrammatic section of a garnet vein.

Zone 2. Epidote zone.

Almost invariably present, particularly when replacement of the wall rock has not taken place. In R.F. 43 (Fig. 22.) no epidote zone is present although epidote is well developed in veinlets at right angles to the garnet and which appear to be continuous with calcite veins in the garnet zone (Fig. 22.).

The epidote occurs either as a brownish granular mosaic, often appearing to replace hornblende, or in idioblastic aggregates of green pleochroic crystals. Granular epidote tends to occur at the margins of the vein and is more typical of wall rock alteration. Clinopyroxene, (augite), stumpy prisms of hornblende, fine actinolite needles and later quartz and calcite are found associated with epidote in this zone.

Optical tests on the epidote (p. 121) show it to be an iron rich variety with up to 30% of the pistacite molecule.

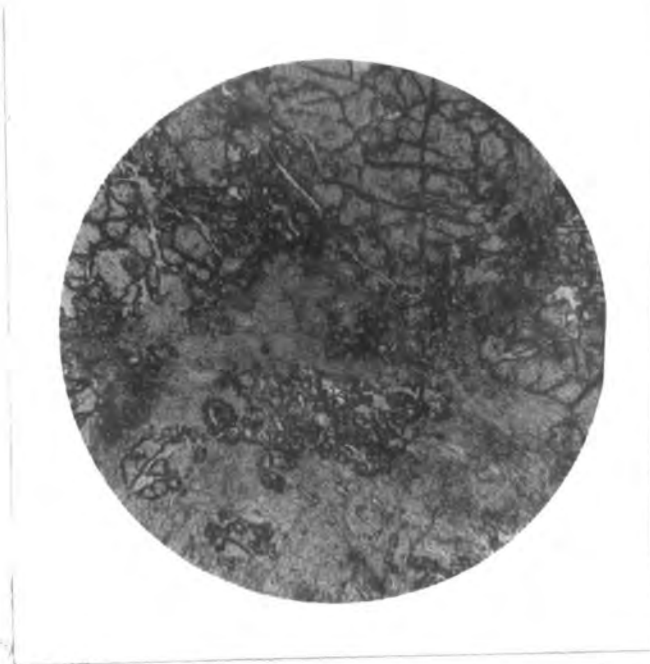


Fig.17. (R.F.162.) Garnet bearing vein, Shap Blue quarry.
Garnet-hornblende association.(x 35)

<u>Zone III</u> <u>Garnet zone.</u>

In the field the garnets vary enormously in size and colour. A variation from a pale orange to a deep reddish brown has been observed. Variations in colour and birefringence are no less striking in thin section. Colour varies from a pale straw yellow to a rich orangy brown, the colour distribution being in roughly parallel bands (R.F.40.) or in irregular patches. More rarely idioblastic garnets show zonary growth. Harker and Marr (1893) illustrated zoned garnets in which the darkest zone was central, but the opposite type of zoning is seen in garnets from a replacement patch. The paler zones tend to be anisotropic and show low birefringence and lamellar twinning.

Idioblastic crystals are rare since fractures in the larger garnets are almost invariably filled with quartz or calcite and partial resorption has often taken place (R.F.40. p. 132 Fig. 26.). Smaller allotrioblastic crystals are often intimately intergrown with epidote and hornblende. This is particularly well seen at the margins of the garnet zone. No pseudomorphs of epidote have been found although garnet appears to be developing at the expense of epidote in many cases.

Optical and chemical tests imply that these garnets are grossular andradites varying in composition from 55 - 70% of the andradite molecule. The darker zones represent the most iron rich composition. Zoning and variations in composition suggest a metasomatic rather than metamorphic origin (p.124).

The garnets are usually unaltered but may be partly replaced along cracks by haematite or chlorite.

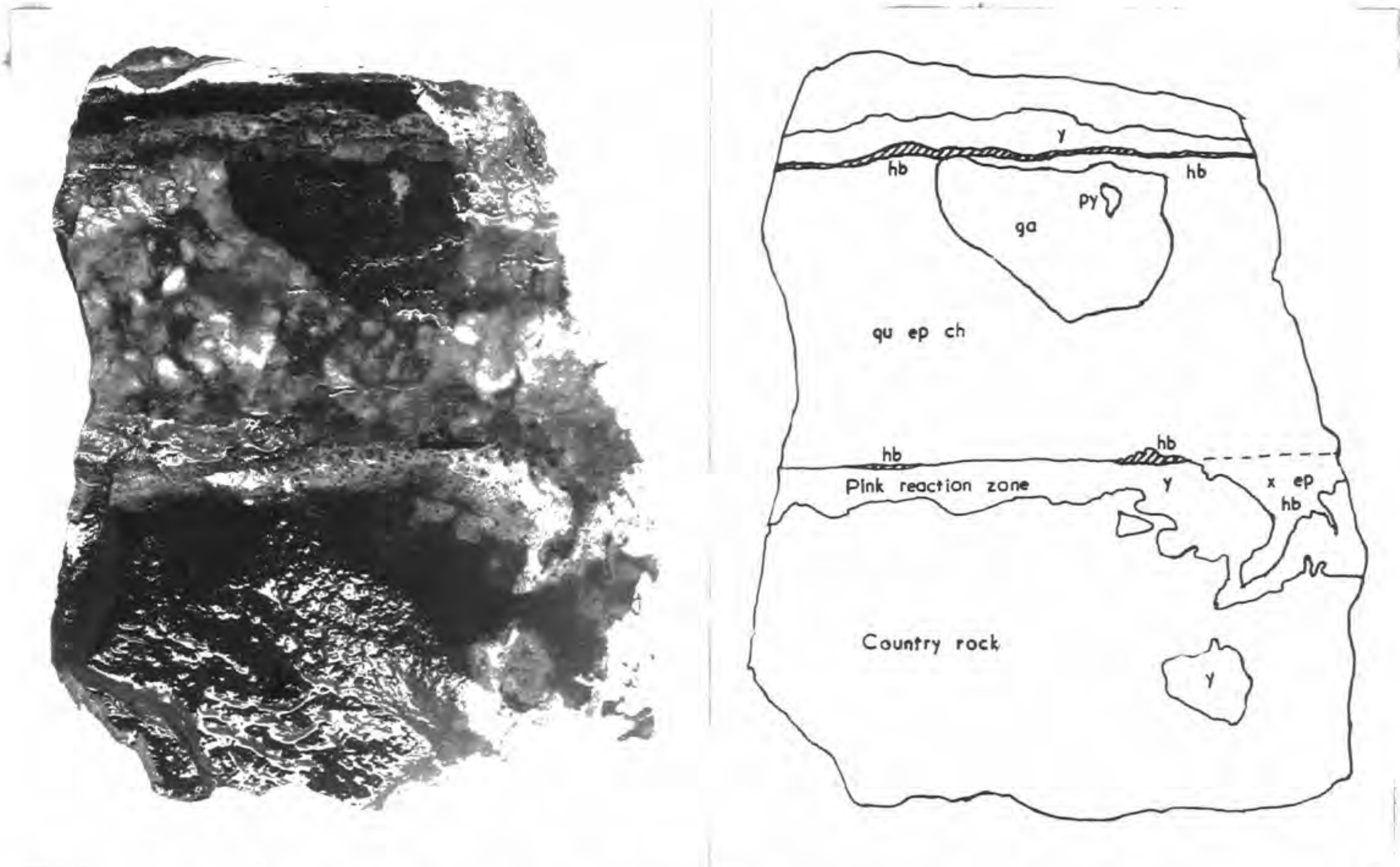


Fig.18. (R.F.173) Garnet vein from Shap Blue Quarry (x 1)
ga = garnet, py = pyrite, hb = hornblende, qu = quartz,
ep = epidote, ch = chlorite, x = wall rock replacement,
y = reaction zone (x 1)

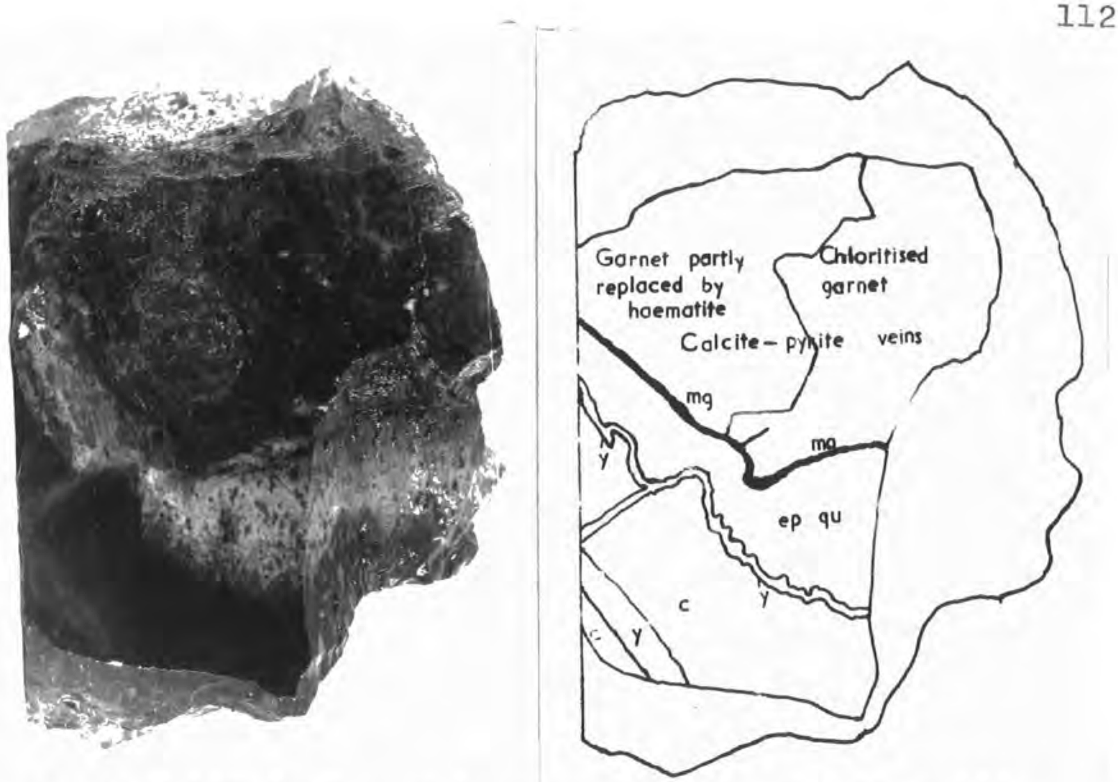


Fig.19.(R.F.128.) Garnet bearing vein from Old Rhyolite quarry. mg = magnetite, qu = quartz, ep = epidote, y = reaction zone, c = country rock. (x1).

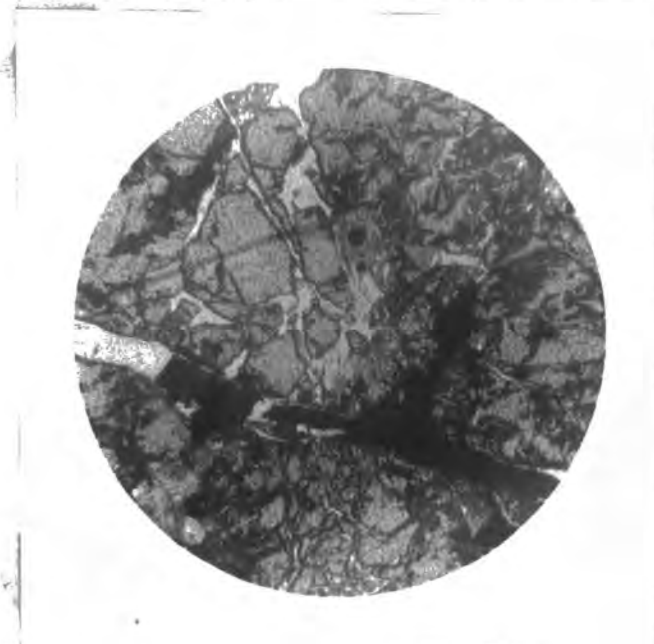


Fig.20.(R.F.128.) Garnet bearing vein. Old Rhyolite quarry. Fractures in garnets are filled with calcite and magnetite. (x 35)

Wall rock alteration.

The margin of garnet bearing veins with the wall rock is rarely well marked or regular, often extensive replacement by epidote has taken place and an inner band of hornblende marks the true edge of the vein (Fig.18. R.F.173). Epidote may also develop along veinlets (R.F.43. Fig.22) and sparsely in the ground mass. R.F. 128 (Fig. 19.) shows replacement of the country rock by epidote in a mosaic of quartz. In this case the country rock is a rhyolite and the excess silica has crystallised as quartz. Solutions permeating the wall rock may chloritise hornblende and biotite (R.F.43. Fig. 22) and extensive epidote replacement may develop in the wall rock in an analagous manner to that around vesicles and epidote veins. Epidote becomes more granular and sparsely distributed towards the country rock.

Beyond this outer epidote zone, or beyond the hornblende zone if this is absent, is invariably a reaction zone. This zone is rarely more than ½" wide and usually pink. White reaction zones occur when the vein is rich in sulphides, and will be considered later (p. 160.). This zone is too finely crystalline for individual minerals to be identified with certainty, but compared with the country rock (metamorphosed andesite) the relative absence of biotite is striking. The pinkish colour seems to be due to a fine dust of limonite or haematite whilst magnetite octrahedra may also be present. In general the reaction zone appears to be much the same as reaction rings around vesicles and alongside hornblende-epidote veinlets, although here sphene has been recorded. It appears to consist largely of a microcrystalline aggregate of quartz and albite and orthoclase, all traces of the original texture of the andesite having been obliterated. An analysis (Table V) is later discussed.

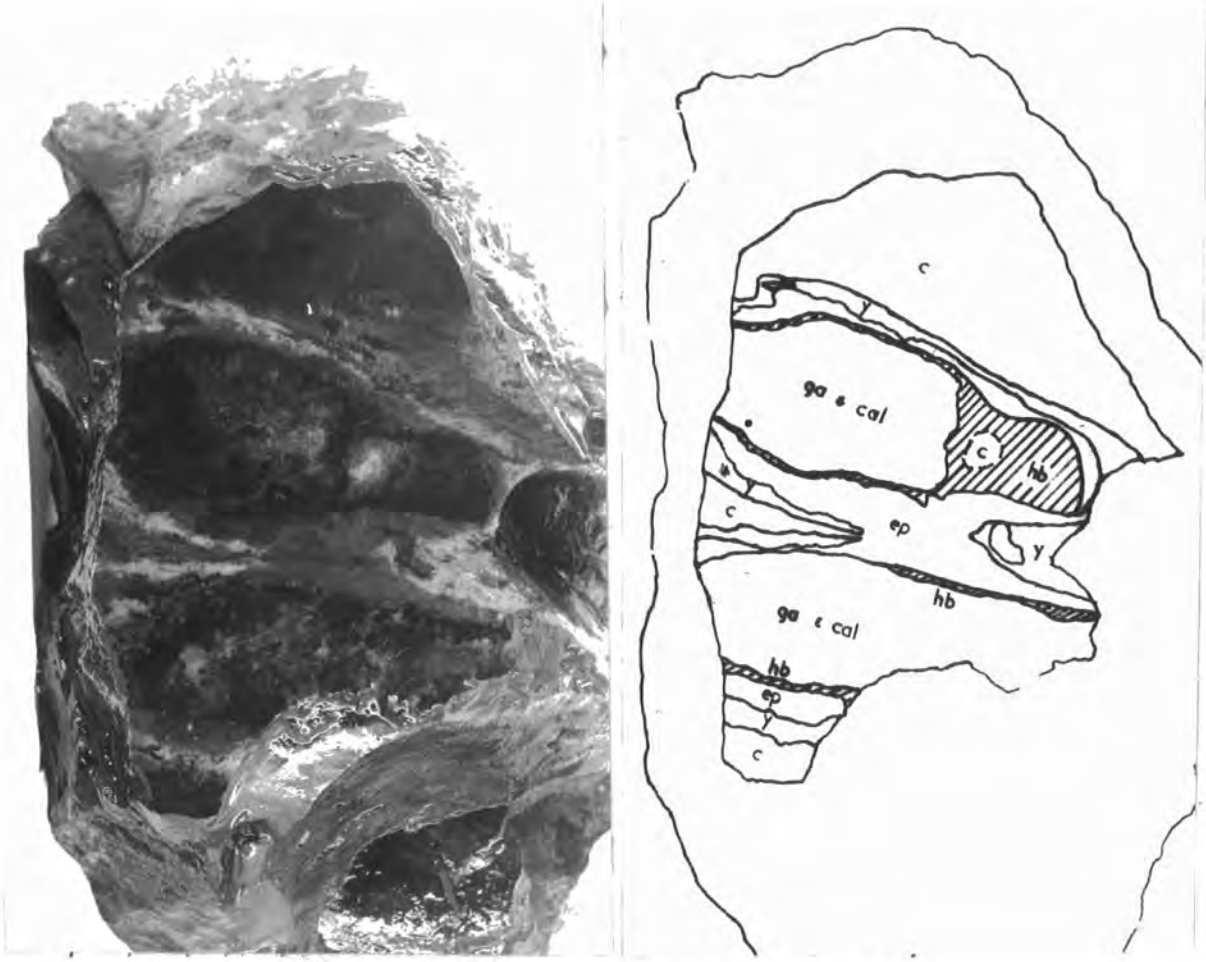


Fig.21.(R.F.31.) Irregular replacement patches.
c = country rock, y = reaction zone,
hb = hornblende, ep = epidote, ga = garnet,
cal = calcite.

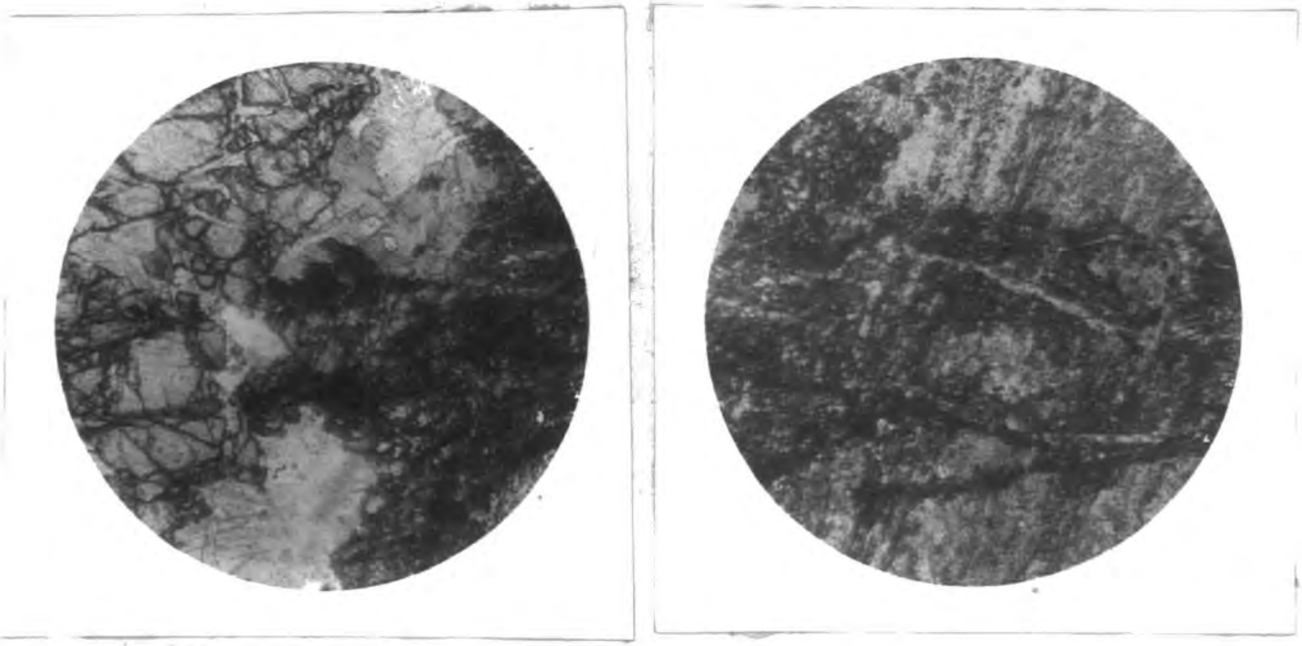


Fig.22 (R.F.43) Garnet bearing vein Shap Blue quarry
a. Garnet zone - fractures filled with calcite
b. Hornblende zone - Hornblende replaced by calcite and chlorite
c. Wall rock epidotised near veinlets
d. Country rock choritised. Granular epidote developed near epidote veinlets.

Where are these?

(iii) <u>Wall rock alteration of high angle joints - the epidote hornblende veins</u>.- Fissure metasomatism along the high pre-granite joint system is less extensive than along the low angle joints. Garnets are only very rarely developed and the high angle joints were not the channels for low temperature hydrothermal solutions and are never veined by later calcite and quartz.

As in the case of the garnet bearing veins, hornblende marks the true edge of the fissure whilst epidote has developed in the wall rock. Probably the hornblende and clinopyroxene in some veins has developed from joint fillings such as chlorite (p. 51.) but the epidote has formed by wall rock replacement.

The evidence for wall rock replacement may be summarised as follows:-

(1) The irregular margins of the epidote zone.
(2) The occurrence of granular epidote at the margin of the epidote zone and in the country rock.
(3) The presence of a pink reaction zone.
(4) The occasional occurrence of pyrite associated with epidote.
(5) Relic structures (e.g. Quartz filled vesicle. R.F.26. Fig.13.).

In addition to this evidence, minute crystals thought to be apatite have been found (R.F.158) and Sphene (R.F.34). These may be relic minerals from the replaced country rock.

The reaction zone is similar to that in the garnet-bearing veins (p141.).

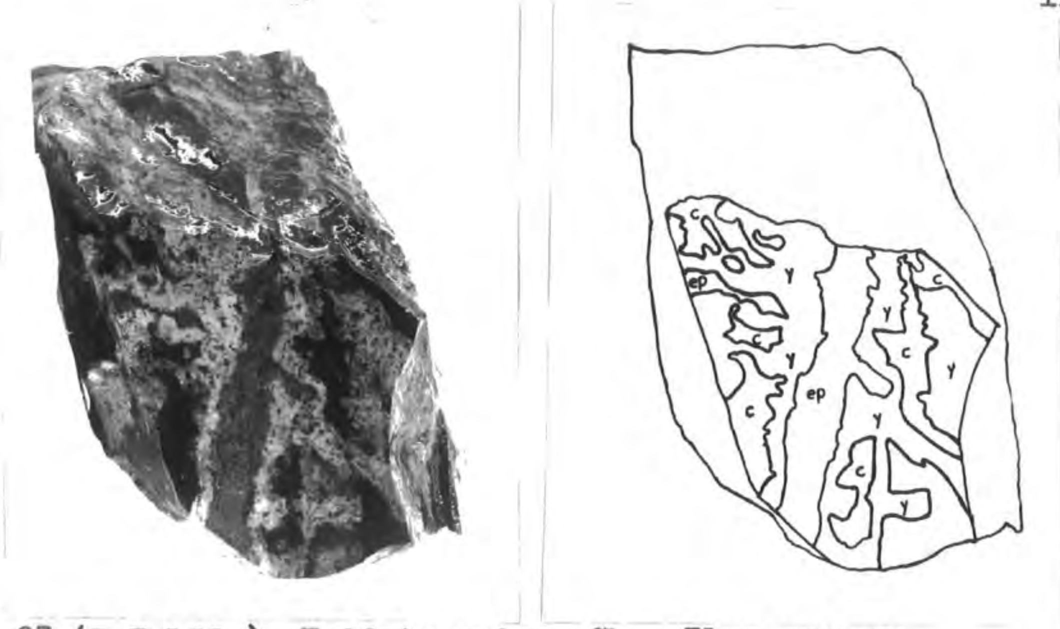


Fig. 23. (R.F.158.) Epidote veins, Shap Blue quarry. Metasomatised joint system. c = country rock (biotite hornfels) y = reaction zone, ep = epidote (x 1).

Fig. 24. (R.F.34.) Epidote vein, Shap Blue quarry. Epidote-calcite-hornblende association. (x 35).

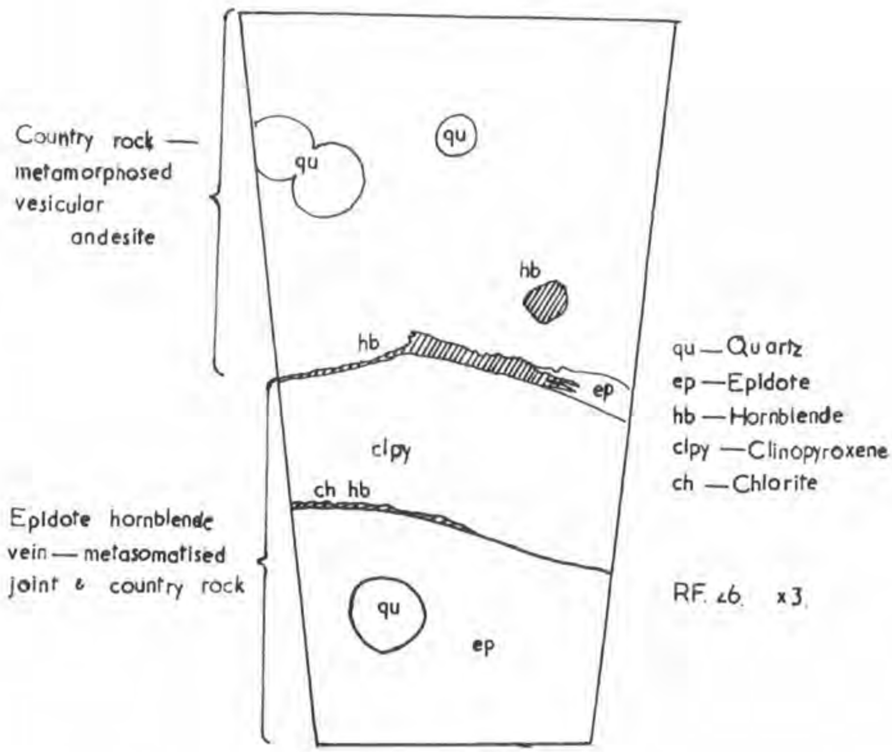


Fig.25.(R.F.26.) Diagrammatic section of a hornblende-epidote vein showing the inclusion of a quartz vesicle in the epidote zone (x 3).

Character of minerals in the Replacement Bodies.

Epidote. Crystal system.- monoclinic. Form.- granular in replaced wall rock but small idioblastic crystals up to 0.25 m.m. across may develop in the replaced wall rock. Idiomorphic crystals are more often developed in the open fissure. Here well terminated monoclinic crystals up to 5 m.m. long occur. Acicular groups are rare. Colour.- Usually grass-green, well formed crystals often darker. Cleavage.- Perfect 001 cleavage developed in all but the granular aggregates. Lustre.- Vitreous transparent. H = 6 - 7.

Optical Properties.- Biaxial negative. Larger crystals are usually zoned, the darker zone being central. All but the granular aggregates are strongly pleochroic

α = pale yellow β = pale yellowish green γ = greenish yellow.

Refractive indices are tabulated below.

	R.F.48	R.F.158	R.F.128.
α	1.732	1.724	1.716
γ	1.773	1.761	1.740
$\gamma-\alpha$	0.041	0.037	0.024

Determined by immersion methods.

Suggested composition from Whinchell's data is R.F.48 30%, R.F.158 25% and R.F.128 15% of the pistacite molecule. The high birefringence strong pleochroism and dark colour of most epidotes suggest that they are iron rich varieties with up to 30% of the

$Ca_2Fe_3(OH)Si_3O_{12}$(pistacite) molecule in every case 2V is large and α to C = less than 5^{o} (Measured by maximum symmetrical extinction method).

<u>Clinopyroxene.</u>- Usually in granular aggregates varying in size from microcrystalline dimensions to over 2 m.m. Also occurs in vesicles. Idiomorphic crystals, not recorded.

<u>Optic properties</u>.- Colour pale bluey green, non pleochroic. Relief and birefringence generally lower than epidote. Refractive indices from R.F.26.

α = 1.692. β = 1.702 γ = 1.719 $\gamma - \alpha$ = 0.027

suggesting an augite composition. Maximum symmetrical extinction α to c = 45^{o}.

<u>Hornblende</u>.- Hornblende occurs in two forms in the replacement structures. Usually it is decussate mosaics of stumpy hypidiomorphic crystals whose average size is about 0.1 m.m. x 0.5 m.m. or more occasionally in acicular groups. Minute needles sometimes occur poikolitically in quartz or calcite, whilst in open fissures the walls may be lined with dark green, lustrous, feathery hornblende crystals.

<u>Optical Properties</u>.- Strongly pleochroic d = yellow brown, = yellow green = bluey green. Refractive indices shown below suggest an actinolitic composition.

	R.F.205. Vesicle.	Garnet bearing vein.	
α	1.628.	1.621	1.615
β	1.640	-	-
γ	1.643	1.649	1.641
$\gamma - \alpha$	0.015	0.028	0.026

These hornblendes are characterised by a bluish colour suggestive of a ferriferous variety.

Garnet.- Garnets vary greatly in size and colour. Idiomorphic (or idioblastic) are rare, but well developed faces are often seen. The larger garnets are usually intergrown and fractures filled with quartz and calcite etc. The largest garnets recorded are about 5 c.m. in diameter. Crystal System.- Cubic. Both dodecahedral and trapezohedral forms occur and commonly a combination of both. Colour.- Varies from a pale orangy yellow to a deep reddish brown. Specific gravity R.F.40 = 3.83 R.F.174 = 3.77.

Optical Properties.- Isotropic or slightly anisotropic, the latter usually showing lamella twinning. Owing to interpenetration of garnets and later fracturing, this twinning is very difficult to interpretate. In the commonest type, the twins are developed parallel to the crystal edges or zoning, show straight extinction, high dispersion and $+^{ve}$ elongation. These are often grouped into triangular patches but interpenetration of twin units often occurs. Spindle shape twins are common and in one instance (R.F.161) a cubic pattern of twinning has been observed. Lamella twinning is more often developed in the paler colour garnets which are lime rich

Zoning is a very common feature which usually takes the form of a series of bands of dark isotropic material grading into paler anisotropic material. These were presumably concentric zones representing stages in the growth of a garnet crystal so that parallel banding seen in some slices (e.g.R.F.40.) may be the shattered remains of large garnets. As with the twinning only in the smaller isolated crystals can a regular pattern be observed. Harker and Marr (1893) described zoning in which an outer isotropic shell encloses anisotropic material and concentric zones with this arrangement seem to be normal. Some of their slices show an isotropic centre and this arrangement has not been observed in the present research.

Refractive index determinations on a zoned garnet show that considerable variations in composition are possible in one crystal. The garnet examined, from a replacement patch (R.F. fig. 21.) consisted of four concentric zones in a crystal about 15 m.m. in diameter. These zones were separately mechanically from a rock slice and the refractive indices determined with phenyl-di-iodoarsine. The limits of error are estimated at ± 0.002.

Outer zone I	isotropic dark reddish brown,	R.I = 1.851
Zone II	isotropic grading inwards to lighter birefringent material	Max R.I = 1.827 Min R.I = 1.822
Zone III.	As above	Max R.I = 1.836 Min R.I within experimental limits of error
Inner Zone IV.	As above	Max R.I = 1.825 Min R.I.= n.d.

These results suggest that the variation within each zone is slight but significant changes in composition are shown in one garnet. Assuming that those garnets belong to the grossularite

-andradite series and contain no impurities, the molecular compositions calculated from Whinchell's tables (1951) are approximately:-

Zone I	$Gr_{30}An_{70}$
Zone II	$Gr_{45}An_{55}$
Zone III	$Gr_{35}An_{65}$
Zone IV	$Gr_{45}An_{55}$

Refractive index determinations of garnets R.F.40 gave a R.I of 1.824 suggesting a composition of $Gr_{45}An_{55}$. A chemical analysis given overleaf of a garnet from a replacement patch (R.F.174) suggests that the presence of pyrope, almandinite and spessaritite molecules lowers the refractive index.

Chemical Composition - A partial analysis of hand picked garnets from a replacement patch (R.F. 174) gave the following result. Garnets were separated from the calcite matrix using bromoform.

Analysis of Garnet R.F. 174 recalculated on the basis of 12 oxygen atoms.

	Wt. %	Mol. Prop.	No. of oxygen atoms	No. of metal atoms to 12 oxygens	
SiO_2	37.03	.617	1.234	3.013	3 = Si^{++++}
TiO_2	0.04	-	-	-	
Al_2O_3	8.92	.087	.261	.850	2.000 = R^{+++}
Fe_2O_3	18.34	.118	.354	1.151	
FeO	2.25	.031	.031	.152	2.977 = R^{++}
MgO	0.83	.021	.021	.103	
CaO	30.26	.541	.541	2.649	
H_2O+	0.48	-	-	-	
H_2O-	0.16	-	-	-	
MnO	1.09	.015	.015	073	
CO_2	n.d				
	99.40		2.457		

Andradite ($Ca_3Fe_2Si_3O_{12}$) = 57.3%
Grossularite ($Ca_3Al_2Si_3O_{12}$) = 31.8%
Almandite ($Fe_3Al_2Si_3O_{12}$) = 5.1%
Pyrope ($Mg_3Al_2Si_3O_{12}$) = 3.4%
Spessartite ($Mn_3Al_2Si_3O_{12}$) = 2.4%

∴ Essentially $Gr_{36}An_{64}$ with some Al, Py and Sp.

Theoretical refractive index and specific gravity of $Gr_{36}An_{64}$ (from Winchell's tables) μ = 1.83; G = 3.70; $\mu_{obs.}$ = 1.827; G_{obs} = 3.77. The lower observed μ and higher G may be accounted for by the presence of almandite and spessartite molecules.

(iv) Late stage veining in garnet-bearing veins.- Without exception in the slicesexamined, veins of quartz and/or calcite occur in the garnet zone. The textures (R.F.40. Fig.26.) are dominantly characteristic of fracture filling but partial replacement occurs and occasionally (R.F.40 and 128.) the garnets are chloritised or altered along cracks to haematite. Furthermore, chloritisation of hornblende and replacement of the wall rocks is probably due to these late stage solutions.

R.F.40.(Fig.26.) provides an interesting example. This vein consists largely of quartz and garnet of typically coarse crystallisation. A rock slice showed the garnet to be fractured, and these fractures were filled with quartz and some calcite; fine needles of actinolite occur poikioblastically within the quartz. In general, the smaller cracks in the garnets are filled with calcite but there is no evidence of pre-existing calcite. The garnets are usually little altered but some chloritisation has occurred. In R.F.128. from the old Rhyolite Quarry, veins of calcite with little quartz similarly shatter the garnet. Furthermore, these solutions brought in iron and sulphur and pyrite, haematite and magnetite fill cracks in the garnet. Haematite is least abundant in zones of chloritic alteration, and may itself be an alteration product: however specular haematite occurs in some veins. In parts it appears to replace garnet in much the same way as does chlorite. Other minerals recorded filling fractures in garnets are sphalerite and galena (R.F.194) whilst chalcopyrite, covellite and marcasite occur interstitially These are considered more fully later (p.175).

In the southern end of the quarry a magnetite-garnet vein was found in situ and other examples of magnetite rich rocks have been found in old tips. These consist of 90% granular magnetite with epidote,pyrite, chalcopyrite and garnet. A rude zonation of garnet and pyrite in the centre and magnetite-epidote in the outer zone seems general. Polished sections show that the magnetite is fine grained and intimately intergrown with transparent minerals. Lamellae of martite occur and alteration to martite is also common along cracks. Some allotriomorphic chalcopyrite partly altered to covellite and idiomorphic pyrite, is commonly found in association with the magnetite whilst in R.F.226. marcasite showing spheroidal structures occurs. Evidence is found of magnetite replacing garnet (Fig.29) and of magnetite replacing epidote whilst lineation of transparent minerals (Fig.R.F.59) might be a relic of the original cleavage in the country rock. The magnetite is singularly free from exsolution lamellae and no spinels have been recorded from these veins.

These rocks are superficially similar to the contact skarns of Skye, but in a horizontal sense they are 400 yards from the granite contact. They have,however, been recorded only from the southern end of the Blue Quarry nearest the granite contact. Further they seem to be invariably associated with the garnet veins and may be due to the replacement of andradite, epidote etc. It is noteworthy that the haematite rarely occurs in the garnet veins whereas magnetite is common. This strongly suggests that the late stage solutions were of relatively high temperature and connected with the high temperature hydrothermal stage of the emplacement of the Shap granite.

Hornblende is also invariably chloritised and in some cases (e.g. R.F.43.) may be replaced by calcite. The formation of some of the epidote along joints and veinlets is attributable to the same late-stage fluids. Calcite veins in the garnet zone (R.F.43. Fig.22.) traced outwards are found to be coincident with epidote veinlets in the country rock.

(v) <u>The pyrite veins and associated metasomatism.</u>- Extensive metasomatism is associated withe the formation of pyrite veins seen in the south end of Shap Blue quarry. Cordierite spots are developed whilst nearer the veins cordierite is replaced by chlorite and sericite abundantly developed in the ground mass. The petrography and geochemistry of this metasomatism is discussed on p.160-170. The pyrite veins are thought to be replacement structures formed by the introduction of sulphur, alumina and potash into the wall rock and the removal of ferrous iron. No field evidence indicating the age of these veins has been found but they are thought to be younger than the garnet bearing veins since sulphides are commonly found in the late stage veins in the garnet zone.

(vi) Late stage hydrothermal veins.- The low temperature hydrothermal mineralisation is described in Section VII but they are genetically connected with the late stage veining in garnet bearing veins. In the latter case, some solution of garnet veins has occurred but generally low temperature hydrothermal veins are characterised by well defined margins and no appreciable wall rock alteration. Some chloritisation has occurred in fault breccias.

Fig. 26. (R.F.40) Garnet bearing vein. Shap Blue quarry. Minor fractures in garnets filled with quartz, chlorite and calcite; later quartz vein. (x 35)

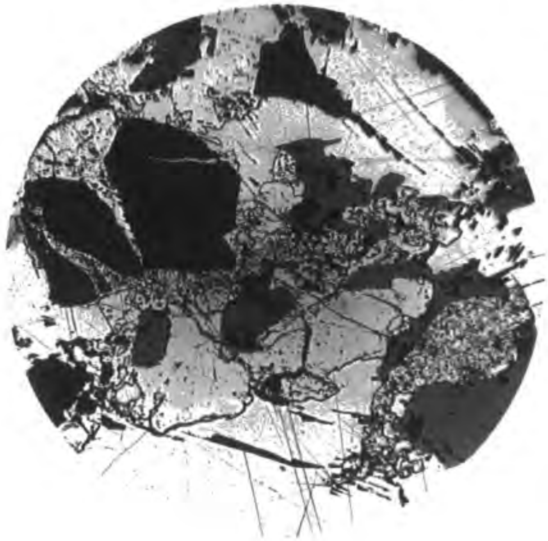


Fig. 27. (R.F. 194) Galena (white) zone blende (grey) and pyrite replacing and filling fractures in garnets. Polished section.(x35)

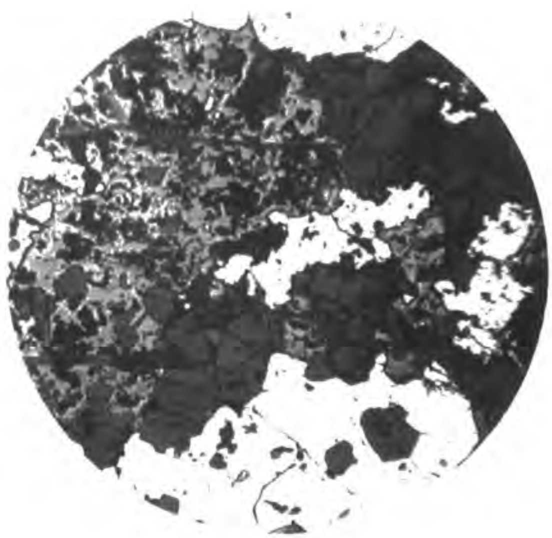


Fig. 28. (R.F. 208) Chalcopyrite partly replaced by
covellite - associated pyrite and magnetite
Polished section from garnet bearing vein (x 35)

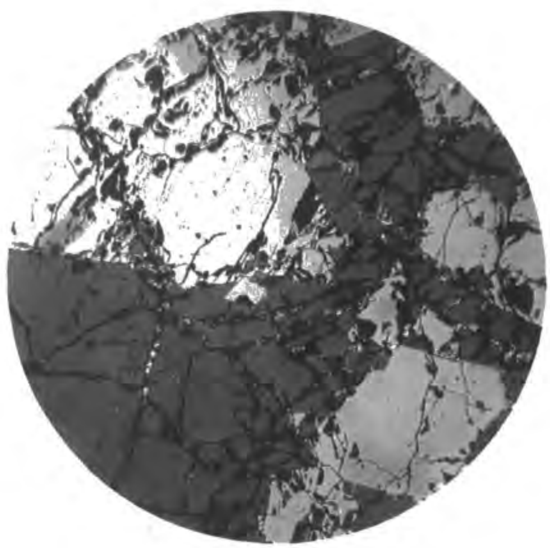


Fig. 29. (R.F. 227) Magnetite replacing garnet.
Polished section from a garnet bearing vein.(x 35)

Fig. 30. (R.F. 69) "Lineation" in magnetite from a garnet bearing vein. Polished section (x 35)

(c) Petrogenesis of the Garnet bearing Veins and related structures.

(i) Introduction.- A petrographic study of the garnet bearing veins has suggested that they are due to fissure metasomatism along a pre-granite joint system. The outstanding petrogenetic problems thus concern the nature and origin of the metasomatising fluids, and the geochemistry of replacement.

An examination of the mineral assemblages shows that the major components are lime, alumina, ferric iron and silica. Ferrous iron and magnesia are important constituents of hornblende but it has been demonstrated (p.51.) that at least part of the hornblende has formed from pre-existing chlorite. No alkali minerals have been recorded from the metasomatic replacement bodies and it seems that, if the metasomatising fluids were rich in alkalies, they permeated wall rocks beyond the reaction zone.

The geochemistry of veins and irregular replacement patches of garnet epidote and hornblende can thus be described essentially in terms of the system:

$$CaO - Fe_2O_3 - Al_2O_3 - SiO_2 - CO_2 - H_2O$$

The common association of epidote and calcite and the abundance of calcite in late stage veins suggests the late stage fluids were rich in carbon dioxide thus facilitating the solution of lime and ferric iron.

(ii) The source of the Components.- The source of components forming minerals in the replacement structures:-

(1) Joint fillings.

(2) The metasomatised wall rocks (i.e. components which, in this geochemical environment, are relatively immobile and whose concentration depends on the initial composition of the metasomatised rocks).

(3) Components displaced from the country rocks nearer the granite by earlier metasomatic processes (i.e. components mobile in the higher temperature conditions nearer the granite and in open fissures, whose concentration depends on the initial composition of the country rocks and the nature and extent of later metasomatism).

(4) High temperature hydrothermal solutions from the granite.

(1). Joint fillings.- In discussing the thermal metamorphism of joints it was shown that hornblende normally develops from chlorite and calcite is of minor significance in the joints. Since no evidence of pre-existing calcite has been found in the garnet bearing veins it is thought that lime from this source was insignificant. However, andradites often develop in replaced limestone and by analogy with such contact skarns it was at first thought that the Shap garnets have a similar origin. The possibility of pre-existing calcite veins has not been conclusively disproved but in the absence of more positive proof

TABLE VI

	Wt. %	Mol. Prop. x 1000	Wt. Norm. (C.I.P.W.)			Niggli Values	
SiO_2	78.73	1312	Quartz		56.46	si	586
TiO_2	0.92	11	Orthoclase		10.01	al	35
Al_2O_3	8.16	80	Albite		20.44	fm	21
Fe_2O_3	0.71	4	Anorthite		0.83	c	18
FeO	2.05	28	Corundum		2.04	alk	26
MgO	0.41	10	Hypersthene		2.72	ti	4.5
CaO	2.15	39	$MgO.SiO_2$	1.00		p	4.0
Na_2O	2.38	39	$FeO.SiO_2$	1.72		k	0.32
K_2O	1.70	18	Magnetite Ilmenite		0.93 1.67	mg	0.21
H_2O+	0.75	-	Apatite		3.02	c/fm	0.86
H_2O-	0.09	-	Calcite		0.70		
MnO	0.06	1					
P_2O_5	1.31	9					
BaO	0.08	1	Normative plagioclase				
Cl_2	0.04	-	$= Ab_{93}\ An_7$				
CO_2	0.29	7					
	99.83						

R.F. 66. Pink reaction zone Shap Blue quarry

TABLE VII

	Wt.%	Mol. Prop.	Wt. Norm (C.I.P.W.)			Niggli Values	
SiO_2	52.21	870	Quartz		7.38	si	160
TiO_2	1.32	16	Orthoclase		25.02	al	39
Al_2O_3	21.68	213	Albite		28.82	fm	30
Fe_2O_3	2.22	14	Anorthite		6.12	c	13
FeO	5.77	81	Corundum		9.28	Alk	18
MgO	2.05	51	Hypersthene		11.96		
CaO	3.78	68	$MgO.SiO_2$	5.10			
Na_2O	3.37	55	$FeO.SiO_2$	6.86		ti	2.9
K_2O	4.21	45	Magnetite		3.25	p	2.2
H_2O+	1.16	-	Ilmenite		2.43	k	0.45
H_2O-	0.02	-	Apatite		3.70	mg	0.32
P_2O_5	1.51	11	Calcite		0.90	c/fm	0.43
MnO	0.18	2					
CO_2	0.38	9	Normative plagioclase				
S	tr		Ab_{71} An_{29}				
	99.86						

R.F. 153 Metamorphosed porphyritic andesite

Shap Blue quarry.

it appears to be unlikely.

(2). Components from the Metasomatised Wall Rocks.- An analysis (Table V.) of a rather wide reaction zone (R.F.66.) may be compared with (R.F.153. p.140) - an average hornfels from the quarry, illustrating the metasomatic processes taking place at the margins of replacement structures. Petrographically R.F.66. (the reaction zone) consists of a very fine grained mosaic of quartz and alkali felspar with accessory apatite, leucoxene and granular epidote. No biotite occurs. It is similar to reaction rings around vesicles and other replacement structures and may be considered representative of reaction zones. The analysis shows that enrichment in silica has taken place whilst the normative composition suggests that almost complete albitisation has occurred. Indeed, lime represented in normatime anorthite probably occurs in epidote in the mode. The presence of 2% corundum in the norm is probably due to the occurrence of epidote and possibly sericite in the rock. By comparison with R.F.153,in which the composition of the normative plagioclase is 29% An, the chief changes which have occurred, in the pink reaction zone, are the addition of silica with the accompanying albitisation of the felspar and the removal of excess alumina, lime and ferrics.

These geochemical relationships can be expressed more precisely by recalculating the analyses in terms of the number of metal ions to 160 oxygen ions (Barth 1948.B). The"rock formulae" are as follows:-

R.F.153.- Metamorphosed porphyritic andesite.

$K_{5.0}Na_{6.1}Ca_{3.8}Mg_{2.9}Fe_{6.0}Al_{23.7}Ti_{0.9}Si_{48.4}P_{1.2}\ [O_{152.6}(OH)_{7.4}]\ 160.$

R.F.66.- Metasomatised andesite.

$K_{1.9}Na_{4.0}Ca_{2.0}Mg_{0.5}Fe_{1.8}Al_{8.3}Ti_{0.6}Si_{67.8}P_{0.9}\ [O_{155.7}(OH)_{4.3}]\ 160.$

Thus, a standard cell of the biotite hornfels, R.F.153, passes into R.F.66 standard cell by adding and subtracting the following:-

	Adding.	Subtracting.
	19.4 ions of Si	0.3 ions of P
		0.3 ions of Ti
		15.4 ions of Al
		4.2 ions of Fe
		2.4 ions of Mg
		1.8 ions of Ca
		2.1 ions of Na
		3.1 ions of K
Total:	19.4 metal ions representing 77 valences.	29.6 metal ions and 3.1 H-ions representing 76 valences.

The above changes are also represented diagrammatically on p. 158. R.F.153 was selected for comparison with the metasomatised cordierite hornfelses (p.161.), but both specimens were collected from the south end of Shap Blue quarry and R.F.153 is unlikely to be very different in composition from other hornfelses in the area. Possibly R.F.153. is secondarily enriched in alkalies displaced from the epidotised rocks and by potash introduced during the formation of pyrite.

Aluminium.- Assuming no volume change in the replacement of wall rock by epidote, the number of Al-ions derived from the replaced rock and the reaction zones will be equal to the sum of the original cations in R.F.153 and the number of Al-ions migrating in from the reaction zones. The latter value will depend on the volume of the reaction zones compared with the volume of epidote replacement. Therefore, in considering veins, the number of ions added to the replaced rock from the reaction zones is directly proportional to $\frac{\text{the sum of the widths of the 2 reaction zones}}{\text{width of epidote replacement}}$ $\left(= \frac{Wy}{Wx} \right)$ or in a garnet vein $\frac{\text{width of reaction zone}}{\text{width of epidote zone}}$ as shown on the graph (Fig.31).

Thus if the width of the 2 reaction zones is equal to the width of the epidote replacement 39.1 of Al will be available for making epidote in a standard cell of 160 oxygen-ions. Similarly in a "vein" whose reaction zone is equal to half the width of the epidote zone 31.3 (i.e. 23.7 + $\frac{15.4}{2}$) ions of Al are available.

Clinozoizite $\left[Ca_2Al_3(OH)Si_3O_{12}\right]$ contains 36.9 ions of Al to 160 ions of O and thus the complete replacement of x standard cells of R.F.153 (160.0-ions in one standard cell) would require 36.9 - 23.7 = 13.2 x Al-ions, which could be derived from 0.86 x standard cells of reaction zone, i.e. a monomineralic replacement

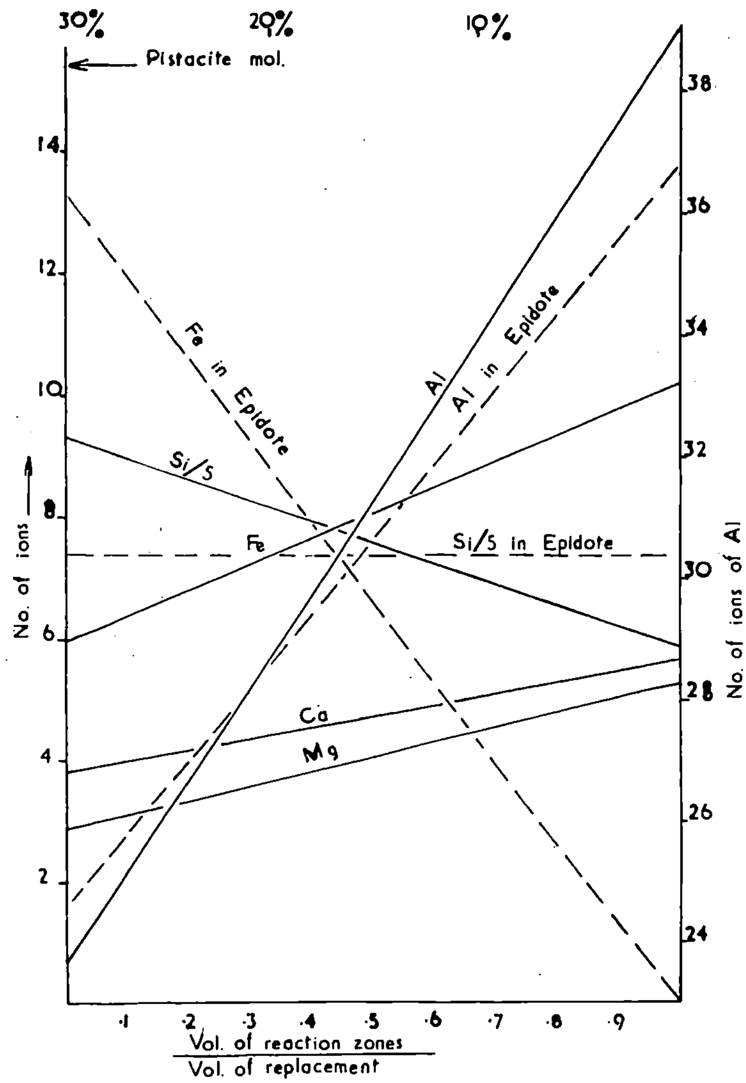


Fig. 31. Graph showing the relationships between the number of ions available in wall rock replacement and the volume of the reaction zone. Dashed lines represent the number of ions in a standard cell of epidote plotted against the % of the pistacite molecule.

"vein" of clinozoizite would theoretically be bounded by two reaction zones totalling 0.86 x the width of the clinozoizite "vein". But refractive index determinations,(p.121) pleochroism and birefringence suggest that the epidotes contain between 13% and 30% of the pistacite molecule $Ca_2Fe_3(OH)Si_3O_{12}$. Variations of Al and Fe requirements in epidotes are plotted on the graph (Fig. 31.). Ca and Si remain constant at 24.6 and 36.9 ions per 160.0-ions respectively. The graph shows that theoretically sufficient Al could be obtained from the replaced country rock, and from the surrounding reaction zones equal to 0.3 x the volume of the replacement. As shown by the modal analysis (p.159.) epidote veins rarely consist solely of epidote but usually contain hornblende and calcite or quartz which reduces the alumina requirements. It is estimated that sufficient alumina for epidote and hornblende in most epidote-hornblende replacement "veins" is obtained from the replaced hornfels and from silicified wall rock amounting to 0.1 of the volume of replaced rock. This agrees well with the observed widths of reaction zones (Table p.159 .). Alumina thus acts here as an "inert" or relatively immobile component, the amount of epidote replacement depending on the availability and mobility of alumina from the reaction zone.

<u>Magnesium.</u>- Enough magnesia is available from the country rock to provide Mg for epidote and probably most of the Mg in hornblende. The presence of clino-pyroxene and little epidote in R.F.147

possibly indicates that the replaced rock was magnesia rich. Hornblende may have formed from pre-existing chlorite vein fillings and it is unlikely that the metasomatising fluids contained much magnesia.

Silica.- Sufficient silica to form epidote is available in the country rocks, but the silicification of the reaction zone and the high percentage of quartz in some epidote veins (Table on p. 159) suggests fluids migrating along the fissures were rich in Si.

Lime.- The available lime in the country rocks is inadequate to form epidote and most of the lime needed must have been derived from other sources.

Iron.- Fig. 31 shows that iron is available for epidote only if country rock equal to 0.41 x the volume of replaced rock is silicified. Only 30% of this iron is in the trivalent state but ferrous iron may have been oxidised by the metasomatising solutions but most of the ferric iron must have come from these percolating solutions and not from the wall rocks. Considerably more ferric iron is required for the formation of andradite garnets (e.g. 25.2 Fe^{+++}- ions to 160 O-ions occur in the analysed garnet R.F.194 p. 126). This could not have come from the wall rocks.

Titanium, Phosphorous and Alkalies.- Ti, P, Na & K do not enter appreciably into the composition of epidote hornblende or garnet and titanium, phosphorous and alkaline minerals have not been recorded from the garnet bearing veins or related structures.

Possibly these elements migrated outwards into the country rocks. Owing to the low mobility of titania and phosphorous (see for example Korzhinsky 1950 A) it is unlikely that these elements migrated far. Sphene is often seen concentrated around the reaction zones surrounding amygdales where presumably lime is available. Soda and potash may have migrated further into the country rocks. This may partly account for the high alkali content of R.F.153. However, assuming that 10% (by volume) of the rocks, in the Shap Blue quarry area are replaced, then the country rocks would theoretically be enriched by an average of 0.5 alkali-ions per standard cell. This approximates to 0.7% by weight and, particularly since 10% replacement is a high figure, this correction may be neglected. If R.F.153 has been further enriched by potash introduced during the formation of pyrite veins and an enrichment of 1.0 alkali-ions per standard cell is accepted, the correction becomes significant and the valency discrepancy (p.142) is resolved. The correction has not been applied, however, since precise geochemical data is not available, and the graph (Fig. 31.) and deductions drawn from it are not materially affected and the valency discrepancy is insignificant.

The evidence presented so far thus suggests that, in the formation of garnet veins and related structures, alumina behaved as an "inert" or relatively immobile component whilst incoming liquids were rich in silica, lime and carbon dioxide and also contain appreciable amounts of ferric iron. Lastly it may be noted here that the metasomatising agents have been tacitly assumed to be aqueous solutions. The validity of this assumption is discussed later but it has been adopted not only because lime, ferric iron and silica are most readily transported in watery mediums but because hydrous minerals occur containing more H-ions than are available from the replaced country rock. Later calcite and quartz are also demonstratably precipitated from aqueous solutions.

(3) <u>Components displaced from the Country Rocks by earlier metasomatic processes</u>.- Chemical analyses and petrographic studies of thermally metamorphosed rocks from west of the granite (p.68-69) suggest that alumina, ferric iron and some lime were displaced during the silicification, and alkali metasomatism of the country rocks. Probably fissure metasomatism took place at about the same time as the metasomatism at the contact and the initial epidotisation of the wall rock was probably caused by the same metasomatising fluids derived from the granite. Since sufficient alumina and much of the iron can be obtained from the wall rocks, for the formation of epidote, (Fig31) it seems unlikely that the early metasomatising fluids contained much iron or alumina. Later enrichment in these components, displaced from the metasomatised country rocks, would in part account for the formation of andradite garnets and for the later metasomatic formation of cordierite (p.170). Some of the lime may well have been derived from metasomatised country rocks.

(4) Components derived from the granite.- A study of the bulk metasomatism has shown that the initial metasomatising fluids were rich in silica and alkalies but there is little evidence of introduction of much lime. However, it has been shown that lime and carbon dioxide must have been derived from solutions percolating along fissures and a granitic origin for these components is favoured. Carbon dioxide can hardly have been derived from the country rocks and the abundance of calcite in low temperature hydrothermal veins shows that lime was concentrated in late stage solutions from the granite. Therefore the initial metasomatising solutions percolating along fissures were probably watery siliceous solutions rich in lime and alkalies, containing CO_2 as the chief volatile component, derived directly from the granite. This was supplemented by some lime, ferric iron and alumina from the metasomatised country rocks.

Given the correct physiochemical conditions, solutions of this composition would cause the epidotisation of the wall rock but would not account for the formation of andradite garnets. It has been shown (p.41.) that haematite is associated with the high temperature hydrothermal stage of the Shap granite. Possibly the solutions were supplemented by ferric iron from the granite at a slightly later stage. Similarly, the components for the lower temperature hydrothermal minerals were derived from the granite under lower temperature conditions.

(iii) Geochemistry of Replacement.-It has been shown that epidote tends to develop in the replaced wall rock whilst garnets often formed in the open fissures. However, both may be intimately associated in replaced wall rock. Since hornblende and clino-pyroxene were probably derived from pre-existing chlorite (p. 51.) the genesis of epidote and garnet remains the outstanding problem.

Genesis of Epidote.- Epidote seems to have formed first as a granular patchy development replacing felspar in the wall rocks, and later, associated with quartz or calcite as a complete replacement. A later generation of epidote associated with the low temperature hydrothermal calcite veins has also been observed (Pl.F.43). Both generations appear to be due to diffusion of components into the wall rock from open fissures.

Epidote has not been synthesised and no experimental data is available, but the stability relationships of the Al-Fe members of the epidote group have recently been reviewed by Ehlers (1953). Discussing the transition from plagioclase to epidote according to the hypothetical reaction

$$4CaAl_2Si_2O_8 \longrightarrow 2Ca_2Al_3(SiO_4)_3(OH) + SiO_2 + Al_2O_3,$$

he states that the theoretical phase diagram is as shown in Fig. 32A. However, since there is less epidote found in nature in contact with more calcic plagioclase than about An_{35} (Ramberg in Ehlers.1953) Ehlers considers a more likely transition curve is as shown in Fig.32B. It thus follows that the albitisation of felspars would favour their replacement by epidote in a right physio-chemical environment.

Albitisation and silicification has taken place at the Shap granite contact and is associated with the removal of lime and alumina from the contact rocks. Geological evidence suggests that the formation of zoisite is favoured by falling temperatures. Epidote, therefore, is unlikely to form in the high temperature conditions at the contact, but may form along cooler fissures, or, as at Eskdale (Part II. p 57.), beyond the zone of biotite hornfelses.

Ehlers (1953) also suggests that the transition point between epidote and plagioclase will be raised in the presence of iron so that pistacite probably forms at higher temperatures than clinozoisite. His suggested phase equilibria diagram is shown (Fig. 33. p.154). Since most of the epidote at Shap is an iron rich variety it seems likely that it was formed at higher temperatures than saussurite.

Turner (1948) has objected to the "conventional" epidote equation since it involves a volume decrease of about 20% and has suggested the following equation:-

$$8\,CaAl_2Si_2O_8 + 4CaO + 2SiO_2 + Al_2O_3 + 3H_2O \rightarrow 6Ca_2Al_3(SiO_4)_3(OH)$$

Anorthite	Clinozoisite
806 cc.	813 cc.

This agrees well with the Shap genesis since evidence has been given of the metasomatic introduction of lime and silica but there is no evidence of introduction of alumina from the fissure but some alumina was introduced from the silicified reaction zone. It has been noted further that the volume of the replacement seems to be dependent on the mobility of alumina and in this connection pH is probably the controlling factor, particularly since the metasomatising solutions were/unlikely to to have been sufficiently acid to transport alumina.

Silicification, albitisation and epidotisation are therefore closely interrelated in the processes of fissure metasomatism at Shap. A suggested mechanism to account for the replacement of wall rock by epidote is as follows.

(1) Percolation along fissures of relatively high temperature watery slightly acidic solutions, rich in silica and lime and containing alkalies some ferric iron and CO_2.

(2) Diffusion through pore spaces into the cooler wall rocks causing silicification and albitisation and the formation of reaction zone.

(3) Almost simultaneous formation of epidote as the concentration of alumina in the liquid phase is increased by alumina displaced from the reaction zone.

Epidote can thus be precipitated hydrothermally in open fissures provided the concentration of alumina is sufficiently high. Whilst a high hydrostatic pressure would probably favour such reactions, the mobility of alumina seems to be the dominant factor depending in turn on pH values. It is significant that acidic solutions containing alkalies, silica, lime, CO_2 and

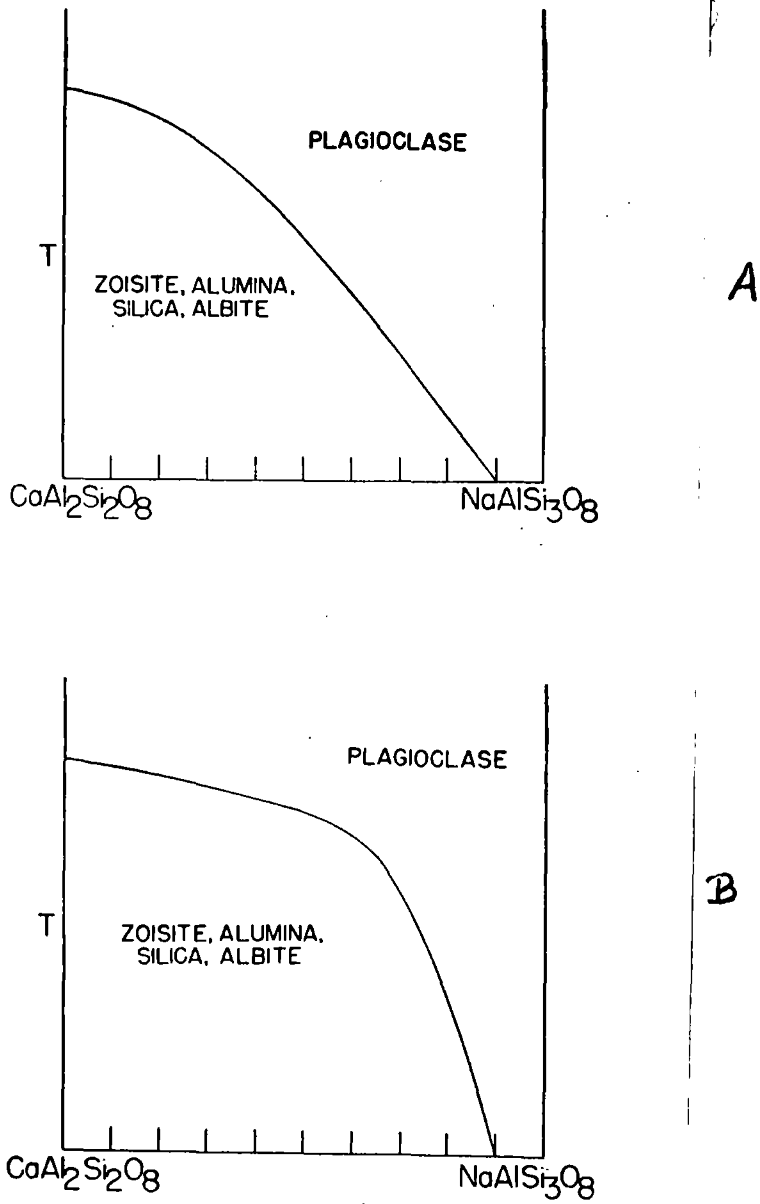


Fig. 32. Phase equilibria diagrams (after Ehlers).

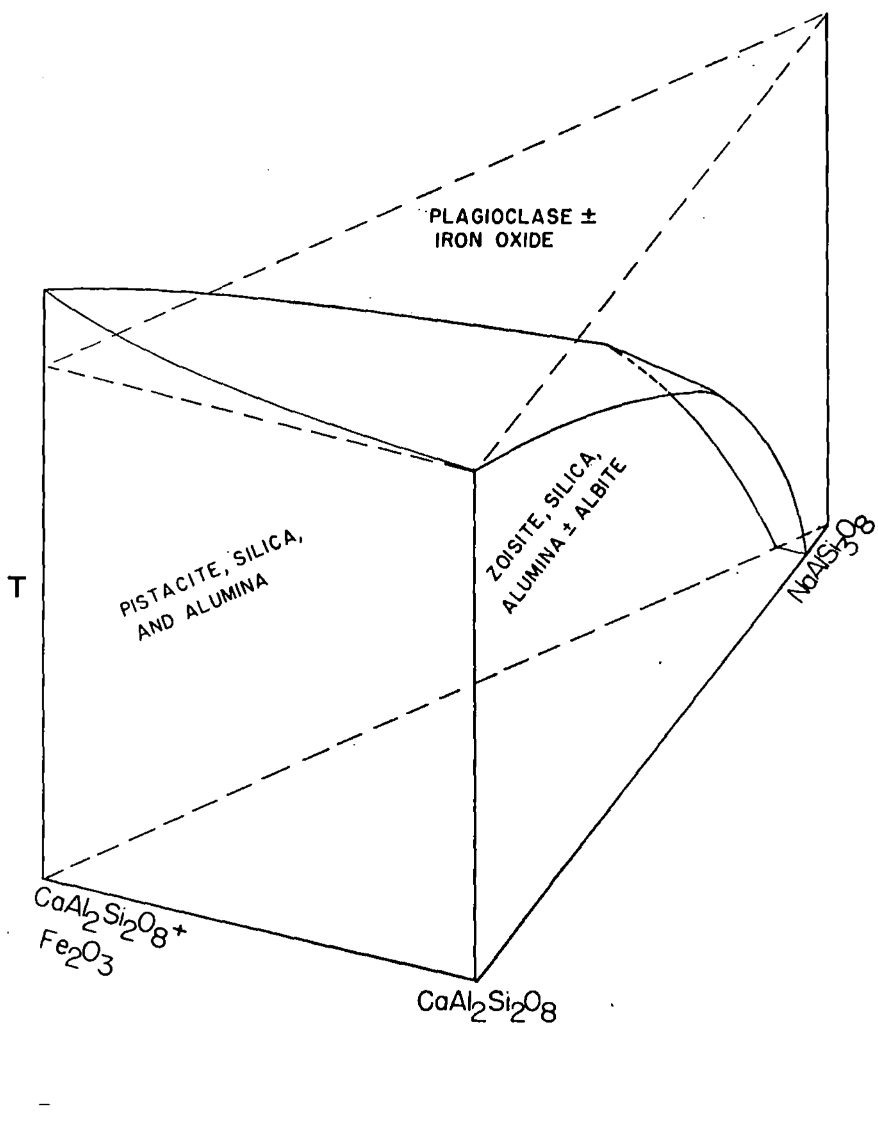


Fig.33. Phase equilibrium diagram (after Ehlers)

alumina have caused sericitisation <u>not</u> epidotisation. (metasomatism associated with the pyrite veins(pp. 160-170.)

Zoned Epidotes.- Epidote in replacement bodies is almost invariably zoned with the most pleochroic, iron rich variety in the centre. Ehlers (1953) has shown that the iron rich pistacite is stable at higher temperatures than clinozoizite. Zoning is therefore probably a function of falling temperature in conditions of limited available ferric iron.

Epidote in Later Veins.- The later generation of epidote, which occasionally occurs in veinlets associated with late stage veins in replacement bodies, shows little evidence of wall rock replacement. Probably it was precipitated from hydrothermal solutions containing alumina. Evidence is given later that the lower temperature hydrothermal solutions were more acid and contained alumina in solution which was derived partly from the granite and partly displaced from the metasomatised country rocks.

Genesis of Garnets.- Andradite garnets are usually developed in the centre of veins and only rarely in the replaced wall rock suggesting:-

(1) That they are formed more readily from solution than in the solid state.

(2) That higher temperatures existing in the open fissures favoured the formation of garnet.

(3) That the percolating fissure solutions more nearly approached the optimum composition for the genesis of andradite garnet than the solutions diffusing into the wall rocks.

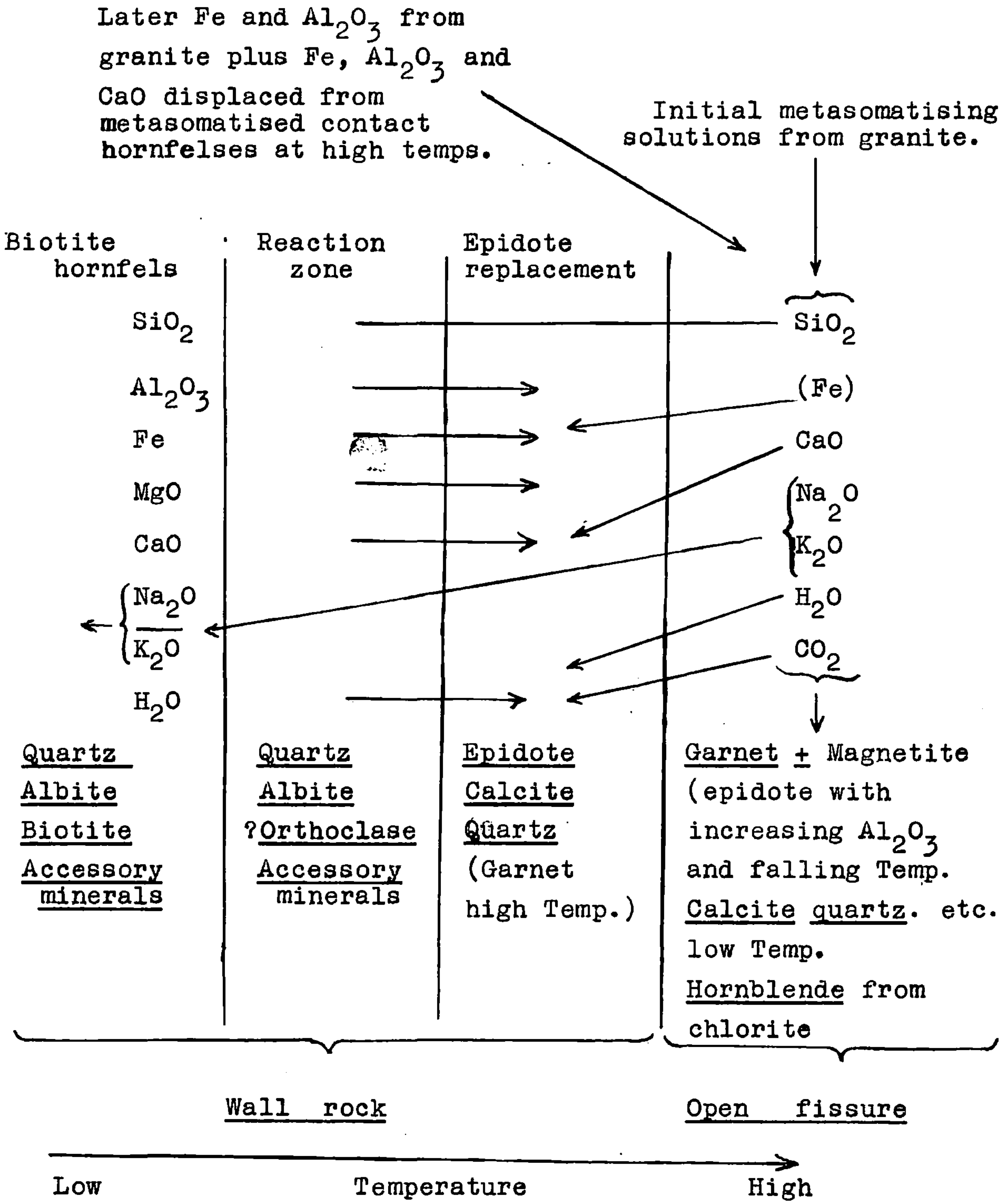
Evidence of epidote pseudomorphing garnet in a vesicle (R.F.149. p. 44.) has been described but usually garnet and epidote appear to be stable phases which have formed at the same time. The fissure solutions differ from solutions diffusing into the wall rock in that they are hotter and probably contain more ferric iron since the mobility of Fe. sharply diminishes with falling temperature (Korzhinsky 1950 A). More alumina is available in the wall rock than in the metasomatising solutions which suggests that in conditions of excess silica and lime, temperature and the Al:Fe ratio determine whether epidote or andradite is formed. The absence of the aluminous garnet-grossularite in the wall rock may indicate that the temperature gradient between the fissure and wall rock was quite steep.

Andradites have not been synthesised but their common occurrence in contact skarns suggests they are formed at high temperatures and as with grossularite (Yoder 1950) high hydrostatic pressure favours their formation but is not a necessity. Yoder (1950) has shown that grossularite is unstable above 750°C and probably breaks down to calcite, quartz and zoisite below 300°C. The absence of wollastonite from a system with excess lime and silica suggests temperatures below 570°C. Magnetite sometimes replaces garnet indicating again that andradite is unstable at high temperatures.

Andradite therefore probably began to form in solutions rich in iron at temperatures between 570°C and 300°C, whilst epidote formed in the wall rock below 300°C. In conditions of excess ferric iron and higher temperatures magnetite replaced garnet whereas with falling temperatures the haematite is formed and garnets may be partly replaced by haematite or chlorite. Epidote could form in the open fissures only with enrichment of solutions with alumina and falling temperature. A further fall in temperature led to the development of low temperature hydrothermal veins (p.127 and . 171.).

The probable geochemical changes leading to the formation of garnet bearing veins are summarised in the table overleaf.

Zoning in Garnets.- Two types of zoning have been described in garnets (p.123.) but the field relationships are uncertain. They may indicate change temperature conditions or concentration of iron - or both.



Schematic representation of the petrogenesis of a garnet bearing vein.

Specimen No.	Epidote	Clino Pyroxene	Hornblende	Quartz	Calcite	Magnetite	$\frac{Wx}{Wy}$	Remarks
R.F. 34	59.5	-	30.5	tr	10.0	-		Sphene Vein
R.F. 158	88.3	-	-	11.4	-	0.3	0.5	Apatite vein
R.F. 128	78.2	-	-	21.2	-	tr.	0.1	Epidote zone of garnet-bearing vein
R.F.205	-	tr	91.1	-	8.9	-	-	Vesicle Epidote in wall rock narrow reaction zone.

Table showing the variations in the mode of three epidote replacement bodies and a metamorphosed vesicle.

(d) Petrogenesis of the Pyrite Veins and associated metasomatism.

(i) Petrography.- White reaction zones in which biotite has been replaced by sericite occur adjacent to pyrite veins and other veins rich in pyrites. This metasomatism is best exhibited in the south end of the Blue quarry where biotite hornfelses, e.g. R.F.153 have been extensively metasomatised. Here leucocratic rocks extend up to a foot from the veins.

These pyrite veins are unlike the later pyrite associations in tension joints, and fault breccias, since they consist of coarsely crystalline aggregates of pyrites associated with epidote, calcite and some chalcopyrite, in veins which appear to have originated by replacement of the country rock. The veins are brecciated and fractures in the pyrite aggregates are filled with calcite. Pyrite is rarely well crystallised and occurs as a mosaic varying in grain size from 0.25 m.m. to 0.5 m.m. Under reflected light it is slightly anisotropic and it is noteworthy, in this respect, that pyritohedrons have occasionally been found. Veins up to one inch wide occur in the south end of Shap Blue quarry. They apparently follow no structural directions and their relationship with the garnet veins is uncertain. Epidote and quartz commonly occur at the margins of these veins, and sometimes the thinner veins (e.g. R.F.246) consist of a mosaic of quartz with hypidioblastic epidote and pyrite. Cubes of pyrite also occur in the ground mass of the metasomatised wall rock,but pyrite also occurs in irregular masses, associated with quartz and chlorite (R.F.219).

Cordierite spots are limited to the hornfelses near the pyrite veins and the field evidence suggests that the formation of cordierite is genetically connected with the pyrite veins. Furthermore, incipient cordierite is associated with sericite in all sections examined and cordierite has not been recorded from the non-sericitised biotite hornfelses. In the field it was observed that leucocratic rocks, adjacent to the pyrite veins, grade outwards into melanocratic rocks. Both contain cordierite spots but in the leucocratic rocks these are replaced by chlorite. Rock slices and polished specimens show that the only significant differences between the two types are that in the leucocratic rocks, cordierite is chloritised and the ~~magnetite~~ ilmenite granules in the ground mass are replaced by pyrite. The limit of fissure metasomatism was at first thought to be defined by the limit of leucocratic rocks but the presence of sericite in the melanocratic rocks suggests that all the cordieritic hornfelses are metasomatic. Alteration of the wall rock thus extends several feet from the pyrite veins.

The alteration of cordierite is interesting. R.F.192, a melanocratic spotted hornfels,shows incipient cordierite developed only in those parts of the rock which have been sericitised. The spots are roughly circular varying in diameter from 2 - 3 m.m.; sometimes a hexagonal cross section is seen and pseudo-hexagonal twinning is exhibited. Inclusions are numerous, but usually minute with iron ores the most prominant; other inclusions appear to have moderate to high birefringence. Some sericitic alteration has taken place. The outer zone is usually altered to a pale yellow green chloritic material. Sericitisation in this specimen is not intense, only the biotite having been partly replaced. Nearer the pyrite veins cordierite may be replaced completely by "Chlorophyllite" (R.F.246.) an outer zone of chlorite and an inner mosaic of quartz and sericite (R.F.249), or by chlorite with an inner zone of quartz and weakly pleochroic biotite. The chlorite is usually a very fine grained aggregate, varying in colour from pale yellow green to bright green usually showing moderate relief and weak anistropy. Chlorite, associated with pyrite, in R.F.219, shows straight extinction and moderate birefringence. Isotropic chlorite from R.F.246 has a refractive index of 1.60. The composition is uncertain but a magnesium chlorite is suggested and in recalculating the analysis the chlorite was first calculated as amesite. The iron ores are usually replaced by pyrite.

Primary minerals and textures are often obliterated

TABLE VIII

	Wt. %	Mol. %	Wt. Norm. (C.I.P.W.)		Niggli Values	
SiO_2	45.99	766	Quartz	10.20	si	232
TiO_2	1.20	15	Orthoclase	37.25	al	52
Al_2O_3	28.03	275	Albite	11.00	fm	25
Fe_2O_3	3.64	23	Anorthite	0.83	c	6
FeO	2.57	36	Corundum	19.79	alk	17
MgO	1.97	49	Hypersthene ($MgO.SiO_2$)	4.90	ti	6.6
CaO	1.72	30	Haematite	3.64	p	0.9
Na_2O	1.28	21	Ilmenite	0.30	k	0.76
K_2O	6.33	67	Pyrite	3.54	mg	0.36
H_2O+	4.44	247	Apatite	1.68	c/fm	0.25
H_2O-	0.74	-				
MnO	0.07	-	Sphene	2.55		
P_2O_5	0.68	5				
S	2.16	68				
	100.82					
-O=S	0.81					
	100.01					

R.F. 244. Metasomatised cordierite hornfels adjacent to pyrite vein. Shap Blue quarry.

with complete sericitisation of the ground mass, but phenocrysts may sometimes be distinguished. These are usually replaced by a mosaic of quartz, albite and some sericite. Adjacent to the pyrite veins ,the ground mass consists of a fine grained felted aggregate of sericite, quartz and pyrite, and the phenocrysts are completely replaced by sericite. In the melanocratic rocks the proportion of sericite appears to be less and possibly only the biotite has been replaced. Abundant magnetite granules occur.

(ii) Chemistry of Replacement.- An analysis of a typical leucocratic rock (R.F.244) is given in Table VIII p. 163. The most striking features are:-

(1) The high alumina figure emphasized by the Niggli value for al = 52 and by 19.79 corundum in the norm.

(2) The high water content (5.18%) suggesting that much of the sericite is hydrous mica (e.g. illite) with adsorbed water (H_2O^- = 0.74%).

(3) The high potash content and very high potash-total alkali ratio (Niggli value k = 0.76).

(4) Almost all the ferrous iron has combined with sulphur to form pyrite.

Compared with R.F. 153 (biotite hornfels) this suggests that the formation of pyrite veins was accompanied by the introduction of alumina, potash,and water into the wall rock and the subtraction of all available ferrous iron to form pyrite. These changes can be expressed more precisely by the Barth method (1948.B.)

In an attempt to obtain a more accurate idea of the modal composition of R.F.244 the analysis was recalculated allocating all the potash to sericite ($K_2O.3Al_2O_3 6SiO_2.2H_2O$) and all the magnesia to amesite ($4MgO.2Al_2O_3.2Si\ O_2.4H_2O$) giving 54.6% sericite and 6.9% amesite. However, there was still an excess of alumina. Probably most of the soda is combined with potash in sericite and it seems unlikely that albite occurs in the mode. The fine grained texture makes it impossible to verify this. However, two analyses of sericite by Th. Berggren (in Odman 1941.p.37) contain 2.27 Na_2O to 9.24 K_2O and 1.99 Na_2O to 9.00 K_2O (i.e. Niggli value k = 0.73 and 0.76 respectively). Therefore, in a sericitic rock with a Niggli value k = 0.76 it seems not unreasonable to assume that all soda is contained in sericite. Recalculating analysis R.F.244 on this basis we have 73.8% sericite and chlorite of the composition 46% antigorite [$Mg_6(OH)_8Si_4O_{10}$] and 54% amesite [$Mg_4Al_2(OH)_8Si_2Al_2O_{10}$] but according to Winchell the theoretical refractive index of chlorite of this composition is β = 1.575. The higher refractive index β = 1.60 for chlorite in the sericitic rocks suggests the presence of the ferroantigorite molecule [$Fe_6(OH)_8Si_4O_{10}$]. Dschang (1931) has shown that ferrous iron in chlorites is readily oxidised and that the refractive indices increase with the tenor of ferric iron. In the absence of more detailed chemical,optical and X-ray data, it is suggested that the chlorite is rumpfite or prochlorite (Whinchell 1951) in which almost all the iron has been oxidised. This partly explains the anomalous haematite in the norm of R.F.244. It is further suggested that in the absence of available ferrous iron the "biotite" partly replacing cordierite is actually ferri muscovite.

Recalculation of the analyses R.F.244 (Table VIII p.163) and R.F.153 (Table VIII p.140.) on the basis of 160.0-ions per standard cell (Barth.1948B)gave the following results:-

R.F.153:- Metamorphosed porphyritic andesite.

$$K_{5.0}Na_{6.1}Ca_{3.8}Mg_{2.9}Fe^{++}_{4.5}Fe^{+++}_{1.5}Al_{23.7}Ti_{0.9}Si_{48.4}P_{1.2}\left[O_{152.6}(OH)_{7.4}\right]160.$$

R.F.244: Sericite-chlorite leucocratic rock-
metasomatised andesite.

$$K_{7.3}Na_{2.3}Ca_{1.7}Mg_{2.6}Fe^{++}_{1.8}Fe^{+++}_{2.5}Al_{29.5}Ti_{0.8}Si_{41.3}P_{0.6}S_{3.7}\left[O_{133.5}H_{26.5}\right]_{160}$$

Thus the biotite hornfels R.F.153 passes into the sericite -chlorite rock R.F.244 by adding and subtracting the following:-

Adding.	Subtracting.
2.3 ions of K	3.8 ions of Na
1.0 ions of Fe^{+++}	2.1 ions of Ca
6.8 ions of Al	0.3 ions of Mg
3.7 ions of S	2.7 ions of Fe^{++}
19.1 ions of H	0.1 ions of Ti
	7.1 ions of Si
	0.6 ions of P
Total. 32.6 cations	16.6 cations
representing 49 valences.	representing 49 valences.

The Fe^{+++} ions added may well be due to oxidation of ferrous iron in chlorite replacing cordierite. Thus it appears that

K, Al and H ions with some S were introduced into the wall rock from fluids percolating along fissures Fe^{++} Ca and Si migrated outwards forming pyrite, calcite and quartz in the fissure and replaced wall rock.

Mg and Ti show little variation whilst the more mobile ions of Na may have migrated outwards into the country rocks, thus partly accounting for the high alkali content of R.F.153. P-ions possibly migrated into the country rocks although the amount involved may not be significant.

(iii) <u>The Nature of the Metasomatising Fluids.</u>- Graton (1940) in discussing the nature of ore forming fluids concludes that the material necessary for the formation of hypogene ores were transported by alkaline aqueous solutions. Bowen (1933) and Fenner (1933) regarded ore forming fluids as primarily gaseous and acid. Schmedeman (1938) concludes that "sericite as a mineral is not indicative of either acid or alkaline attack, but probably forms (when potash is added) only from alkaline or weakly acid solutions." "Experimental investigations by Noll (1936) showed that sericite is formed from potash-bearing alkaline solutions. Gruner (1944) further demonstrated experimentally that sericite may form readily from soda felspars, at temperatures above $350^{\circ}C$, when the concentration of K-ions and the ratio $\frac{\text{Al-ions}}{\text{Si-ions}}$ are both high. Gruner further suggests that "the alteration of individual felspar crystals to sericite is in the nature of leaching of SiO_2 and the simultaneous addition of Al_2O_3 and K_2O".

In the present case, it has been demonstrated that K,Al and H-ions are added and principally Fe^{++} and Si-ions subtracted from the sericitised rocks. Alumina and sulphides are best transported in acid solutions.

Alumina and potash may in part be derived from the wall rock replaced by pyrite, but this would not account for the widespread sericitation. Similarly it is thought that all ferrous iron was derived from the metasomatised wall rock. The possibility that metasomatising fluids contained Si,Ca and Fe cannot be precluded but seems unlikely in view of extent of wall rock alteration.

The metasomatising fluids are, therefore, considered to be acid aqueous solutions containing potash, alumina, sulphur and carbon dioxide. The sulphur may have been transported either as H_2S or SO_2. Grüner's (1944) evidence suggests a temperature of at least 350°C. A gas phase is not favoured owing to the difficulty of transporting alumina but later gaseous introduction of carbon dioxide and hydrogen sulphide or sulphur dioxide is possible.

Whilst a magmatic source for sulphur, potash and carbon dioxide is favoured, the source of alumina is uncertain. Alumina-silicates are uncommon in the low temperature hydrothermal minerals, nacrite, chlorites, and laumontites being the only recorded examples. Furthermore, it has been demonstrated that at higher temperatures, as in the formation of garnet bearing veins, alumina behaves as an "inert" or relatively mobile component. Evidence has been given of a general increase in alumina content towards the margin of the thermal aureole (p. 84), and an outward migration of alumina associated with potash metasomatism and silicification nearer the granite contact. Possibly alumina was partly derived from hornfelses nearer the granite.

The precipitation of pyrites from an acid solution presents no special problems particularly in the presence of excess sulphur in the form of H_2S. The complete wall rock replacement is less easily explained, but is probably due to a concentration of Fe -ions displaced from sericitised biotite, ilmenite and magnetite combined with S - ions diffusing into the country rock. The absence of pyrrhotite suggests a temperature below 575°C. This would agree with Gruner's data (1944) for the formation of sericite. The common occurrence of pyrite and sericite may thus be explained as above.

(iv). Summary.- The stages in the petrogenesis of the pyrite veins and associated metasomatism may be summarised as follows:-

(1) Introduction along fissures of weakly acid aqueous solutions of alumina, potash, carbon dioxide and sulphur. Temperature probably about 550° C or lower under high hydrostatic pressure.

(2) Diffusion of watery solutions alumina and potash into the wall rock and the consequent replacement of biotite by sericite and the formation of incipient cordierite from the displaced magnesia.

(3) Replacement nearer the fissures in higher temperature conditions of ~~magnetite~~ ilmenite by pyrite and the alkali felspars by sericite.

(4) Replacement of cordierite by chlorite (rumpfite or prochlorite) associated with the more intense sericitisation. Probably cordierite is metastable in these conditions and breaks down to chlorite with the removal of alumina for sericite.

(5) Simultaneously with reactions (2) (3) and (4) Si, Ca and Fe, diffused towards the fissures to form quartz, calcite and pyrite in the pyrite veins.

VII. LOW TEMPERATURE HYDROTHERMAL MINERALISATION.

(a) Introduction.

Shand (1944) in reviewing the literature of the late magmatic and post-magmatic processes advocated dividing post magmatic changes into:-

(1) Deuteric or high temperature hydrothermal stage.
(2) Low temperature hydrothermal stage.

However, the division between the two stages is not clearly marked. According to Shand (1944) the deuteric stage is characterised by the replacement of silicates in the solid rock by hydroxyl-bearing minerals, whilst the low temperature hydrothermal stage is characterised by carbonates or scaly, fibrous, or colloform minerals containing abundant water.

At Shap, hydrothermal mineralisation includes the development of metasomatic replacement bodies and of mineral veins in deformation structures caused by the emplacement of the Shap granite. The former are characterised by the development of epidote in the wall rock, whilst the latter may contain hydrous minerals such as laumontite or nacrite. Therefore a classification similar to Shand's has been adopted.

(1) High temperature hydrothermal mineralisation in which wall rock replacement has taken place.
(2) Low temperature mineralisation in which no wall rock alteration has occurred.

The pyrite veins formed by replacement of the country rocks (p.160-170) are thus included in the high temperature stage, whilst late stage veining of the garnet bearing veins is considered to be part of the low temperature mineralisation. Furthermore, this classification is partly structural since high temperature hydrothermal mineralisation is restricted to pre-granite fractures. In the absence of reliable "geological thermometers" the actual temperature difference between high and low temperature mineralisation cannot be accurately estimated but the evidence (p.150.) suggests that epidote replacement was caused by solution above 400°C.

Low temperature mineralisation at Shap can be sub-divided on a structural basis. A study of the tectonics in Shap Blue Quarry has revealed the presence of fault breccias (p. 93) and shear joints developed during the latter stages of the emplacement of the granite. Minerals coating some joints are often slickensided and may be designated to the pre-shearing period. Minerals filling tension joints, which presumably originated during the period of relief of pressure, may be further sub-divided by considering transecting veins.

The following tentative-time sequence has been adopted.-

(1) Pre-shearing period - chlorite, nacrite, haematite and pyrite.

(2) Post-shearing period.
  (i) Haematite and goethite.
  (ii) Pyrite, marcasite, chalcopyrite, malachite galena, (erythrite) (sphalerite)

(iii) Pectolite and laumontite.
(iv) Barite, psilomelane(?)

Quartz and/or calcite occur as gangue minerals at almost any stage whilst barytes may be associated with galena. Fluorite, molybdenite and bismuthinite, all of which commonly occur in the veins in the granite, have not been recorded from the Blue Quarry but a molybdenite-quartz vein outcrops west of the granite.

(b) Pre-shearing period.

Chlorite, nacrite and some haematite and pyrite are the principal minerals associated with this stage.

Chlorite.- The composition of slickensided chlorites on shear joints and in fault breccias has not been determined. Possibly this chlorite has a similar origin to chlorite in the granite (p. 40) but some chlorite may also have developed from sheared andesites, particularly in sheared fault breccias.

Nacrite.- $Al_4(OH)_8 Si_4 O_{10}$.- Nacrite was identified by X-rays and is the subject of a separate paper (Firman 1953). X-ray data are given on p. [illegible] and compared with those obtained by Gruner (1933) and Hendricks (1939). The optics likewise agree with the data given in the literature, viz. $\alpha = 1.559$ $\gamma = 1.567$; birefringence 0.008 ($\pm$ 0.002).

Nacrite appeared to be confined to microcrystalline crystalline aggregates coating shear joints in fault breccias where it is associated with chlorite, haematite, pyrite and traces of erythrite and often with later quartz, calcite and barytes veins.

A typical locality is shown in Fig. 34.It is recognised in the field by its colour, varying from pale apple green to white with a sub nacreous lustre, softness (1.5) and greasy feel. The variations in colour are possibly due to chlorite impurities since the colour is removed by warm diluted HCl. Impurity lines were found on some films at 10.3 4.81 and 3.28 Kx but have not been identified.

Ross and Kerr (1931) suggested a pneumatolytic or hydrothermal origin for nacrite from Saxony and Colorado, whilst nacrite occurring in sphaerosiderites in the Kladno Coal Measures and Ordovician slates in Bohemia is thought to be hydrothermal (Kasper 1933 Ulrich,1935). The present occurrence most closely resembles that at Groby, Leicestershire (Claringbull 1952) where fine grained aggregates of nacrite occur in belts of shearing in syenite. The Shap mineral is clearly associated with hydrothermal effects of the Shap granite but is confined to the pre-shearing period.

Haematite Fe_2O_3.- Much of the haematite in fault breccias shows horizontal slickensides. Both earthy and crystalline varieties occur but no specular haematite has been recorded although it is common in the garnet bearing veins. This haematite may be associated with haematite and pyrite occurring in veins in the Shap granite.

Pyrite $Fe\ S_2$.- Some of the pyrite in fault breccias is slickensided but most of the pyrite belongs to the post-shearing period.

(b) Post-shearing period.

(i) Haematite Fe_2O_3 and Goethite $H\ FeO_2$.- Massive haematite associated with goethite and, where deeply weathered, limonite is found in many fault breccias and shatter belts. Goethite is also found associated with metaliferous sulphides in tension joints and latter veins.

(ii) Metaliferous sulphides.- Pyrite is the commonest of the sulphides and appears to have formed under a variety of conditions.

Marcasite $Fe\ S_2$.- Marcasite, shewing concretionary structures, has been recorded only from the garnet bearing veins. Experiments by Allen and others (1912) suggest that marcasite can only be formed from acid solutions; Above 450°C it inverts to pyrite. Temperatures of c.200°C seem to be the optimum for its formation.

Chalcopyrite $CuFe\ S_2$.- Traces of Chalcopyrite are associated with pyrite in the high temperature pyrite veins. It is of more common occurrence in fault breccias but nevertheless comparatively rare. Often it is associated with malachite.

Covellite $Cu\ S$.- Covelitte is a common alteration product of chalcopyrite detected only in polished sections.

Malachite $Cu_2CO_3(OH)_2$.- Traces of malachite are found in all fault breccias and occasionally well crystallised acicular varieties occur. It is thought to be a secondary mineral developed from chalcopyrite.

Galena PbS.- Galena normally occurs in tension joints and is often associated with pyrite, chalcopyrite and malachite, and occasionally with barytes. Veins of galena have been found cutting garnet bearing veins and the only galena found in these latter veins (R.F.194) is demonstratably later than the formation of garnet.

No evidence for pre-granite metalliferous mineral veins has been found (Marr 1916. p.33) and their occurrence seems very improbable. Specimens exhibited by Marr (1902), to the Geological Society were almost certainly garnet bearing veins with late stage veins containing galena, pyrite and chalcopyrite.

Sphalerite ZnS.- Only one record of sphalerite from the Blue quarry is known but Grantham (1928) noted sphalerite associated with galena in veins in the Shap-granite quarry. Sphalerite was detected in a specimen of galena encrusting garnet (R.F.194 presented by W.F.Davidson). Thin and polished sections show that sphalerite and galena fill fractures in the garnets. Examination under reflected light revealed anomalous properties. Internal reflections are weak, the typical ruby red colour is seen only at the crystal edges. Reflectivity is higher than is usual and a weak anistropy and occasional polysynthetic twinning is characteristic. Possibly this is a ferriferous variety. Minute yellow inclusions were not identified.

Erythrite $Co_3As_2O_8.8H_2O$.- Traces of erythrite have been found associated with nacrite but cobalt arsenides or sulphides have not been identified.

(iii). Pectolite and Laumontite.- Pectolite and laumontite are demonstratably later minerals than the metalliferous sulphides, and probably earlier in formation than the barite veins. They do not occur together, but no time relationship between them has been proved.

Pectolite $HNaCaSi_3O_9$.- Pectolite is often associated with calcite and is common along tension joints. Pinkish varieties occur, but the usual colour is a creamy white; a radiating habit is usual but discrete spherules resembling wavellite occasionally occur.

Laumontite* $\left\{\begin{array}{l} nCa_7\ Si_{26}Al_{14}O_{80}.25\ H_2O \\ nNa_2\ Ca_5\ Si_{28}Al_{12}\ O_{80}.25\ H_2O \end{array}\right.$.- The optical properties and X-ray powder data for Shap laumontite are given on p. 179 The salmon colour is characteristic and may be due to ferric iron replacing aluminium or to inclusions of minute particles of haematite. Laumontite is occasionally associated with slickensided chlorite in shear joints which have later been opened tensionally. It has also been recorded from a garnet bearing vein. Usually it occurs in coating tension joints.

(iv) Barite veins.- These veins transgress all others and

* X-ray data seen after this was written suggests partially dehydrated laumontite (Coombs Am. Min 1952)

have been found well outside the aureole, in Sherry Gill and near Tod Crags. Calcite is usually associated with barite in veins in shatter belts, fault breccias and master joints. Traces of psilomelane also occur.

Barite $Ba\ SO_4$,- Like the barite in the granite the dominant habit is the cockscomb variety. The pink colour is chacteristic of all barite associated with the granite.

LAUMONTITE.

Crystal System.- Monclinic   Form.-radiating

Colour.- Red or Pink   Lustre.- Vitreous, translucent.

Hardness 3.5 - 4   Cleavage.- perfect cleavages // c axis

Optical Properties.- Biaxial $-^{ve}$ Elongation $+^{ve}$

γ to c 35^{o} $\alpha = 1.512$ $\beta = 1.518$ $\gamma = 1.521$ ($\pm .002$)

Birefringence 0.009

X-ray powder data, camera 9cm. ~~radius~~ diameter CuK_{α} radiation

Shap d_{obs}	l	A S.T.M. d_{obs}	l	Shap d_{obs}	l	A.S.T.M. d_{obs}	l
10.02	vs	10	100	2.086	w	2.08	20
9.19	vs	9	100	1.984	w	1.99	20
7.24	m	7.2	60	1.945	w	1.95	40
6.45	m	6.6	60	1.863	mbr	1.87	40br
6.10	w	-		1.767	vvw	1.76	20
5.14	vw	5.0	20	1.702	vvw	1.70	20
4.51	w	4.6	40	1.624	mbr	1.62	60
4.26	s	4.29	70	1.588	vvw	1.59	20
4.09	s	4.07	80	-	-	1.57	20
3.74	w	-		1.492	mbr	1.52	40
3.58	s	3.56	80	1.481	w	1.49	20
3.45	s	3.40	60	1.436	mbr	-	
3.32	w	-		1.340	wbr	-	
3.21	w	3.24	60	1.265	w	-	
3.10	m	3.13	40	1.259	wbr	-	
2.99	m	3.02	40	1.227	w	-	
2.92	vw	-		1.215	wvbr	-	
2.84	w	2.85	60	1.129	wvbr	-	
2.76	vw	2.79	40	1.086	vw	-	
2.62	w	-		1.042	wbr	-	
2.55	w	2.59	40				
2.44	m	2.43	60				
2.377	vw	2.36	40				
2.318	vw	2.26	20				
2,143	mbr	2.17	60br				

Order of decreasing intensities: vs, s, m, w, vw, vvw,
br = broad
$\lambda = 1.5374$

	Shap			Hendricks(1938)		Gruner (1933)	
obs	d	d	d	I	d	I	d
s	7.12	7.07	7.15	100	7.38	100	7.08
vw	4.81	5.12	-	50	4.98	10	4.90
vs	4.35	4.40	4.42	90	4.53	80	4.40
m	4.10	4.15	4.06	70	4.12	30	4.13
-	-	-	-	-	-	20	3.93
s	3.58	3.50	3.58	100	3.63	90	3.58
w	3.38	3.34	3.36	50	3.13	br 10	3.44*
vw	3.26	3.19	-	-	-	-	-
s	3.06	3.000	3.06	-	-	br 10	3.04
vw	-	2.82?	-	20	2.71	10	2.69
m	2.52	2.57	2.58	50	2.56	br 10	2.54
s	2.410	2.415	2.413	100	2.43	100	2.42
	-	-	-	-	-	10-20	2.39
-	-	-	-	20	2.31	10	2.32*
w	2.242	2.257	2.293	-	-	br 5-10	2.26
wm	2.100	2.080	2.128	20	2.13	vbr 10	2.07
br	-	2.009	1.907	-	-	-	-
vw	1.958	1.896	1.862	60	1.93	20-30	1.90
-	-	-	-	50	1.80	10	1.80
vw	-	1.723	-	-	-	br 5-10	1.74
br	1.697	1.695	1.676	50	1.67	br 20	1.68
-	-	-	-	50	1.62	-	-
-	-	-	-	20	1.55	10	1.58
	1.491	1.491	1.484	90	1.50	80	1.49
s	1.480						
vw	1.458	1.458	1.451	60	1.46	br 40	1.46
-	-	-	-	50	1.43	5-10	1.43
vw	1.372	1.376	1.375	50	1.37	vbr 10-20	1.36
br	-	-	1.330	20	1.29	5	1.31*
vw	1.275	1.287	-	60	1.27	10	1.28
wm	1.263	1.264	1.263	-	-	30	1.26
vw	1.240	2.229	1.151	50	1.24	vbr 20	1.23
vw			1.040				
			0.961				
vw			0.894				
vw			0.859				

* = Dickite lines

X-ray powder data for nacrite
Diameter of camera = 9 c.m. CuK_α radiation (λ = 1.5374 kX)
Order of decreasing intensities vs, s, m, wm, w, vw, vvw
br = broad.

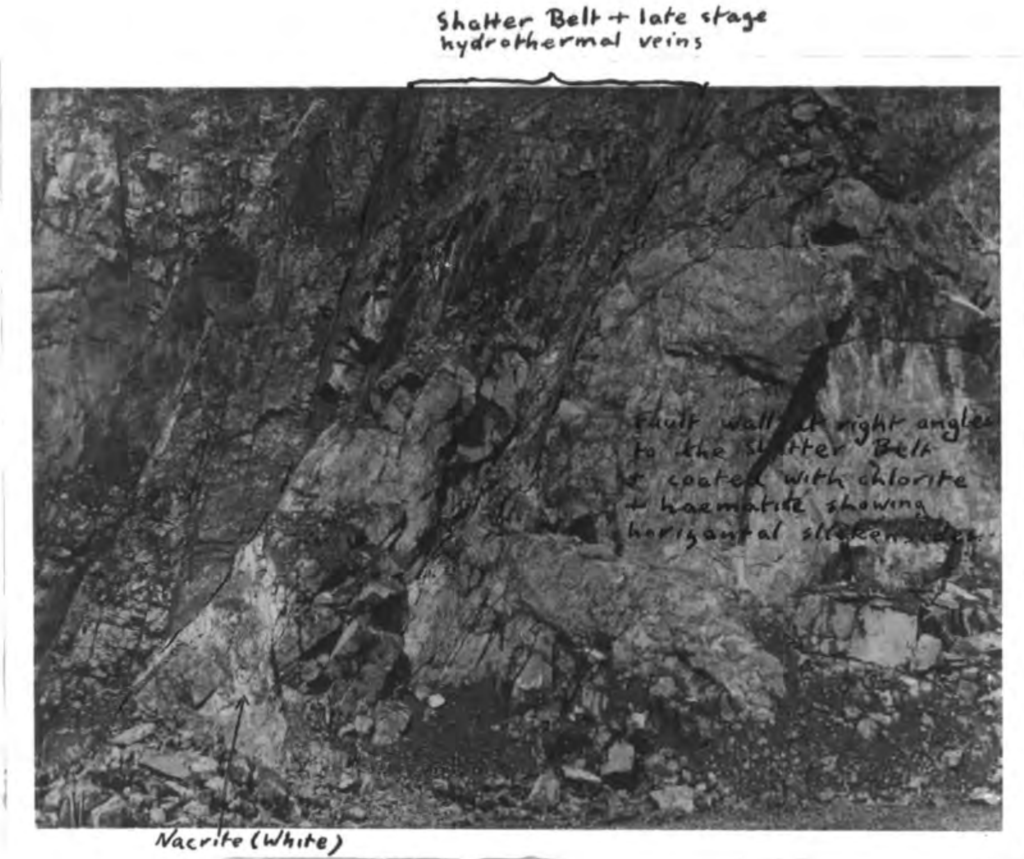


Fig. 34. Nacrite locality Shap Blue quarry showing the shatter belt. (Photographer W. F. Davidson)

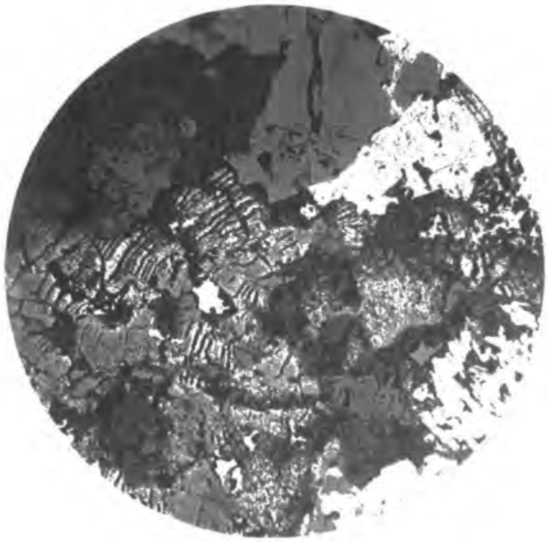


Fig. 35. Marcasite showing spheroidal structure with associated magnetite and pyrite

VIII SUMMARY AND CONCLUSIONS.

A study of the rocks around the Shap granite has shown that metasomatism was important, particularly in the Wrengill andesites, which, owing to their high water and CO_2 content, are considered to be most susceptible to such changes. Alteration of the country rocks was caused by fluids percolating or diffusing through the aureole as a whole. Solutions migrating along joints or other open fissures caused characteristic more localised alteration in the wall rocks.

This metasomatism is consistent with the introduction of high and low temperature fluids derived from a cooling granite magma although some material may have been introduced early in the history of emplacement. No evidence of pre-granite metalliferous mineral veins has been found and all low temperature hydrothermal minerals are thought to be associated with the Shap granite. The intrusion is post-tectonic and caused deformation of the country rocks. Compressional structures such as faults, shatter belts and shear joints transect replacements caused by fissure metasomatism but appear to be similar to the faulting caused by the "long range effects" of an intrusion (Balk 1937). They may be due to the invasion of Stage II granite, but since this precludes any fissure metasomatism connected with the granite stage, it is more likely that the compressional structures were formed during the final phases of crystallisation of the main granite mass. Relief of pressure with solidification and further cooling resulted in tension joints which are similarly filled with hydrothermal minerals.

An attempted correlation between the tectonics and petrogenesis of the granite and surrounding rocks is shown in the table overleaf. Insufficient geochemical data is, as yet, available to relate phases in bulk metasomatism with the individual granite stages.

SHAP GRANITE	COUNTRY ROCKS	TECTONICS
Petrogenesis of the Shap Granite	Metamorphism, metasomatism and Mineralisation	Pre Bala earth-movements. Folding on N.N.E.-S.S.W. axes.
		Caledonian orogenesis
Generation of Shap granite magma at depth	Low grade regional metamorphism leading to chloritisation, epidotisation, sericitisation.	(1) Folding on E.N.E.-W.S.W. axes. (2) Faulting (3) Development of cleavage (4) Relief of pressure and development of joint system in B.V.s
	Thermal Metamorphism and Mineralisation	Tectonics associated with the emplacement
Emplacement of Granite stages	Thermal metamorphism and metasomatism Early Na metasomatism possibly connected Stage I granite	Movements caused by the emplacement of the granite stages.
High temperature Hydrothermal Stage		
Pneumatolysis kaolinisation and deposition of molybdenite	(1) Bulk metasomatism principally effected by the introduction of Si with Na and K and the outward migration of Al. with Ca.	(1) Pushing aside the country rocks
	(2) Fissure metasomatism (i) Introduction of Si Ca and Fe with CO_2 and H_2O - the garnet bearing veins. (ii) Introduction of S.K. and Al - pyrite veins (iii) Magnetite in garnet bearing veins.	(2) Opening fissures in the pre-granite joint system

Low temperature hydrothermal stage

	(1) Minerals of the pre-shearing period - chlorite nacrite, haematite and pyrite	(3) Development of compressional structures towards the end of the high temp. stage - Shatter belts, faults shear joints etc. Several movements
	(2) Minerals of the post shearing period	(4) Relief of pressure leading to the formation of a tensional joint system. Possibly due to shrinkage of the granite when solidified.
(i) Some early haematite	(i) Haematite and goethite	
(ii) Metallic sulphides	(ii) Metallic sulphides Molybdenite and bismuthinite not found in blue quarry	
(iii) Quartz calcite fluorite haematite chlorite	(iii) Fluorite not found in Blue quarry. Much of haematite and chlorite earlier - some late.	
(iv)	(iv) Pectolite and Lanmontite	
(v) Barite	(v) Barite.	

PART II. METAMORPHISM AND METASOMATISM AROUND THE ESKDALE GRANITE.

Contents.

1. INTRODUCTION.

(a) Historical.

The Eskdale Granite and surrounding rocks were first described by J.G.Marshall in 1858 who regarded the granite as originating from the metamorphism at depth of the Borrowdale lavas and ashes. This theory was supported by J.C. Ward who, in a paper of 1875, outlined five stages in the progressive metamorphism of volcanic ashes into granite.

1. Felstone-like (and streaky) altered ash.
2. Felstone-like with purplish hue.
3. Purplish base with imperfect crystals porphyritically embedded.
4. Bastard granite.
5. Granite.

These opinions undoubtedly influenced the Officers of the Geological Survey who,under Ward's direction, mapped the area. Thus, apart from dykes and the crystalline centres of thick lava flows mapped as "traps", and thought to be intrusive, most of the ground immediately east of the granite was mapped "altered ash and lava". However, the general structure and tectonics of the area were well understood, dips being accurately recorded, and the major faults inserted.

The first detailed petrographic account of the Eskdale Granite was given by A.R.Dwerryhouse (1909) although the common rock type had been previously described by Teall (1888). Both Dwerryhouse and Simpson (1934) regarded the intrusion as a laccolith. Officers of the Geological Survey (1937) favoured a stock like form. Neither Simpson nor Dwerryhouse gave any description of the metamporhpic aureole although Dwerryhouse (1909) and Walker (1904) described isolated contact specimens and Simpson (1934) indicated the character of the surrounding rocks on his sketch map. Marr (1916) briefly noted the similarity of rocks in the Eskdale aureole to those previously described at Shap (Harker & Marr 1891) and had tentatively assumed a similar age and origin.

However, until the re-mapping of the Gosforth Sheet 37 by the Officers of the Goelogical Survey, no detailed description of any part of the aureole had been attempted. Only a small part of the aureole falls within Sheet 37; exposures are poor and disoontinuous and the influence of the Ennerdale Granophyre is uncertain.

Investigation of the stratigraphy of the Borrowdale Volcanic Series, begun principally by J.E. Marr, and J.F.N. Green in the 1900's and extended later in detail by G.H.Mitchell and J.J.Hartley, has elucidated the stratigraphy structure and tectonics of the B.V.S. outcropping from Shap to the Coniston Wrynose area. Until the author's and R.L. Oliver's unpublished mapping was begun no detailed investigation had been carried out of the Borrowdale Volcanis Series immediately east of the Eskdale granite.

(b) Objects of the Present Research.

The primary object of the present research was to carry out a field and petrographic survey of the Northern and North Eastern part of the Eskdale Granite aureole. It was also found desirable to extend the detailed mapping Eastward and North Eastward in order to:-

(1) examine unmetamorphosed representatives of the Borrowdale Volcanic Series equivalent to hornfelses within the aureole.

(2) elucidate the structure and stratigraphy of the area.

(3) examine mineral veins and mineralised rocks apparently genetically related to the Eskdale Granite.

(4) link up with the areas mapped by J.J.Hartley and R.L.Oliver.

Owing to lack of time it was decided to defer until a later date the mapping of the Southern part of the aureole and the geochemical investigations..

(c) Area mapped.

All mapping was carried out on the six inch scale. The granite contact was accurately mapped being followed from Wastwater to Devoke Water. Detailed mapping of the ground East of this contact was carried out and in addition Harter Fell, Hard Knotts and Border End were mapped. Apart from the haematite veins little attention was paid to the granite itself.

II BORROWDALE VOLCANIC SERIES.

(a) Stratigraphy and Field Characters.

(i) Introduction.- J.C.Ward mapped most of the rocks in the area as altered ash with some lava. Recent investigation has shown that the ground is predominantly occupied by massive porphyritic intermediate lavas and subordinate bedded tuffs. Individual flows may be distinguished by the character and abundance of phenocrysts, flow brecciation, and type of weathering among other features. Apart from the acidic flows, the bedded tuffs form the most easily mapped horizons. Furthermore these tuff bands are more persistent over a wider area than most lava flows.

(ii) Field Character of Lavas.- Porphyritic andesites occupy most of the aureole and much of the ground east of Upper Eskdale to Mosedale where they appear to be continuous with Hartley's Mosedale Andesites. Individual flow can be mapped with difficulty only where exposures are good or where diagnostic flows occur. On Harter Fell and Border End a series of escarpments represent individual lava flows, the top and base of which are often marked by flow brecciation or vesicularity. Here most flows are estimated to be between 50 and 100 feet thick. Rarity of flow brecciation and vesicular lavas suggests that most flows in the area are fairly thick.

The most characteristic types are those with abundant small stout felspar phenocrysts 2-3m.m. long and subordinate ferro-magnesian phenocrysts set in a bluish or greenish ground mass. Garnets are of rather sporadic occurrence and have been found in both acid and basic lavas and tuffs.

Epidotisation is a common feature of lavas outside the limit of scaly biotite and felspars are often replaced by grass green epidote; often much more of the ground mass is epidotised. Pink reaction rings around vesicles and altered phenocrysts are reminéscent of those in the Shap Blue quarry. Ferro-magnesian phenocrysts are usually replaced by chlorite or hornblende.

Darker more flinty andesites with fresher phenocrysts, well exhibited on Harter Fell, probably represents the massive centres of the andesite flows. Alteration of the felspar phenocrysts to pink alkali felspar is also common.

Flinty rocks, with leucocratic weathering sometimes provide easily mapped horizons, and are undoubtedly distinct lava flows, probably dacites, but silicification of basic lavas, presumably by percolating solutions, is common, good examples being seen North of Yew Crags. Silicified andesites within the aureole may have a similar origin.

A rhyolite flow some 150 feet thick has been mapped westward from Great Whinscales. Here it forms a marked feature and consists of an aphanitic grey rock flow banded at the base and nodular toward the top.

(iii) Bedded Tuffs.- Bedded tuffs vary greatly in lithology and grade. Some tuffs such as those mapped on Harter Fell change laterally, in this case becoming coarse and less well bedded eastward. Nevertheless bedded tuffs form the best datum lines in the field and can be followed over greater distances than lavas. The interpretation of the structure of the Eskdale district rests largely on the mapping of these tuffs.

Fine grained tuffs outcrop at the top of Hardknott Pass and on Harter Fell. Here they are pale blue in colour and finely laminated. Patches of grass-green epidote often occur. The coarser tuffs often show well developed graded bedding but current bedding has not been recorded.

(iv) Correlation.- Owing to the lenticular nature of the beds correlation with other areas is uncertain. Hartley's description of the aphanitic Mosedale Andesites makes it clear that the lowest andesites in the Great and Little Langdale area are dissimilar to the porphyritic andesites west of Hardknott Pass. However both groups are overlain by Bedded Tuffs and mapping the ground from Hardknott to Mosedale suggests that they are contemporaneous and possibly interdigitated. It is therefore tentatively suggested here that the porphyritic lavas outcropping in this area are contemporaneous with J.J.Hartley's Mosedale Andesites and that they originated from two different eruptive centres.

To the west of the granite Survey Officers mapped a series of lavas lying above the Mottled Tuffs which consisted of the following succession.

Andesitic and rhyolitic lavas (undivided).
Rhyolites with subordinate andesites and thin bands of tuff.
Andesites with subordinate tuff bands.
Mottled tuffs.

This succession differs from that east of the granite largely by the greater abundance of acidic lava flows. Thus in general the lower andesites West and North West of the Eskdale granite are thought to be contemporaneous with Hartley's Mosedale Andesites and lavas above the Mottled Tuffs mapped by the Survey on Sheet 37.

A small patch of highly cleaved micaceous hornfels outcrops adjacent to the greisen on Water Crag, Devoke Water. This was mapped by the Survey as Skiddaw Slate. It is directly overlain by hornfelsed porphyritic andesites. If this is metamorphosed Skiddaw Slate then it would appear that the porphyritic andesites of Eskdale are at the base of the B.V.S. succession. However correlation with other areas must await the completion of mapping south of this area.

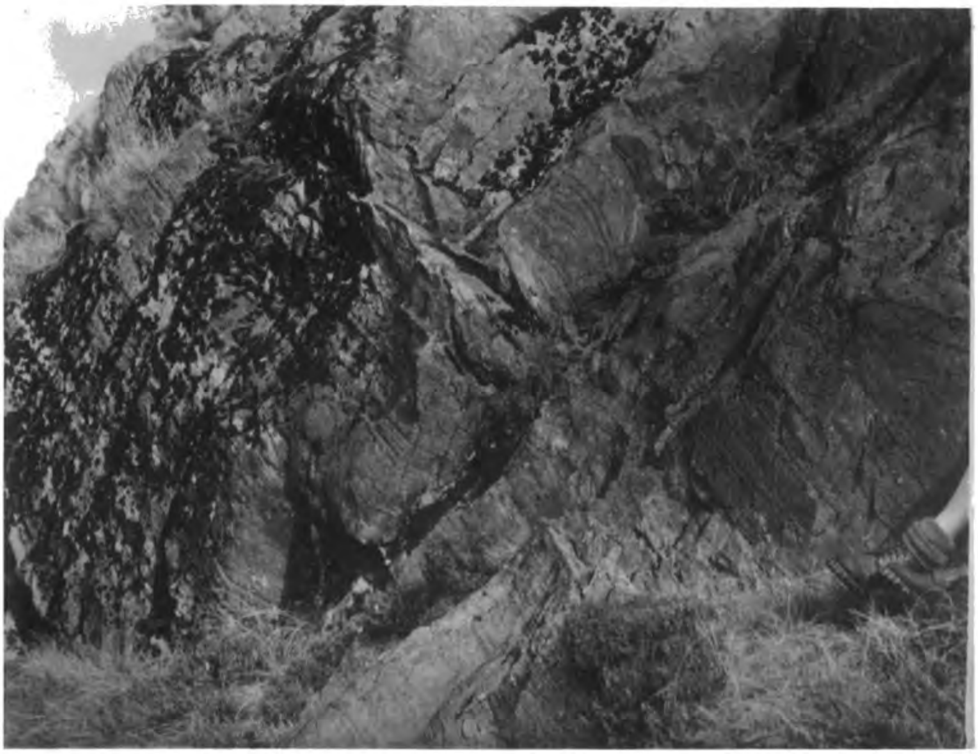


Fig. 2. Bedded tuffs. Harter Fell, Eskdale.

(b) Petrography.

A petrographic study of the lavas from this area has shown a wide variation in character and secondary alteration. The dominant type is porphyritic with abundant stout plagioclase phenocrysts, about 2-3m.m. long, usually occurring singly but showing a tendency, in some specimens, for smaller phenocrysts to occur in glomero-porphyritic aggregates. Pyroxene phenocrysts are usually absent and when present are represented by chloritic aggregates. Alteration of the felspar phenocrysts makes accurate determination of their composition difficult but measurements of extinction angles by the maximum symmetrical extinction angle and Carlsbad-albite twin methods have shown a variation from An_{35} to An_{60}. Most felspar phenocrysts were found to be of andesine composition (An_{40} to An_{45}). Zoning is a marked feature in all phenocrysts, the outermost zone being more albitic in composition and less frequently altered.

Pyroxene andesites outcrop on Harter Fell and on Southern shore of Devoke Water (Survey collection E 16944). In both these cases pyroxene phenocrysts are replaced by a pale green hornblende, pleochroic in yellow-green and bluish-green. Elsewhere pyroxene phenocrysts are represented by chloritic fibrous aggregates and magnetite granules.

More acidic lavas probably approaching dacites in composition have been mapped in the field by their flinty siliceous character and paler colour. Microscopic examination has confirmed the field deductions. One very porphyritic flow North of Slight Side has albite phenocrysts; other acidic flows near Hardknott Castle have more basic phenocrysts.

The ground mass is normally fine grained with an intersertal texture but varies greatly in grain size. Secondary alteration particularly in the fine grained types often obscures the original texture. Maximum symmetrical extinction angle measurements of the ground mass felspars shows that the composition varies from An_{15}-An_{35} but in most cases sericitisation makes accurate determinations impossible. Interstial pyroxenes have been replaced by chlorite and iron ores. Ilmenite is the most abundant accessory mineral whilst apatite and magnetite often occur.

Vesicular and flow brecciated lavas are rare. Among the minerals which have been recorded filling amygdales are chlorite, epidote, hornblende, quartz, chalcedony, calcite and iron-ores. Often zoning of minerals filling the amygdales is seen (e.g.R.J.114) a typical zonation being an outer rim of iron ores, epidote, calcite with a mosaic of quartz or chalcedony in the centre.

Garnetiferous lavas have been found in the field but have not been traced over a wide area. It would appear that only certain parts of flows contain garnets. The chief localities are:- Illgill Heads, Raven Crag, Slight Side, Yew Crags, Hardknott Gill, south of the Great Whinscales and near Tarn Crag (Birker). All these garnetiferous rocks are very porphyritic flows with felspar phenocrysts ranging in composition from An_{50} to An_{55}, The garnets are rounded and usually altered along cracks to a yellow mineral of low relief. No evidence of the genesis of the garnets was found. The apparent displacement of the ground mass and phenocrysts around the garnets may be interpreted either by the porphyroblastic growth of the garnets or due to flow structures in the lava enclosing early formed garnets.

Secondary alteration is a common feature but the lavas are far less altered than those in the Shap area. The rocks have not been cleaved or sheared, consequently cataclastic effects and chloritisation are not marked features. Epidotisation is marked particularly in the Border End and Harter Fell areas. In hand specimen grass green epidote is seen replacing felspar phenocrysts and developing in irregular patches in the ground mass. Microscopic examination shows that granular epidote is often developed in the ground mass with associated calcite and secondary felspar and that replacement of the felspar phenocrysts is rarely complete. Replacement usually takes place at the centre of the crystal and the albitic zone, where present, is rarely altered. The epidote is usually brownish and non pleochroic, with moderate birefringence. Idiomorphic crystals are rarely developed. Epidote also occurs occasionally in veinlets (R.J.69 B) and here appears to have a different genesis. It is pale green, non pleochroic and has a comparatively low birefringence (estimate from Michel Levy Chart 0.027).

Epidotisation is the most widespread secondary alteration and whilst it appears to be unconnected with the thermal effects of the Eskdale granite, the most intensively epidotised andesites outcrop in a zone immediately east of the biotite hornfelses. Possibly this epidotisation in this area is due to lime metasomatism (see pp.56-60).

Near Kepple Crags and on Harter Fell secondary albite is often developed as well as epidote. This felspar is normally pink and the rocks in hand specimen are characteristically mottled green and pink. Microscopic examination shows the secondary albite to be intimately associated with idioblastic or hypidioblastic epidote and calcite usually forming a fine grained mosaic.

Extensive chloritisation is uncommon but pyroxene phenocrysts in the ground mass are usually replaced by chlorite. Replacement of pyroxene phenocrysts by hornblende has been noted, but this may be due to autometamorphism. It is significant that the pyroxene andesites at Great Whinscales are beneath a rhyolite which the field evidence suggests to be intrusive. The occasional wisps of biotite and amphibole seen in the ground mass in specimens from outside the aureole might possibly be due to thermal metamorphism of one flow by another.

The felspar phenocrysts are usually altered to a fine grained mosaic of sericite, epidote, zoizite, quartz and alkali felspar. The albitisation of ground mass felspar with the associated development of calcite or the complete sericitisation of felspars seen in Shap andesites is not characteristic of this area. Furthermore the felspars are rarely completely replaced. Often the alteration, no more than a turbidity when seen in thin section, and individual secondary minerals, cannot be recognised.

A rhyolite has been mapped at Great Whinscales and other rhyolite flows have been mapped by Oliver near Slight Side. No representatives outcrop within the aureole although a flinty, flow banded, epidotised rock at the granite contact near High Ground is probably a metamorphosed rhyolite. The rhyolite at Great Whinscales is a pale green aphanitic rock with a flinty fracture. The base of the flow is flow banded and the top spheroidal. A rock slice of the spheroidal type shows it to be microcrystalline with felspar microliths showing a regular alignment suggesting a flow structure. Individual spheroids differ in texture and alignment of microliths. Epidote, pale brown with low birefringence, occurs in veins and around the edges of spheroids.

Bedded tuffs vary greatly in lithology and grade. They consist of angular or subangular fragments of andesite, up to one inch in diameter, set in a matrix of felspar crystals. The finer tuffs consist of attrited felspars in a chloritised or epidotised matrix. Many tuffs show graded bedding but current bedding has not been recorded. Epidotisation varies but often the felspars in the matrix are replaced by granular epidote. Veinlets and irregular patches of epidote are sometimes developed and can be seen in hand specimens. As in the case of epidotised lavas epidote is most strongly developed towards the granite but is not found within the zone of biotite hornfelses.

Fig.3.(R.J.95.) Epidotised andesite. Kepple Crag,Eskdale. Gground mass of porphyritic andesite is partially replaced by epidote and calcite. Part of a vesicle filled with hornblende and cut by an epidote veinlet is seen at the bottom left of the figure (Magnification x 35.)

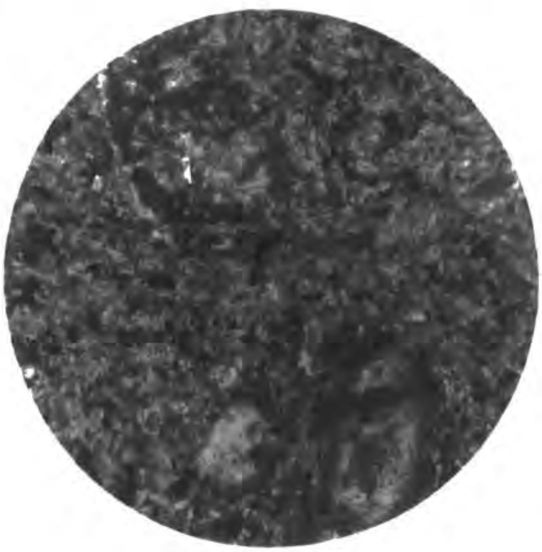


Fig.4.(R.J.109.) Porphyritic andesite. Great Whinscales,Eskdale. Felspar phenocrysts saussuritised. Ground mass consists of felspar, iron ores, granular epidote and amphibole (Magnification x 35).

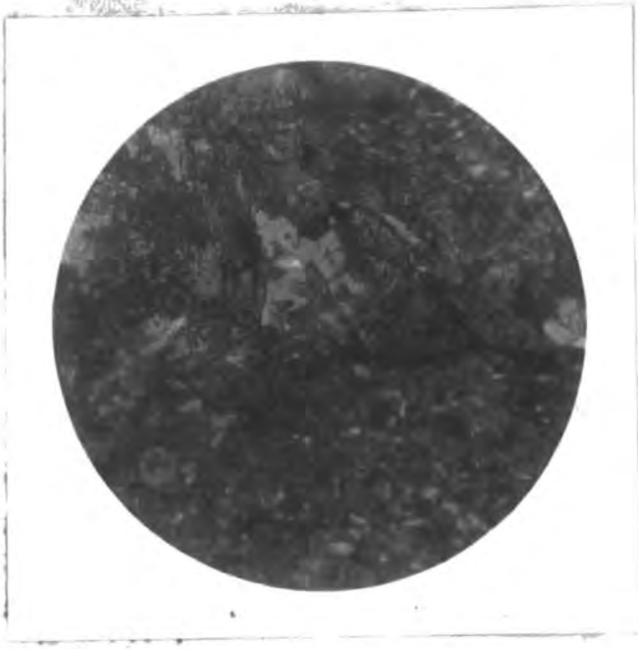


Fig.4.(R.J.41.). Bedded tuff. Harter Fell, Eskdale.
Graded bedding in an unmetamorphosed epidotised tuff. (x 35).

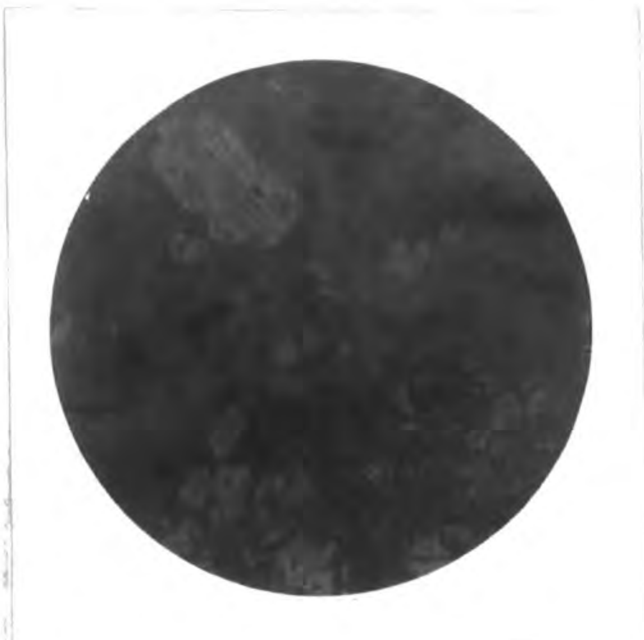


Fig.5.(R.J.81.). Garnetiferous andesite. Hardknott Gill, Eskdale.
Unmetamorphosed porphyritic andesite with garnets.(x 35).

III STRUCTURE.

(a) General.

The structure of the area is attributable to Caledonian earth movements modified by later Hercynian and Tertiary movements. From evidence obtained by mapping the Coniston Limestone unconformity (Mitchell 1940,1932) it has been shown that the B.V.S. was folded and faulted in pre-Bala times. No evidence of pre-Bala movement is found in this area. The general sequence of events appears to be folding, intrusion and faulting.

(b) Folding.

The main structural elements of the area (Fig.1) are a broad eastward pitching syncline - the Scafell Syncline and the Eskdale-Oxendale Anticline. Both structures were recognised by Marr (1899-1900) and mapped in detail by Hartley (1928) and Oliver (unpublished work). The present work has also demonstrated an anticlinal axis along the top of the Screes trending E.N.E.-W.S.W. which appears to be superimposed on the Scafell Syncline.

The Oxendale-Eskdale anticlinal axis (See Fig.1) can be traced into a greatly faulted zone near Bull How and this faulting may be associated with the granite intrusion. South of this anticline the lavas and tuffs of Harter Fell and Birker Moor dip steadily S.E. or South an average dip being 30^o. The Wrynose-Duddon anticline does not extend over Hardknott Pass but is probably represented by the belt of shearing and the Hardknott fault which is thought to be a tear fault.

(c) Faulting.

A pre-Bala fault system has not been recognised in the area and it is thought that most of the faulting is of Caledonian age.

The major faults have been located in the area and the faults are normal faults with small throw. Where exposed in stream sections some fault breccias can be seen which hade at angles between 65^o-75^o. Where the throw can be estimated, as on Harter Fell, it is rarely more than 50 ft. In cases of faults bounding the granite no accurate estimate of the throw can be made.

The dominant fault system is a conjugate set of fault fractures trending north 30^o-45^owest and a north east-south west set. The former are best exposed since they are dip faults, structural changes being more easily observed, and further,many youthful streams flowing into the Esk have established themselves on fault breccias often cutting deep gorges. The north west-south east system is well exposed between Stoney Tarn and Bull How where a series of shallow gullies mark the direction of faults throwing granite against B.V.S. Two depressions north east- south west and north 52° E -south 52°West extend 200 to 300 yards into the granite. Only in one case at Devoke Water, can granite be seen thrown against B.V.S. bya north west-south east fault but a study of the drainage system suggests that the same conjugate system of faults is represented within the granite but this remains to be verified. Furthermore all haematite veins mapped trend north-west - south east suggesting that these fractures also originated in Caledonian times.

Other faults trending in a general north-south direction bound the granite east of Esthwaite Farm and near Low Ground and High Ground north-east of Devoke Water. Fault breccias with a similar trend have been mapped on the screes.

This conjugated fault system with subordinate north-south faults is similar to that mapped by Oliver in the Scafell-Great Gable area (personal communication). The faults in the area mapped by the author thus appear to be due to regional tectonic movements rather than the local effects of intrusion of the granite.

The Hardknott shatter belt,which consists of a belt of sheared and epidotised porphyritic andesites, extends over Hardknott Pass to Cockley Beck. Both East and West Hardknott Gills have established themselves on haematised fault breccias and the shearing of the surrounding andesites was probably due to lateral movement along this fault. Mapping of tuff bands and normal faults suggests that the Hardknott fault is a sinistral tear fault but the evidence is not conclusive. However the shatter belt was formed after the formation of the conjugate fault system and was probably due to renewed movement along the Wrynose-Duddon anticlinal axis. It may further be noted that the axis of the Wrynose-Duddon anticline and the Hardknott shatter belt is in line with the glaciated valley of the Esk from Wha House to the sea. Furthermore haematite veins north and south of Eskdale cannot be correlated and possibly the Hardknott fault system affects the Eskdale granite.

(d) Cleavage.

Lavas and tuffs of the Borrowdale Volcanic Series are rarely cleaved in this area. The lavas are usually massive and well jointed whilst the tuffs rarely show any effects of shearing. Local shearing associated with drag folding is sometimes seen in bedded tuffs.

However a belt of shearing has been mapped from the top of Hardknott Pass east down Hardknott Gill. This shearing is limited to a shatter belt 400 yards wide and seems to be associated with the Hardknott fault system.

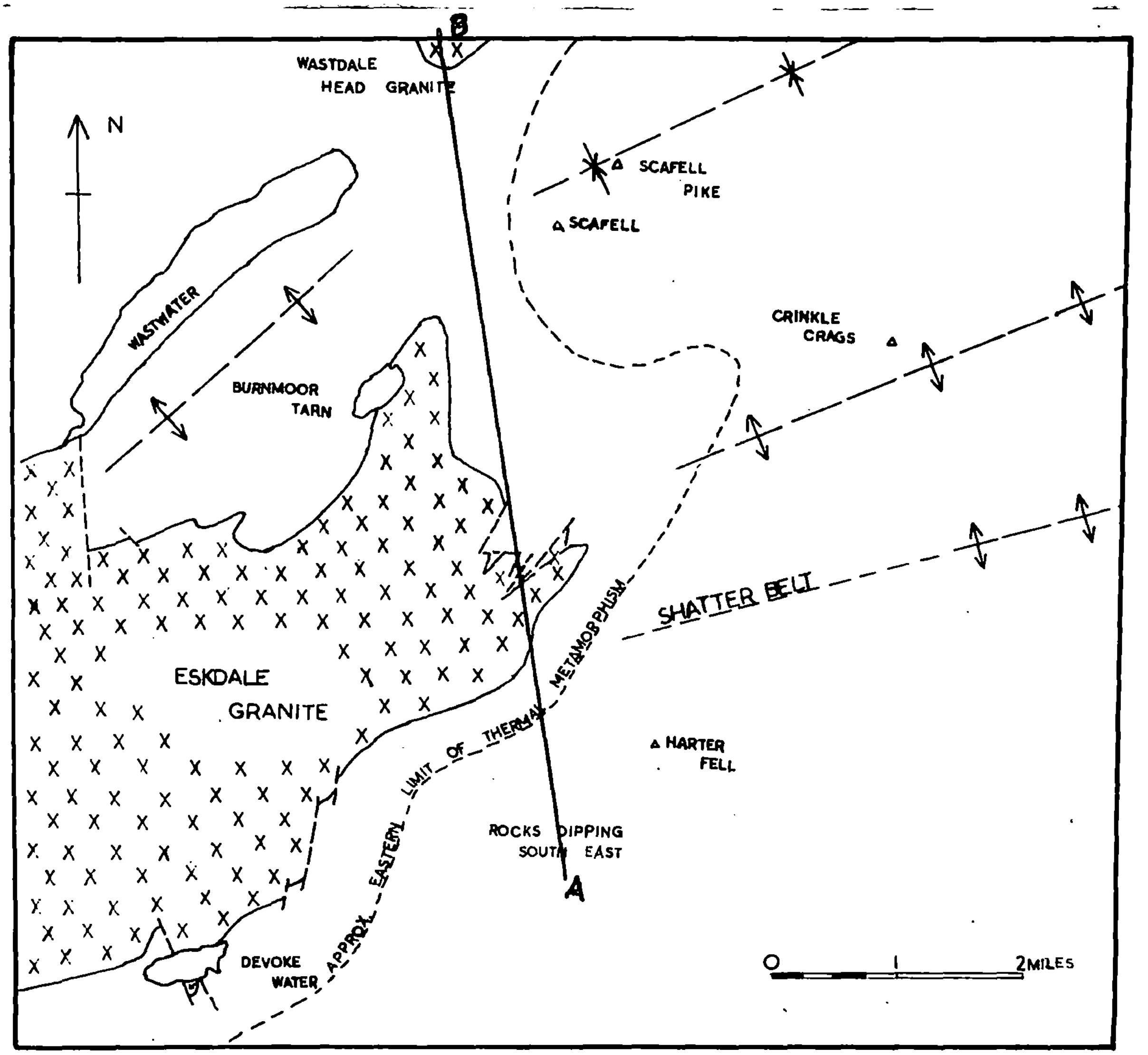


Fig.1. Sketch map of the Eskdale district showing the chief structural features and the thermal aureole.

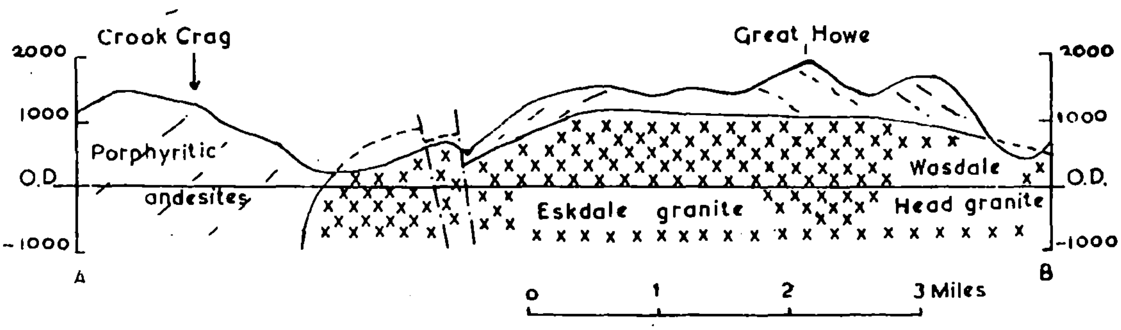


Fig. 1a. Section north-south (Line A-B on Fig 1.)

IV ESKDALE GRANITE.

(a) Introduction.

The Eskdale granite was first described by Marshall (1858) and later by Ward (1875) both of whom regarded it as resulting from the metamorphism of country rocks (see p. 1). Dwerryhouse (1909) described the granite in greater detail. His main conclusions were that the granite mass is a laccolith formed by the intrusion of molten granitic magma under great pressure. He described the two main types of granite and commented on the marginal varieties which he maintained were always more acidic.

Simpson (1934) recognised three granites. He agreed with Dwerryhouse that the granite mass was intruded under great pressure and that the shape is a laccolith. Further, he drew attention to the widespread sericitisation and chloritisation. Simpson also regarded the intrusion as a laccolith whereas officers of the Geology Survey (1937) believed it was a stock.

(b) Form of the Intrusion.

(i) Introduction.- Marr (1899-1900), Dwerryhouse (1909) and Simpson (1934) regarded the intrusion as a laccolith, the main lines of evidence being:-

(1) Where exposed the granite contact is at a low angle and in some places horizontal.

(2) The existence of outliers of metamorphosed B.V.S. on Blea Tarn Hill and Great Barrow (Dwerryhouse 1909).

(3) In general the Borrowdale Volcanic Series dips away from the main axis of the granite as if domed when the granite was intruded (Dwerryhouse 1909). Alternative views have been expressed by the Survey who found evidence of a stock like form in the south-west of the area (1937) and by Green (1917) who suggested that the contact for two miles north-west of Devoke Water was a thrust.

(ii) Field evidence.- At the western end of Wastwater the granite is faulted against porphyritic andesites. This north-south fault may be traced southward for ½ mile. The contact is obscured by drift on Whin Rigg but probably follows the 850' contour to Robin Gill. Exposures here and in Mitredale are not inconsistent with a laccolith since the contact is at a low angle and the granite is overlain by metamorphosed B.V.S. From Mitredale to Burnmoor Tarn the contact is partly obscured by drift but from Hardrigg Gill where the contact is seen at 1100 feet O.D. to Whinscales sheepfold an almost continuous outcrop of the contact may be followed. The contact is almost horizontal at 1100' O.D in Oliver Gill but is at more than 1500' O.D south of Black Apron descending again to 1250' at Whinscales sheepfold. Throughout this section the granite contact is dipping 10° to 15° east and the general form of the contact appears to be a broad anticline pitching east. South of the sheep-fold the granite contact is less well exposed although north-west of Stoney Tarn a steep contact has been recorded. From here to Scale Gill the granite and country rocks have been heavily faulted (Simpson's Shatter Zone) by a series of faults trending generally north east - south west (see Fig.1.). Where exposed the granite contact is almost horizontal. An unfaulted contact can be followed for ½ mile from an unnamed gill south of Scale Gill. This contact is steep and dips of up to 65° south east have been recorded. The contact is seen south of the Esk at 650' O.D. near the footpath from Birker Farm. A continuous outcrop to Hartley Crags, where it is seen at 550' O.D, shows the contact dips a few degrees south south-east. South of Hartley Crags the granite contact is faulted by faults trending north 15° east-south 15° west. From High Ground to Devoke Water the contact is covered with drift.

Consideration of the contact mapped thus suggests that this part of the intrusion is a laccolith affected by later faults. The outliers of Blae Tarn Hill and Great Barrow support this view but these outliers are also faulted and it is uncertain that these indicate the true roof of the granite. Furthermore, the evidence for a laccolithic form is not conclusive since the intrusion might equally well be a partially unroofed stock and the observed steep contacts may represent the denuded sides of a stock.

The form of the metamorphic aureole has not hitherto been considered and this should provide evidence of the underground contours of the granite. The form of any metamorphic aureole principally depends on:-

(1) The form of the intrusion.

(2) The type and distribution of the country rocks.

(3) The degree of metasomatism and the porosity and structure of the country rocks allowing the migration of metasomatising fluids or ionic diffusion.

(4) Post granite faulting.

The rocks within the aureole are lithologically similar and equally susceptible to metamorphism. Further metasomatism was limited. The form of the aureole should therefore reflect the form of the intrusion. Fig. 1 shows the form of the aureole as recognised in the field by the presence of biotite and general hardening and darkening of the lavas. It will be noted firstly that the rocks North East of the granite contact at Devoke Water are strongly metamorphosed for at least 2 miles from the contact and that a continuous tract of metamorphosed lavas outcrop between the main Eskdale granite mass and the Wasdale Head granite. This suggests that this area is underlain by granite co-extensive with the Wasdale Head granite. Secondly the aureole east of the granite is narrow and limited to 200 to 300 yards. In Upper Eskdale this may be associated with the steep contact but on Birker Crags the contact is at a low angle and possibly the sides of granite plunge steeply as in Fig. 1a. No evidence of the thrust suggested by Green (1917) has been found and the section in Rigg

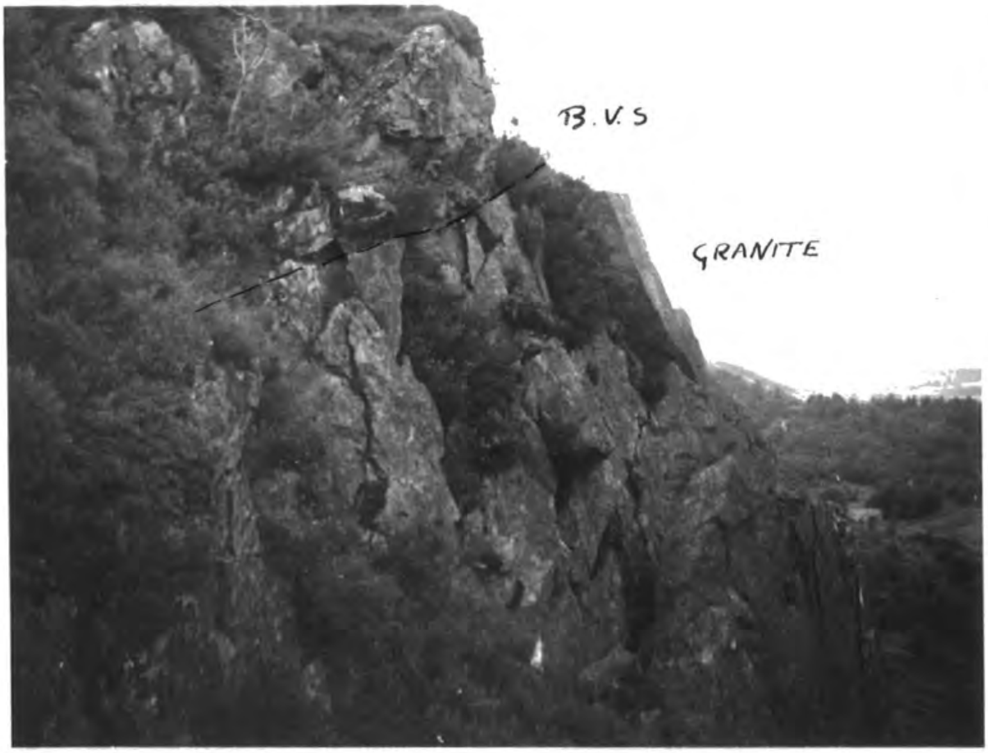


Fig.6. B.V.S. - Granite contact. Birker Crags, Eskdale.
(Photographer R.J. Firman).

Fig.6a.B.V.S. - Granite contact. Birker Crags, Eskdale.
(Photographer Sankeys)

Beck south of Devoke Water is best interpreted as granite thrown against metamorphosed andesite by a normal fault.

Thus whilst consideration of the granite contact suggests that the granite may be a laccolith partly affected by later faulting, the form of the aureole suggests that it may well be a partially denuded stock-like body.

(c) Age of Intrusion.

The only definite evidence of the age of the intrusion is that it is intruded into and metamorphoses andesites and tuffs of the Borrowdale Volcanic Series and that pebbles of Eskdale granite occur in the Permian Brockram at Wellington, near Gosforth. In 1937 Mr.R.C.B.Jones discovered a pebble of Eskdale Granite in the Sand Rock Mine (Highest Coal of the Millstone Grit) thus proving that the intrusion took place before the formation of the Coal Measures.

The officers of the Survey believed that the granite was intruded shortly after the main Caledonian Earth Movements whilst Green believed it to be Ordovician.

The main lines of evidence supporting the Survey's view are:-

(1) The outcrop of the Eskdale Granite is roughly concordant with a major Caledonian anticlinal axis trending E.N.E. north of the Esk.

(2) The granite is affected by faults thought to be of Caledonian age. Faults trending north east-south west have

been recorded by Oliver (personal communication) as a dominant type of faulting in the area north east of the granite and similar faults may be traced into the granite in the Stoney Tarn area - Eskdale area (Simpson's Shatter Zone).

The accurate dating of faults affecting the granite is thus essential to establishing the date of the granite intrusion. As previously demonstrated (p. 17.) it is likely that most of them are Caledonian and that the intrusion of the Eskdale Granite took place directly after the main period of Caledonian folding. It is noteworthy however that many Caledonian faults are haematised and it is as yet uncertain whether these mineral veins represent crystallisation from late stage hydrothermal liquids associated with the granite or with later Tertiary fluids.

(d) Petrography.

Little original work has been carried out by the writer and the account below is largely a review of descriptions by Dwerryhouse (1909), Simpson (1934) and Hollingworth (in Trotter 1937). Three types of granite were distinguished by Simpson.

(i) The pink granite.- This rock predominates in the area mapped by the writer. It is a coarse grained muscovite-biotite granite in which the amount of mica is usually less than 2% and biotite may be absent or converted to Chlorite with leaching out of iron in the form of haematite. The felspars are usually highly sericitised and this may be apparent in hand specimen. One striking feature of the granite in Beckfoot quarry is the abundance of large radiating clusters of blue-green tourmaline in the body of the rock. The essential minerals are quartz and perthite, which together constitute 90% of the rock, plagioclase ranging from albite to oligoclase in composition, biotite and muscovite. Among the accessory minerals recorded by Simpson (1934) are tourmaline, zircon, andalusite, apatite, garnet, haematite, limonite, ilmenite and pyrrhotite. Fluorite is very rare whilst topaz appears to be confined to the fine grained rocks and the Devoke Water greisen.

(ii) The Green Granite.- This is a biotite granite richer in orthoclase quartz and biotite than the pink granite but otherwise similar in structure and mineral content. It is confined to patches near Eel Tarn, Stoney Tarn and Linbeck Gill.

(iii) The Grey Granite.- This variety does not occur in the area mapped by the writer.

(iv) The marginal varieties. Dwerryhouse (1909) maintained that the granite mass becomes more acid towards the margin. Neither Simpson (1934) nor officers of the Geological Survey (1937) found this to be generally the case. However, near unfaulted contacts in Robin Gill, Hardrigg Gill and Oliver Gill fine grained marginal varieties occur. These appear to represent the chilled contacts.

In other areas, notably on Hartley Crag and near Taw House much veining and interpenetration of the country rock has taken place and quartz veins occur along the margins. Injection breccias due to the forcible intrusion of granite magma were first described by Dwerryhouse (1909) and are well developed near Stoney Tarn and Whinscales. In some areas, principally near Devoke Water, greisen is developed.

(v) Late Stage Deuteric Effects.- Seritisation and chloritisation of felspars is widespread and is an almost constant feature of all varieties of the Eskdale Granite. Furthermore the micas are normally chloritised. These effects may be attributed to the high temperature hydrothermal stage as re-defined by Shand (1944). Chloritisation of biotite in contact hornfelses (p. 54.) and the formation of greisen are probably also associated with this stage of the emplacement of the Eskdale granite.

(e) Associated Dykes.

Dykes in the neighbourhood of the Eskdale granite were described by Dwerryhouse (1909) who stated that only the quartz felsite dyke which can be traced from Great Bank over the south eastern slopes of the Screes to Wasdale Head is associated with the granite. The present mapping suggests the presence of two or three such dykes intruded en echelon but peat and drift cover prevent this hypothesis being confirmed. There is some evidence of displacement by later faults trending north-west -- south-east in the Wasdale Hall area. The width of the main dyke varies from 150 feet near the granite contact to 20 feet in Lingmell gill; on Illgill Head it is 30-40 feet wide.

Petrologically these dykes are reddish quartz porphyries usually with large phenocrysts of orthoclase. The latter are often zoned in an analogous manner to those at Shap (Grantham 1928) and show a tendency to be partly replaced by epidote or more rarely by chlorite. The ground mass consists of quartz, felspar and biotite.

Small pink, fine grained felsite dykes outcrop on the Screes and in Great Grain gill and in hand specimen are very similar to the fine grained marginal variety of the Eskdale granite.

Other doleritic dykes mapped by the Geological Survey have not been studied in detail although some on the screes appear to be feeders to flows and at least one, in a gully near Broad Crag, has been interpreted in the field, by the writer, as a metamorphosed fault breccia.

(f) Mineralisation.

No detailed study of the mineralisation associated with the Eskdale Granite has been attempted. Low temperature hydrothermal mineralisation was not mentioned by Dwerryhouse (1909) or Simpson (1934).

Copper bearing mineral veins have been worked, notably in Spothow Gill, either for haematite or copper, whilst haematite veins were worked in the granite near Boot. It is uncertain whether these veins, which fill fault breccias in the granite and country rocks, are the result of hydrothermal mineralisation associated with the granite or have a similar origin to the haematite bodies in Furness and West Cumberland. These latter are thought to have originated by downward percolation of iron rich solutions from the New Red Sandstone and the application of this theory to the Eskdale granite would suggest a former covering of New Red Sandstone over the area. The presence of quartz, calcite, chalcopyrite, and malachite suggests hydrothermal mineralisation connected with the granite. Possibly the haematite, which in the Boot veins, constitutes 90% of the vein, was of later origin and unconnected with the Eskdale granite.

A study of the mineralisation in Beckfoot granite quarry, one mile west of Boot, Eskdale, has shown that the chief mineral assemblages along joints are earthy haematite; calcite and specular haematite; epidote and pyrite and quartz veins. No time sequence was established although it was noted that tourmaline (p.29.) is not restricted to joint faces and is probably associated with the high temperature hydrothermal stage.

V THERMAL METAMORPHISM and METASOMATISM.

(a) Historical.

No detailed work has been done on the Eskdale aureole although contact hornfelses were mentioned briefly by Walker (1904) Dwerryhouse (1909) and Simpson (1934). Harker and Marr collected specimens from the aureole and Marr (1916) stated that the metamorphism is similar in type to that at Shap.

In the Sheet 37 Memoir (1937) metamorphosed rocks from the Irt Gorge are described but it is uncertain how much of this metamorphism was due to the Ennerdale granophyre.

(b) Form of the Aureole.

In mapping the thermal aureole of the Eskdale granite the appearance of scaly brown biotite is taken as representing the outer limit of thermal metamorphism, but it is probable that the epidotisation of andesites beyond this limit is due to the influence of the granite. However, in an area, such as the Eskdale district, of rocks of similar composition and state of decomposition, the limit of biotite formation forms a convenient datum for describing the form of the aureole.

Fig.1 shows that south of the Esk this aureole is half to three quarters of a mile wide, whereas in the north-east of the area biotite occurs two miles from the granite contact. Lavas and bedded tuffs on Scafell and Slight Side are also incipiently metamorphosed and the form of the aureole strongly suggests that Scafell is underlain by granite co-extensive with Wasdale Head Granite (p.25.)

The outer limit of biotite is difficult to map with precision and could be accurately plotted only with the aid of hundreds of rock slices. Since the lavas are normally hard and dark blue in colour, hardening and introduction of biotite are very difficult to detect in the field. However, rock slices and an examination of the Geological Survey collection has confirmed the mapping.

(c) Thermal Metamorphism of Porphyritic Andesites.

The thermal metamorphism of porphyritic andesites in the Eskdale district is similar to that at Shap. However, in the Eskdale district the lavas are much fresher, and completely recrystallised biotite-albite-quartz hornfelses are restricted to near the contact. Furthermore, the larger felspar phenocrysts are often not recrystallised, even in contact specimens, and can always be seen in hand specimens. Epidote is rarely found in the thermal aureole, as defined by the biotite bearing rocks, and none of the metasomatic epidote hornblende or garnet bearing veins characteristic of Shap have been found. Joints outside the aureole are usually open and only rarely filled with chlorite or calcite, so that a metamorphosed joint system is not found around the Eskdale granite.

(i) <u>Vesicles.-</u> Amygdaloidal lavas are rare but, as at Shap, changes in the vesicles are most easily recognised in the field. In Dod Knott Gill, 800 yards from the granite contact, a vesicular andesite (R.J.94) outcrops which may be compared with the amygdaloidal lava (R.J.114), 3/4 mile from the contact east of Whinscales (see p.10.). Here the rock is unaffected by thermal metamorphism and the vesicles are filled with epidote, chlorite, calcite, quartz etc., whilst in Dod Knott Gill hornblende and biotite have developed. Biotite often forms the outer zone and occurs as ragged porphyroblasts intimately associated with the hornblende. Sometimes the whole vesicle is filled with biotite or a biotite-quartz iron ore association. This biotite, like that in the ground mass, is moderately pleochroic in yellow browns. Pale hornblende with similar properties to that from Shap fills most of the vesicles and has presumably, as at Shap, developed from chlorite or calcite. The association of biotite and hornblende has not been recorded in the Shap metamorphosed Wrengill andesites but seems characteristic of the Eskdale aureole. A rough zonation seen in some amygdales of an outer zone of biotite, with inner zones of hornblende and quartz suggests pseudomorphing of the original zoning shown in some unmetamorphosed vesicular lavas. On top of the screes at the west end vesicular lavas outcrop and here the amygdales consist of mosaics of recrystallised quartz, whilst other smaller vesicles are filled with biotite.

Small amygdales of hornblende and quartz, almost indistinguishable in hand specimen, have been recorded from nearer the granite.

Pink reaction rings similar to those at Shap also occur around the larger hornblende filled vesicles (R.J.94 B) and along hornblende and epidote veins (p. 50). They apparently have a similar origin to those at Shap.

(ii). Pyroxene Phenocrysts.- The first signs of thermal metamorphism are the development of wisps of amphibole or biotite in the ground mass and the development of hornblende at the expense of chloritised pyroxenes. In the latter case it is uncertain whether the change is due to thermal metamorphism, since pyroxene is sometimes uralitised during the deuteric stage of the cooling lava. Slices in the Geological Survey Collection (E.86 from North of Slight Side and E 16944 from Devoke Water) show pyroxene replaced by hornblende although no other evidence of thermal metamorphism is seen. Large ragged decussately arranged porphyroblasts have usually developed (R.J.109 Great Whinscales and R.J.86 Hardknott Pass) or occasionally a single crystal of hornblende may pseudomorph a pyroxene phenocryst The fibrous and scaly development of uralite is not seen and it is therefore suggested that the mineralogical change towards equilibrium (i.e. pyroxene $\rightarrow$ uralite) has been effected by thermal metamorphism (Harker 1939. p.102). Specimens from

North of SlightSide (e.86) and Great Whinscales (R.J.109) lie outside the zone of biotite bearing rocks, being more than a mile from the granite contact, but may be regarded as having been affected by thermal metamorphism. Wisps of amphibole in the otherwise unaffected rocks may similarly be due to alteration of pyroxenes.

Nearer the granite (e.g.E.87) and R.J.5 from the top of the Screes) hornblende is intimately associated with biotite in patches which appear to be pseudomorphs after pyroxene. Near Throstle Garth, 1½ miles from the granite contact, pyroxene phenocrysts are replaced by minute scales of biotite. At the granite contact (e.g. R.J.39 Whinscales,R.J.62 Blea Tarn Hill and R.J.37 Raven Crag) clots of decussate strongly pleochroic biotite probably represent the pyroxene phenocrysts.

From the field and petrographic evidence it would appear that with thermal metamorphism of pyroxene andesites, chloritised pyroxene is normally replaced by hornblende whilst in higher grades of metamorphism biotite replaces hornblende (cf. Shap.p.48.). However, no direct evidence of biotite pseudomorphing hornblende has been found. Possibly some potash metasomatism may have taken place.

(iii) <u>Plagioclase Phenocrysts.</u>- Changes in the felspar phenocrysts due to thermal metamorphism seem to depend more on the state of decomposition of the original felspars than on composition or grade of metamorphism. In some contact hornfelses (e.g. at Blea Tarn Hill.R.J.62.Fig.8.) the plagioclase phenocrysts are apparently unaltered, whilst elsewhere (e.g. near Whinscales R.J.39) the phenocrysts are partly recrystallised. Furthermore, a specimen from Robin Gill, 200 yards from the granite contact, shows more advanced recrystallisation of phenocrysts than most contact specimens examined.

A survey of plagioclase felspars from outside the aureole (p. 13.) shows that the chief changes are sericitisation and saussuritisation. Felspars are rarely fresh although they are often zoned and the outer albitic zone is hardly ever altered. The alteration varies from an indefinite cloudiness in which individual decomposition products (R.J.109) cannot be identified to complete sericitisation (E.86) or replacement by epidote (R.J.95). Staining with sodium cobaltinitrite using the technique suggested by Chayes (1952) shows that some of the cloudiness both in contact specimens (R.J.62) and further from the granite (R.J.34) is due to exsolved potash felspar or sericite. Within the aureole sericitised plagioclase may be partly replaced by biotite (R.J.1 A.) or may show similar characteristics to phenocrysts outside the aureole. At or near the contact, recrystallisation has sometimes taken place (E 16944, R.J.23, and R.J.37) with the development of a mosaic of quartz, clear albite, granular epidote, zoizite (?) and occasionally sericite. In other cases (E 154 - Black Apron and R.J.62 Blea Tarn Hill) the felspars are cloudy but appear to be relatively unaltered although the ground mass is completely recrystallised. MacGregor (1931) has discussed the problem of clouded felspars in thermal metamorphism and cites many instances in which clouded felspars are due to thermal metamorphism. Teall first connected cloudy felspars with contact metamorphism. Kynaston (1905) recorded cloudy felspars in metamorphosed andesites around the Cheviot granite. Similar phenomena have been recorded in thermally metamorphosed lavas in Glen Etive (Kynaston 1901), Glen Coe (Bailey 1916.pp.204-9).

Cloudiness of the peculiar type described by MacGregor (1931), due to minute inclusions giving the felspar a faintly bluish appearance has been observed in many contact hornfelses (e.g.R.J.62.Fig. 8.). As noted by MacGregor (1931) the outer albitic zone of zoned plagioclase is rarely altered. In the Eskdale district, however, cloudy felspars occur both at the granite contact and outside the aureole and it is impossible to estimate how much of the "clouding" in felspar phenocrysts is due to thermal metamorphism.

Kynaston (1905) recorded apparently unaltered felspar phenocrysts in hornfelsed andesites at the contact with the Cheviot granite. Similar phenomena occur at the Eskdale granite contact. In some parts of the contact (e.g. Raven Crag.R.J.37) even the larger felspar phenocrysts are granulitised and consist of a mosaic of granular epidote, quartz and albite. At Black Apron only the smaller phenocrysts are granulitised. As noted by MacGregor (1931) the larger phenocrysts are more stable.

A survey of felspar phenocrysts in the Eskdale district thus suggests that effect of thermal metamorphism depends largely on the original state of decomposition and that the larger phenocrysts tend to be most stable. Furthermore, differing degrees of granulitisation of felspar phenocrysts in contact hornfelses suggests variations in equilibrium conditions along the contact.

(iv) The Ground Mass.- The ground mass being fine grained is most susceptible to thermal metamorphism. Furthermore it is often highly altered and as at Shap (p. 47), it is these decomposition products which show the first signs of metamorphism.

The texture of andesitic lavas in the Eskdale district is usually ophitic or intersertal. Pyroxenes in the ground mass are invariably chloritised with consequent development of secondary iron ores. The ground mass felspars are often altered to sericite or partly replaced by granular epidote. The grain size varies greatly from felspar laths 0.1 - 0.2 m.m. long to a microcrystalline felsitic aggregate.

The first signs of thermal metamorphism are the appearance of wisps of amphibole developing at the expense of chlorite (R.J.109) and biotite forming from the sericitised felspars. Biotite normally replaces the hornblende although in many slices these two minerals are intimately associated. Where fresh and relatively unaltered the ground mass felspars are not replaced (e.g. R.J.64) 250 yards from the granite contact. Complete recrystallisation of the ground mass is usually limited to hornfelses close to the granite contact. An apparent exception (R.J.23) outcrops 200 yards up-stream from the granite contact in Robin Gill. However the contact here is almost horizontal and it is probable that the specimen came from less than 100 feet above the granite. In these granulitised rocks iron ores are usually absent and the iron was probably used in the formation of biotite. In most contact hornfelses the ground mass consists essentially of a mosaic of quartz, biotite and clear albite. However where iron was in excess, secondary octahedra of magnetite may form (E 16982 Great Barrow).

(v) <u>Hornblende in Aphanitic Andesites.-</u> It has been suggested (p. 37.) that the replacement of pyroxene phenocrysts by hornblende is due to thermal metamorphism and that this change may be unaccompanied by the development of biotite in the ground mass. Aphanitic andesites outcropping south of Slight Side and on Yew Crags are characterised by irregular veins of hornblende often up to one inch wide. Similar veins do not occur in aphanitic andesites further east and the development of hornblende is thought to be due to the influence of the Eskdale granite. No biotite occurs in the ground mass of these andesites but wisps of amphibole are present. Furthermore the aphanitic andesites outcropping in Eskdale (described by Oliver) lie within the limit of scaly brown biotite. It seems likely therefore that these andesites have been subjected to similar conditions to pyroxene andesites in which the pyroxene phenocrysts have been replaced by hornblende (p. 37.).

The irregularity of these hornblende veins makes it unlikely that they are metamorphosed chlorite-filled joints as at Shap. Possibly they represent metamorphosed deuteric calcite veins. These hornblende veins are apparently confined to the aphanitic andesites south of Slight Side and near Yew Crags although hornblende is associated with epidote in veins in a massive andesite near Kail Pot in Upper Eskdale.

(vii). The Garnet Problem. Garnets occur in several places in the aureole of the Eskdale granite - at the contact near Ramshaw Beck (Le Bas, personal communication) and at Raven Crag. Also garnets have been found in metamorphosed porphyritic andesites on Illgill Heads, Yew Crags and Birker Fell.

(Walker (1904) suggested that "spongy garnets" from xenoliths west of Stoney Tarn are probably contact garnets, whilst those in Borrowdale lavas were thought to be pyrogenetic.

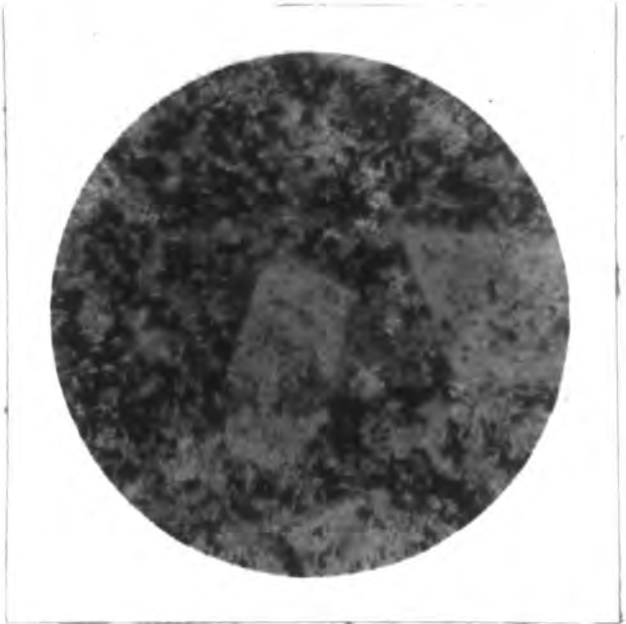


Fig.7.(R.J.26.) Metamorphosed porphyritic andesite.
Great Grain Gill, Eskdale.
Felspar phenocrysts sericitised. Ground mass impregnated with haematite.(x 35).

Fig.8.(R.J.62.) Contact hornfels, Blea Tarn Hill, Eskdale.
Metamorphosed contact hornfels. Ground mass completely recrystallised with development of a mosaic of quartz alkali felspar and biotite. Felspar phenocrysts comparatively unaltered. (x 35).

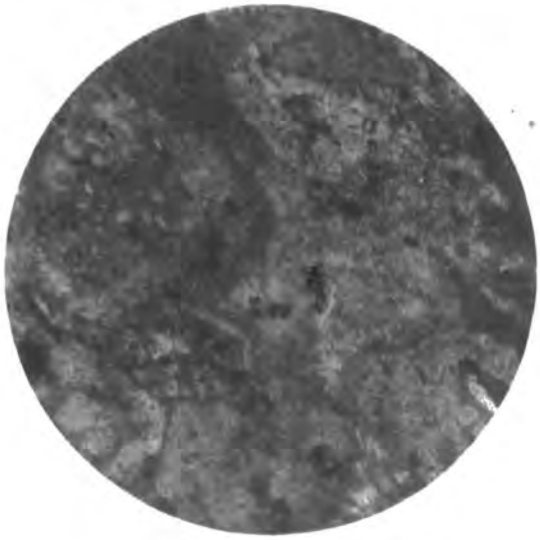


Fig.9.(R.J.63.). Metamorphosed bedded tuff near Whin Crag, Eskdale.
Biotite developed in the matrix together with magnetite. Andesite fragments sericitised. (x 35).

Although Oliver's recent work tends to confirm this, the possibility that garnets are due to low grade regional metamorphism, remains, but does not affect the following argument since all garnets are pre-granite.

Microscopical examination of the specimen from near Ramshaw Beck suggests, at first sight, that garnet is being replaced by biotite and is therefore unstable in the presence of the granite. These garnets are well formed but apparently corroded around the edges and along cracks. Biotite, with minute granules of magnetite, is developed in the cracks and also concentrated around the garnets. However this is not necessarily evidence of disequilibrium conditions. Pyrogenetic garnets in Oliver's slices and in the writer's (e.g.R.J.81. Fig.5.) are usually partly replaced along cracks and around the edges by a scaly yellow-green chloritic material with associated iron ore granules. Rock slices made from garnetiferous rocks from the edge of the thermal aureole (e.g.R.J.68 from Yew Crags, Eskdale and Oliver's rock from Pier's Gill) show scales of biotite developing at the expense of the chloritic material; this biotite is particularly concentrated around the margins of the garnet. Under high grade contact metamorphism all the chloritic material would have been replaced by biotite and an appearance of replacement of garnet by biotite would result. The garnets from the Ramshaw Beck contact are thus thought to be pre-granite and pyrogenetic but were stable in the presence of the granite, biotite having developed from chlorite decomposition products. However the cell size of these garnets (Oliver, personal communication) is 11.557 (± .002) suggesting an almandine with fairly high manganese content. This is not characteristic of other pyrogenetic garnets examined by Oliver from flows.

Garnets from the contact at Raven Crag and Illgill Heads in tuffs or flow brecciated lavas are idioblastic sometimes containing inclusions of biotite (R.J.37.Fig.10). There is no evidence of the garnet being unstable in the presence of the granite and indeed the good crystal shape, in contrast to other garnets from Borrowdale lavas, suggests equilibrium conditions. The refractive indices are 1.805 (± .002) (Illgill Heads R.J.16 A) and 1.801 (± .002) (Raven Crag R.J.37) suggesting a pyrope-almandine garnet with 70-80% of the almandine molecule. This agrees with the composition of other pyrogenetic garnets from outside the aureole (Oliver, personal communication). Furthermore, apart from the chloritic alteration products being partly replaced by biotite, garnets elsewhere in the aureole are very similar to garnets from other Borrowdale lavas, and it appears that garnets are largely unaffected by thermal metamorphism.

However the "spongy garmets" from near Stoney Tarn (Walker 1904) are very different. Walker (p.102) states, "Garnets of very irregular outline are also produced, the border being of very spongy character freely penetrated by quartz and plagioclase". He believed these garnets were formed from chloritic aggregates and from brownish isotropic minerals (possibly picotite). Anisotropic garnets are also recorded. Examination of the original rock slice (Cambridge. Collection 3887) shows that the rock consists of a granular mosaic of quartz, albite, biotite and garnet. Chlorite appears to be developing at the expense of biotite (see p.54) some spinellid and anisotropic mineral with high relief (possibly grossular, Walker 1904)occurs. The isotropic garnet occurs in patches suggesting the breakdown of pre-existing pyrogenetic garnets rather than the beginnings of the formation of contact garnets. The granoblastic texture supports this hypothesis since garnet normally has a greater crystalloblastic strength than biotite, quartz or albite. Therefore it is suggested that, with the higher temperature in xenoliths, "spongy garnets" have been formed from pyrogenetic garnets by replacement by biotite and albite along the cracks and margins. Grossular may have been formed from excess lime resulting from the albitisation of felspar.

A study of pyrogenetic garnets in the thermal aureole of the Eskdale granite shows they are usually stable, biotite developing from chloritic decomposition products. In some places , notably Raven Crag and Illgill Head, equilibrium

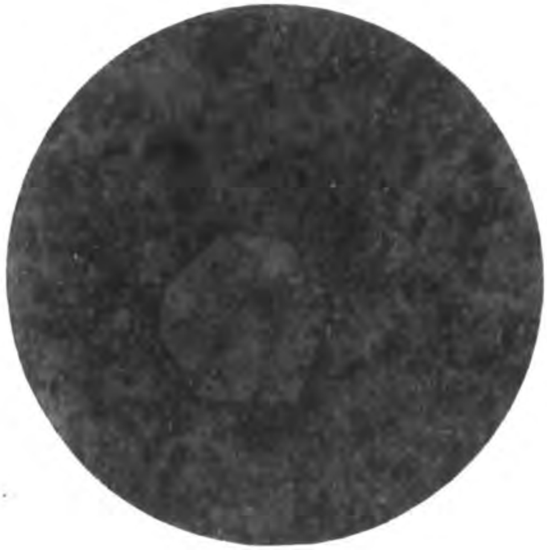


Fig.10.(R.J.37b.) Hornfels near the granite contact, Raven Crag, Eskdale.
Idioblastic garnet in a ground mass, mosaic of biotite, penninite (after biotite) quartz, albite and iron ores. (x 35).

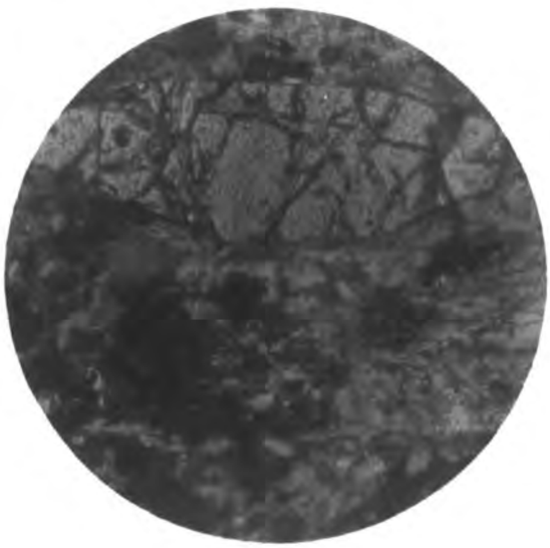


Fig.11.(R.J.16.A.) Garnetiferous biotite hornfels, Illgill Heads, Wastwater.
Garnets developed in a (?) flow brecciated andesite. Felspars clouded.(x 35).

conditions were favourable for the recrystallisation and formation of idioblastic almandine garnets, whilst in xenoliths near Stoney Tarn the garnets were unstable.

(vi) Epidote in the Aureole.- Epidote is rare within the aureole of the Eskdale granite although epidotised andesites occur beyond the aureole on Border End and Harter Fell. It is suggested later (p. 60) that this epidotisation may be due to metasomatism. Epidotised lavas also outcrop south of Devoke Water not far from the granite but have not yet been investigated.

Within the aureole, as defined by the biotite bearing rocks, epidote occurs either in veins or as granular replacements of felspar phenocrysts. Epidote veins similar to those at Shap (p. 117) are extremely rare but have been recorded from Kail Pot, Upper Eskdale, where it can be demonstrated that epidote veins cut hornblende structures, and from High Ground. In the latter occurrence large irregular patches of epidote have developed replacing parts of a contact metamorphosed flow banded rhyolite. Possibly the formation of this epidote is analogous to the formation of irregular epidote veins in Shap Blue Quarry by wall rock replacement. Both the epidote here, at High Ground, and in Upper Eskdale, is brownish and non-pleochroic, quite unlike the material from Shap.

Some of the granular epidote in recrystallised felspars at the granite contact shows anomalous blues under crossed nicols and it is thought to be zoisite.

(vii) Flow Breccias.- Flow breccias are not common in the Eskdale District and as at Shap are difficult to distinguish from unbedded tuffs in the field. Garnetiferous rocks on Illgill Heads are probably flow breccias but contain angular fragments and may be tuffs. They are overlain by bedded tuffs and underlain by siliceous porphyritic lavas. The metamorphism of the fragments is similar to the lavas described (p.35.). The matrix is recrystallised to a microcrystalline felsic mosaic with a lot of magnetite. Similarly a garnetiferous hornfels near Raven Crag may be a flow breccia or tuff. Here angular fragments of porphyritic lava are set in a microcrystalline quartz matrix.

(d) Bedded Tuffs.

No systematic study of bedded tuffs has been attempted. They are more susceptible to metamorphism than most lavas since the matrix is usually more highly altered, matrix. Metamorphism of the individual fragments is similar to that described for the andesitic lavas. Although most tuffs outside the aureole are epidotised no epidote has been recorded in the hornfelses. A specimen (R.J.63) from near Dawsonground Crags, Upper Eskdale, is interesting for the abundance of pyrite and foxy red biotite in the matrix.

(e) Acid Lavas.

As demonstrated by Harker and Marr (1891) rhyolites are less susceptible to thermal metamorphism. In the Eskdale district only one acid lava, a flow banded rhyolite,outcrops in the contact zone. Here, at High Ground, the rock is recrystallised into a microcrystalline aggregate of quartz and felspar and partly replaced by epidote.

(f) Skiddaw Slates.?

A small patch of micaceous hornfels at the granite contact on Water Crag, Devoke Water, was mapped by officers of the Geological Survey as metamorphosed Skiddaw Slates. This ~~was~~ view was later accepted by Green (1917. p.13) and the outcrop shown on his sketch map.

Only about six feet of strata are exposed at the contact and the dip 75° south 20° east. In the field these rocks look very much like metamorphosed argillaceous sediments being a greenish grey very micaceous and well cleaved - quite unlike contact bedded tuffs of either the Shap or Eskdale area. It is overlain by a metamorphosed porphyritic andesite.

Under the microscope the so called Skiddaw Slates are seen to consist of an aggregate of quartz and muscovite with some weakly pleochroic yellow green or yellow brown mica. Sericitisation has been recorded from contact hornfelses near Bootle (Rose in Trotter. 1937) and probably the abundant sericite is due to metasomatism by late stage solutions which caused the griesenisation of the adjacent granite. However, most of the larger muscovite flakes are primary. There is no evidence of sericitisation in the overlying biotite hornfels and nearby metamorphosed lavas.

(g) Metasomatism.

(i) Albitisation.- As at Shap it has been noted that the ground mass felspars have a refractive index lower than Canada balsam. Staining with sodium cobalti-nitrite shows that no potash felspar is present and indicates that the clear felspar in the ground mass is albite. It thus appears that in the high grade thermal metamorphism of andesite under equilibrium conditions all the available potash goes into biotite and the soda into plagioclase. The lack of calcic plagioclase suggests that lime is removed and it is later suggested (p.59.) that this lime is carried outwards in solution and has been responsible for the epidotisation of andesites beyond the thermal aureole. This process would be favoured by a certain amount of soda and silica metasomatism and the presence of volatiles, particularly carbon dioxide. As discussed previously (part i. p. 86) laboratory experiments by Eskola, Vuorista and Rankama (1937) showed that heated under pressure with sodium carbonate, silica and excess carbon dioxide anorthite is readily converted to albite according to the following reaction:-

$$CaAl_2Si_2O_8 + Na_2CO_3 + 4SiO_2 \longrightarrow 2NaAlSi_3O_8 + CaCO_3$$

Anorthite Albite.

Similar conditions are likely to occur at the granite contact but lack of chemical data prevents any estimation of the importance of the above reaction in the Eskdale district. It should be noted however that only the ground mass felspars are albitised. Twinned felspar of labradorite composition has been recorded from recrystallised phenocrysts in contact rocks.

The formation of secondary albite accompanies the epidotisation of andesites on the fringe of the thermal aureole and this is described later (p.).

No definite evidence of potash metasomatism has been found although biotite apparently replacing hornblende has been recorded.

Chloritisation.- Contact hornfelses from various parts of the granite contact show varying degrees of alteration of biotite whilst some (e.g.R.J.82 from Blea Tarn Hill) are quite fresh and unaltered.

This chloritisation is best seen in slices of rocks from the Oliver Gill - Whinscales granite contact but similar though less extensive chloritisation has been recorded from

Great Barrow (E 16982). Biotite in the former area is sometimes replaced by muscovite but more often by a strongly pleochroic chlorite, probably penninite. This replacement has a patchy distribution in the rock but within these patches the biotite is almost completely replaced optically by scales of chlorite. Most of this chlorite is strongly pleochroic - yellow to olive green $\omega > \varepsilon$ sign +ve. Under crossed nicols the anomalous blues characteristic of penninite are seen. The composition of the muscovite has not been investigated.

At the contact in Robin Gill chloritisation is more intense the rock consists of an aggregate of isotropic scaly green chlorite sericite and iron ore granules. It seems probable that the andesite from Rigg Beck, south of Devoke Water, is another chloritised contact hornfels. Green (1917. p.13) maintains that this andesite is unmetamorphosed but a rock slice in the Geological Survey Collection (E 16946) shows it to be very similar to the Robin Gill specimen.

Probably this chloritisation of contact hornfelses is associated with the late stage chloritisation and sericitisation of the granite (Simpson 1934).

Epidotisation.- Towards the outer limit or just outside the zone of biotite bearing rocks lies a belt of epidotised andesites. Associated with this, secondary felspars (albite) and some calcite have developed. Officers of the

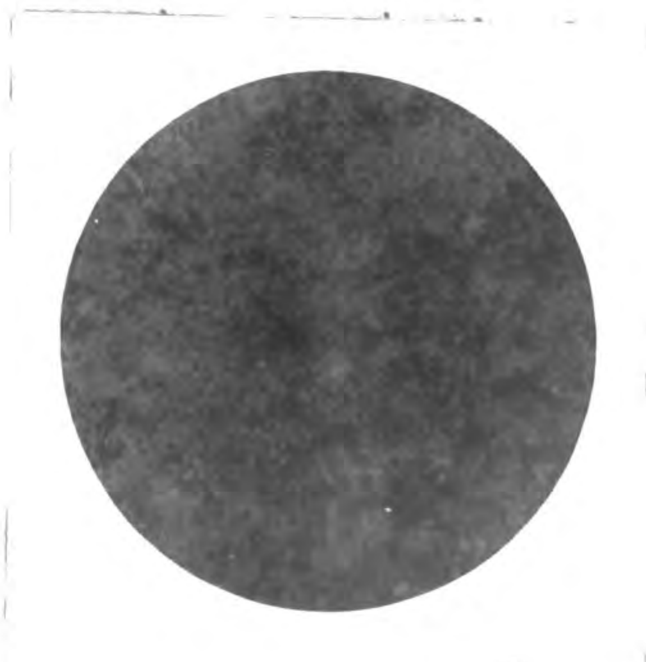


Fig.12.(R.J.37a.) Hornfels near the granite contact
Raven Crag, Eskdale.
Penninite replacing biotite in the ground
mass.(x 35.).

Geological Survey (1937.p.33) noted "a good general increase in the intensity epidotisation eastward towards the igneous masses of Ennerdale and Eskdale " on the west side of these intrusions. . They further suggested that, "these intrusions may have played a part in effecting some of these changes." Green (in Hartley 1932) also noted the abundance of epidote in lavas around the Eskdale granite.

The writer has not mapped far enough eastward to confirm that the epidotised andesites form a definite zone outside the biotite hornfelses but mapping by Oliver and the writer suggests this. The porphyritic lavas of Border End - Harter Fell - Kepple Crags area are certainly more intensely epidotised than is usual in the Borrowdale Volcanic Series. Furthermore a traverse from Wrynose over Hardknott Pass and Harter Fell suggests an increase in intensity of epidotisation westward towards the biotite hornfelses of the Eskdale granite aureole. The epidotisation and formation of secondary albite appears on too large a scale to be explained by autometamorphism.

In discussing saussuritisation of plagioclase, Turner (1948.p.121) points out that it is often complementary to changes such as the uralitisation of pyroxenes which take place simultaneously. The chemical reactions involved in the epidotisation of plagioclase can thus be represented as follows, secondary albite being derived from the breakdown of basic felspars.

$$8\ CaAl_2Si_2O_8 + 4\ CaO + 2SiO_2 + Al_2O_3 + 3\ H_2O \longrightarrow 6\ Ca_2Al_3(SiO_4)_3(OH)$$

Anorthite 806 cc.   Clinozoizite. 813 cc.

Furthermore it has been suggested (Turner 1948) that the necessary lime, silica, and alumina could be contributed as by-products of the uralitisation of pyroxene. Thus with the introduction of some water, epidotisation could take place in conditions which favour the uralitisation of pyroxene. It has been noted that the development of hornblende from chloritised pyroxene seems to be due to thermal metamorphism, (p. 37.) and, since hornblende is often associated with epidote, it would appear that the above reaction could take place with slight elevation of temperature and the introduction of watery solutions. However, it is doubtful if sufficient alumina would be available solely from the uralitisation of pyroxene. Such conditions would be expected at the margin of the Eskdale aureole. However, epidote could equally have been formed during the deuteric stage in crystallisation of the andesite lavas. Similar conditions also existed in low grade metamorphism and much of the epidote in sheared lavas elsewhere in the Lake District has this origin. Further, in many instances (e.g.R.J.109) where pyroxene phenocrysts have been replaced by hornblende the felspars are comparatively unaltered. The large scale of the epidotisation and its proximity to the granite suggests the metasomatic introduction of material from the granite.

Turner suggests that clinozoizite and albite may be formed by the metasomatic introduction of soda and silica as follows:-

$$12\ CaAl_2Si_2O_8 + Na_2O + 6\ SiO_2 + 3H_2O$$

$$\longrightarrow 6\ Ca_2Al_3\ (SiO_4)_3(OH) + 4\ Na\ AlSi_3O_8 + \underset{\text{(removed in solution)}}{Al_2O_3}$$

It has been suggested (p.) that some of the alumina and lime for the formation of epidote veins in the Shap hornfelses has been derived as a result of albitisation in contact hornfelses. Possibly, due to the abundance of open joints, aqueous solutions in the Eskdale district have extended further than at Shap. Furthermore as at Shap calcite is intimately associated with epidote and the formation of epidote was undoubtedly accompanied by the introduction of carbon dioxide. At Eskdale there is little direct mineralogical evidence of the composition of the granite residual liquid. However as at Shap it is likely that the late stage hydrothermal solutions were rich in silica, lime and volatiles such as carbon dioxide. Solutions causing epidotisation may have been derived directly from the granite.

Thus, whilst epidotisation of andesites and tuffs may be partly due to deuteric effects, or low grade regional metamorphism, the intense epidotisation in the Harter Fell area is attributed to the effect of watery solutions from the Eskdale granite. Epidote and secondary albite will form from plagioclase in conditions conducive to the uralisation of pyroxene but the abundance of calcite and epidote suggests the metasomatic introduction of lime, alumina and carbon dioxide. These were probably derived mainly from granitic residual liquids, but some lime and alumina may have been by-products of the albitisation of plagioclase felspar at the granite contact.

VI SUMMARY and CONCLUSIONS.

The study of the north eastern part of the Eskdale granite aureole has shown:-

(1) The aréa north and east of the Eskdale granite is predominantly occupied by porphyritic andesites and interbedded tuffs. These are probably equivalent to Hartley's Mosedale Andesites (1928) but differ in lithology and probably originated from a different source. The porphyritic andesites are fresher and less altered than the Wrengill andesite around the Shap granite.

(2). These Borrowdale lavas and tuffs were folded and faulted during the Caledonian orogenesis. A conjugate fault system was developed and evidence has been found of a later east-west shatter belt with associated shearing and tear faulting extending from Cockley Beck over Hard Knott Pass.

(3). The exposed part of the Eskdale granite mass probably represents a partially unroofed stock, the steep sides of which may be seen in Upper Eskdale near Taw House.

(4). The form of the aureole reflects the form of the granite mass and suggests that Scafell and Slight Side are underlain by granite and that the Wasdale Head granite is part of the Eskdale granite.

(5). The age of the granite intrusion is doubtful but it is affected by faulting thought Caledonian in age and it has metamorphosed the

Borrowdale Volcanic Series into which it has been intruded.

(6). Metamorphism of the surrounding lavas and tuffs is generally similar to that at Shap. Complete recrystallisation of both phenocrysts and ground mass is rare and limited to the contact hornfelses. This may be partly due to the fresher character of the unmetamorphosed lavas and partly to lower temperatures at the granite contact compared with Shap.

(7). Garnets thought by Oliver to be pyrogenetic are generally stable in the presence of the granite.

(8). Metasomatism appears to be limited to chloritisation of biotite in some contact hornfelses and epidotisation, with associated albitisation, of andesites near the outer limit of thermal metamorphism.

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On the occurrence of nacrite at Shap, Westmorland.

By R. J. Firman, B.Sc., F.G.S.

Department of Geology, Durham Colleges in the University of Durham.

[Taken as read June 11, 1953.]

During a recent investigation of the hydrothermal mineralization associated with the Shap granite, nacrite was found in a quartz vein in the Shap Blue quarry. This quarry has been opened for roadstone in the metamorphosed Borrowdale lavas, 700 yards north of the granite contact on the west side of the Penrith–Kendal road, three miles south of Shap village. Further examination showed that nacrite often coats shear joints in fault breccias and shatter belts in the metamorphosed andesites. It is associated with chlorite, haematite, pyrite, and traces of erythrite, and often with later quartz, calcite, and baryte veins.

Nacrite from this locality occurs as microcrystalline aggregates on joint faces, usually only in thin layers but layers up to 5 mm. thick have been found. It varies in colour from a pale apple-green to white with sub-nacreous lustre and is recognized in the field by its colour, softness (hardness 1·5), and greasy feel. The refractive indices are α 1·559, γ 1·567, birefringence 0·008 ($\pm$0·002). The variations in colour are possibly due to chlorite impurities, since the colour is removed by warm dilute HCl, and whilst no chlorite lines occur on the X-ray powder films, nacrite treated with HCl gave a better, more clearly defined powder pattern. The X-ray powder data given in table I is comparable with other data in the literature.

Table I. X-ray powder data in kX units for nacrite from Shap.

d.	Int.	*d.*	Int.	*d.*	Int.	*d.*	Int.
7·15	s	2·413	s	1·484	m	1·040	w
4·42	vs	2·293	w	1·451	vw	0·961	vvw
4·06	m	2·128	mw	1·375	vw	0·894	vvw
3·58	s	1·907	m b	1·330	w b	0·859	vvw
3·36	w	1·862	vw	1·263	mw		
3·06	s	1·676	w b	1·230	w b		
2·58	m	1·630	w b	1·151	vvw		

Order of decreasing intensities: vs, s, m, mw, w, vw, vvw; b broad. 9 cm. diameter camera Cu-*Ka* radiation ($\lambda = 1·5374\ kX$). Impurity lines were also found on some films at 10·3, 4·81, and 3·26.

A bibliography given in a recent paper by von Knorring, Brindley, and Hunter (1952) lists the occurrences and gives X-ray data for the mineral species nacrite as redefined by Ross and Kerr (1931). The material described above appears to be identical with this species. Ross and Kerr suggested a pneumatolytic or hydrothermal origin for nacrite from Saxony and Colorado, whilst nacrite occurring in sphaerosiderites in the Kladno Coal Measures and Ordovician slates in Bohemia is thought to be hydrothermal (Kasper, 1933; Ulrich, 1935). The present occurrence most closely resembles that at Groby, Leicestershire (Claringbull, 1952), where fine-grained aggregates of nacrite occur in belts of shearing in syenite. The Shap mineral is clearly associated with the hydrothermal effects of the Shap granite, since it is found in fault breccias which have been proved to have formed after the metasomatism of the country-rocks, but which themselves are filled with minerals of the Shap granite genesis. However, nacrite is confined to shear joints and does not occur in tension joints so that it appears to be associated with the period of shearing.

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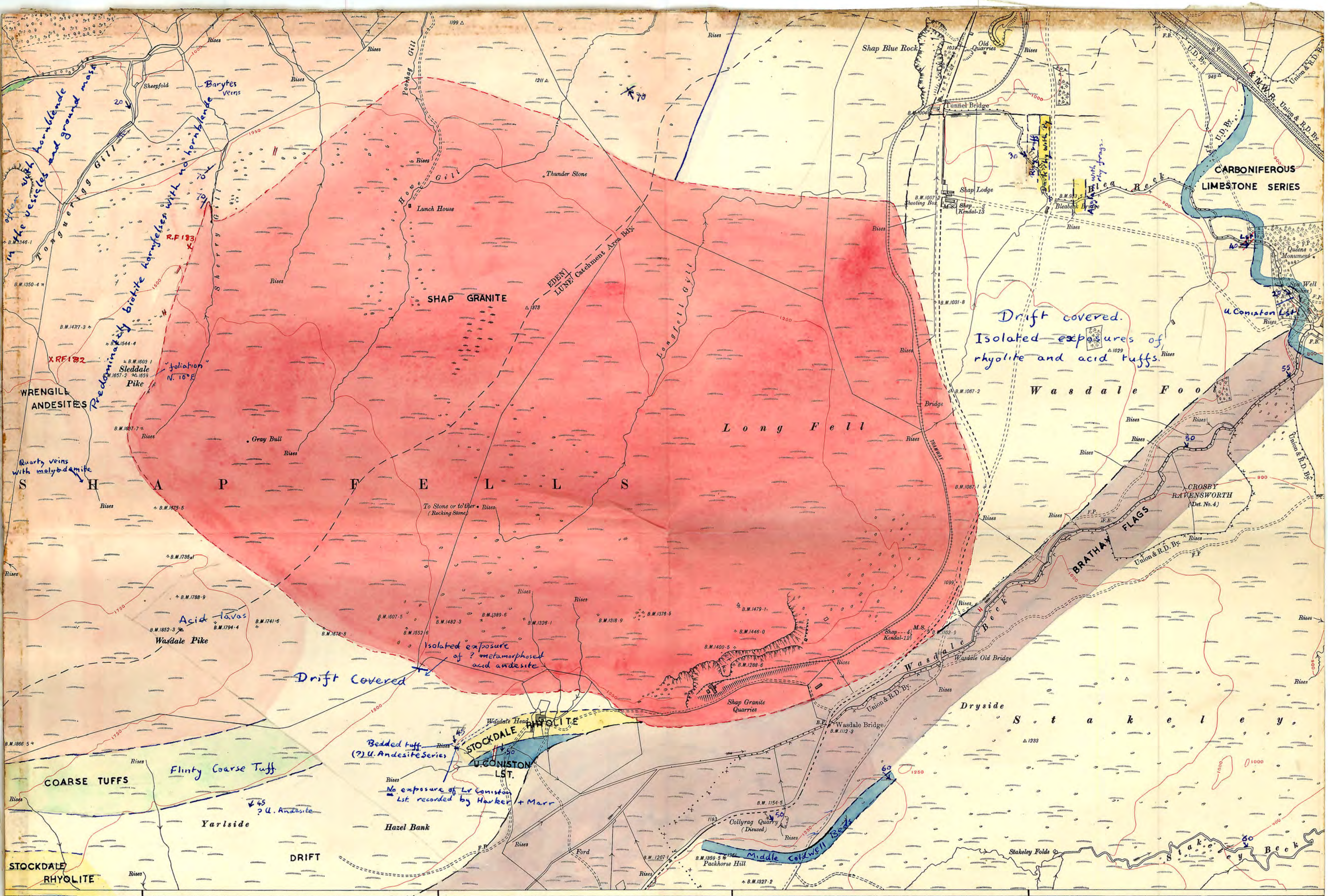

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Surveyed in 1858-9. Revised in 1911. Levelling Revised in 1914. Reprint. 76/84. 76/86. 50/45.

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EAST AND WEST WARD UNIONS BIRKBECK FELLS COMMON (Undivided Moor)

Scale _ Six Inches to One Statute Mile or 880 Feet to One Inch = 10560

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County Boundary
Parliamentary Division Boundary
Union Boundary
Rural District Boundary
Parish Boundary
Catchment Area Boundary

Antiquities, Site of
Arrow, shewing direction of flow of water
Contours Instrumental 200
Contours Sketched 225
Trigonometrical Station

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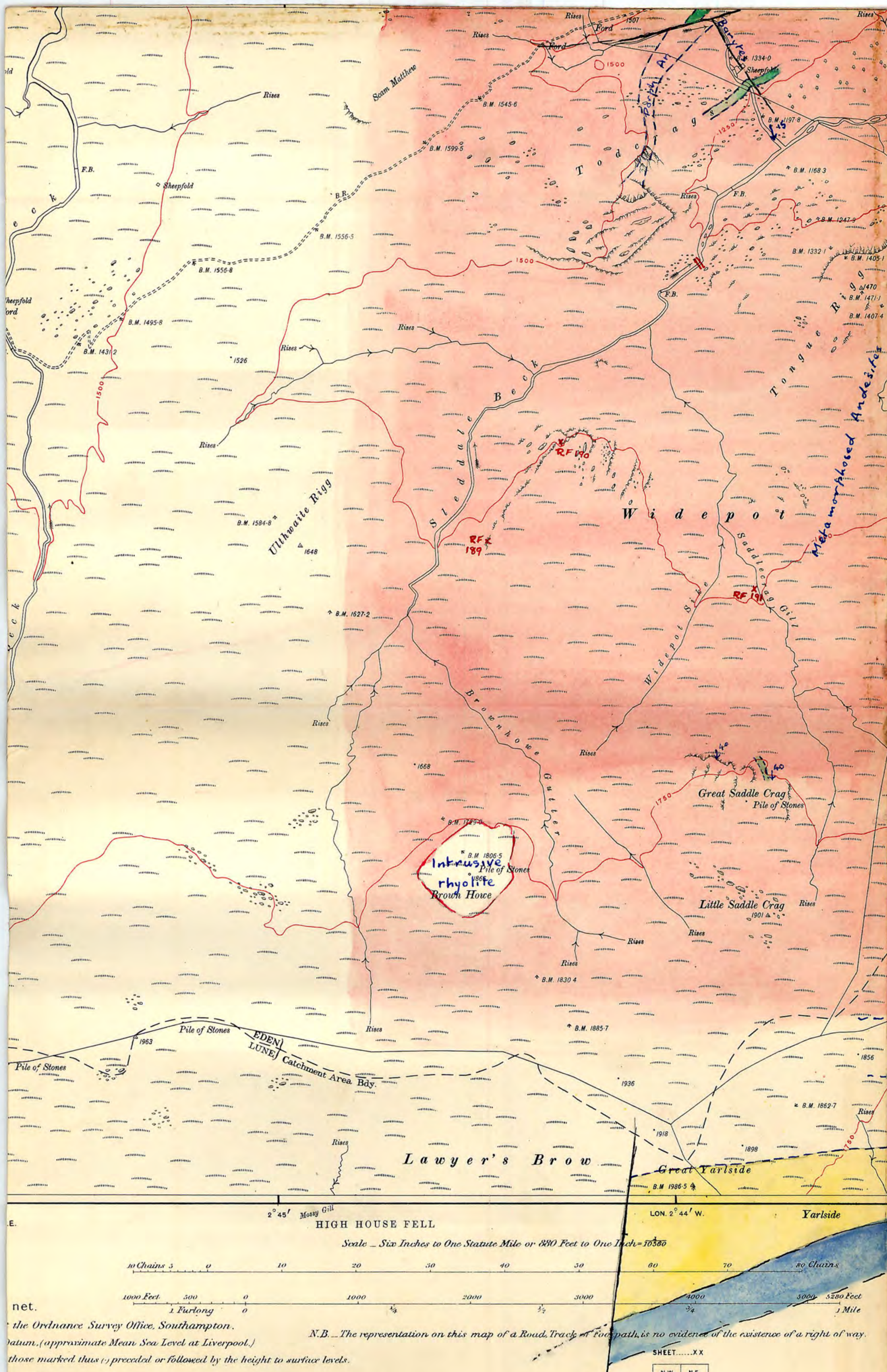
S.W. S.E.



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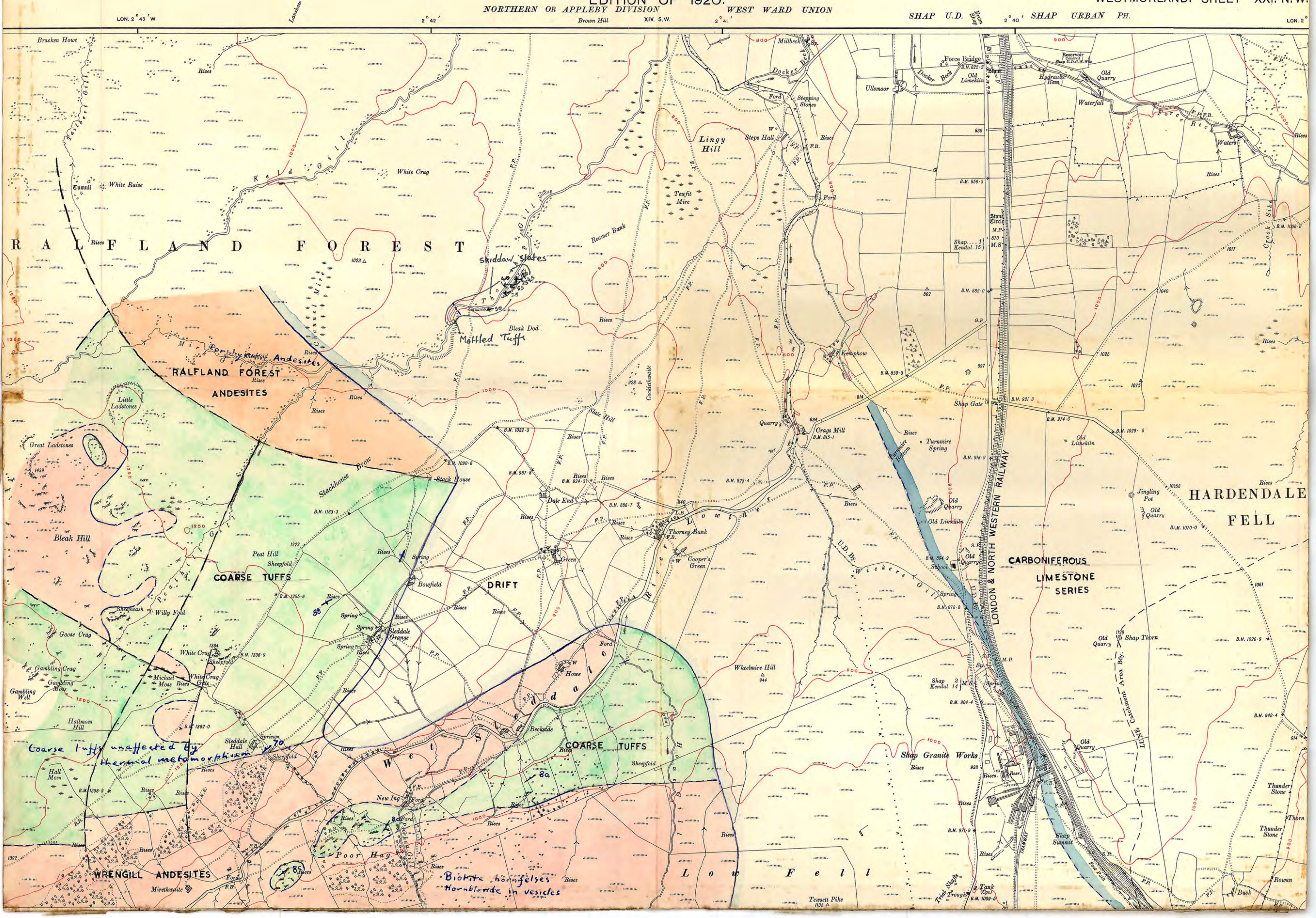
WESTMORLAND. SHEET XXI. N.W.



KEY

Eskdale granite

Associated dykes

Bedded tuffs

Rhyolite

Acid andesite

Porphyritic andesites uncoloured

Boundaries

Observed

Inferred

Conjectural

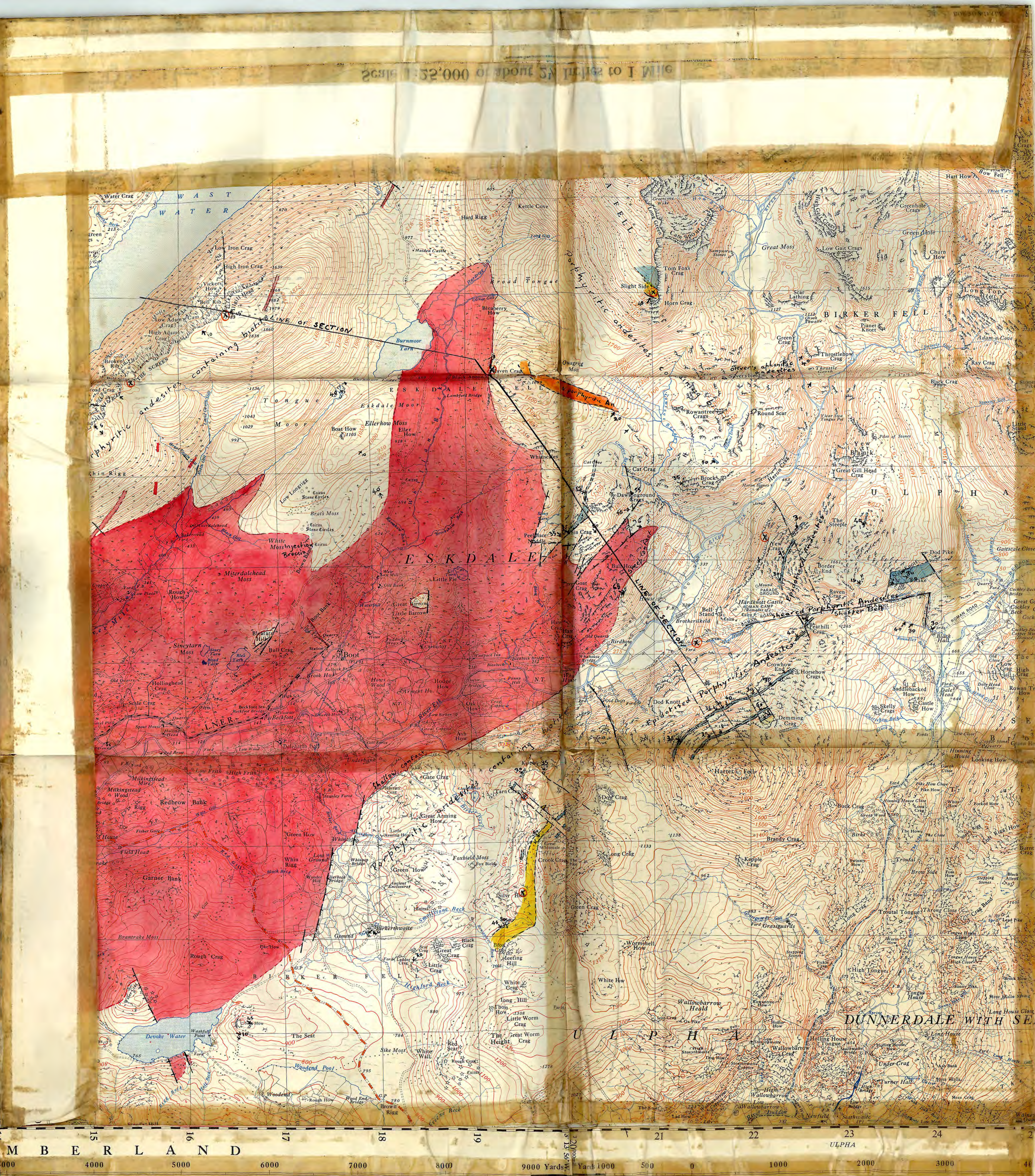
Granite contacts in red

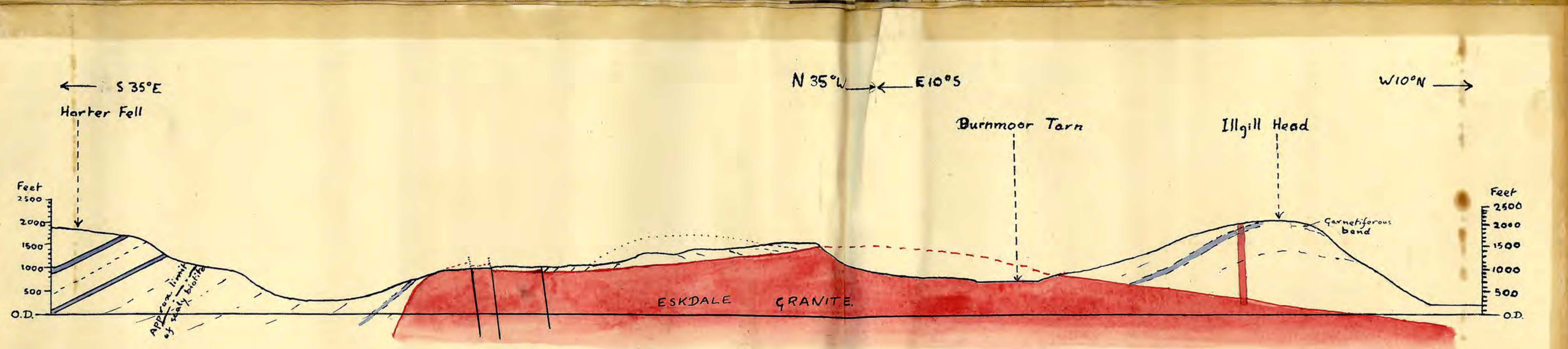
Garnetiferous localities

Map constructed from 6" field slips

07
06
05
03
02
01
500000mN.
54° 23′ 21″
99
98
97

Miles 5 4 3 2 1 0 1 2 3 4 Furlongs 4 3


LINE OF SECTION
Burnmoor Tarn
ESKDALE
BIRKER FELL
Porphyritic andesites
Sheared Porphyritic Andesites
Shatter Belt
Harter Fell
Devoke Water
ULPHA
DUNNERDALE WITH SE
MBERLAND
9000 Yards


S 35°E
Harter Fell
N 35°W
E 10°S
W 10°N
Burnmoor Tarn
Illgill Head
Garnetiferous band
Feet
2500
2000
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1000
500
O.D.
ESKDALE GRANITE