GEOLOGY OF THE

GREENSIDE LEAD MINE, CUMBERLAND.

BY

DAVID GOUGH

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Greenside Lead Mine viewed from the south side of the Glenridding Valley.

Abstract

The Greenside Vein, an isolated ore deposit in the Lake District mining field, has yielded approximately 200,000 tons of lead concentrates. The ore deposit is a simple fissure infilling along a normal fault; a study of the factors controlling the localisation of the fault, and the individual ore shoots, forms the greater part of this Thesis.

The area in the vicinity if the mine is composed of two series of strata - the Skiddaw Slates and the Borrowdale Volcanic Series. The former series, of which only the topmost strata are represented in this area, are composed of shales. The overlying Borrowdale Volcanic Series, which is 5000 to 8000 feet in thickness, includes andesites, basalts and rhyolites, in addition to volcaniclastic rocks. Caledonian dykes and small plugs, composed of several rock-types, intrude the strata. The two main folds in the area are broad open structures, and probably have a Caledonian age, although they were accentuated during later earth movements. The tectonic sequence is complex, and three groups of faults, each with a characteristic type of mineralisation, have been recognised; the groups can be referred to the Caledonian, Hercynian and post-Triassic earth movements. The fault along which the Greenside Vein lies, was formed as a result of doming during the Hercynian earth movements; it was localised by the junction of the Skiddaw Slates and the Borrowdale Volcanic Series, and by a quartz-porphyry dyke. The ore shoots are controlled mainly by favourable variations in the dip and strike of the fault. A graphical representation of the fault plane, which provides a quantitative approach to the localisation of ore shoots, has been developed.

In addition, the wall rock alteration associated with the ore deposit, and the paragenesis, zoning, and geochemistry of the vein have been studied, and have enabled the physico-chemical conditions during ore deposition to be outlined. The relation of the Greenside Vein to the Lake District mining field has also been discussed.

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CHAPTER 1

INTRODUCTION

1. Geography

The Greenside Lead Mine, prior to it's closure in 1961, was the property of Greenside Mines Ltd. The mine is situated in the Lake District, one and a half miles west of the south-western shores of Ullswater (Fig. 1.1). The main London to Glasgow railway passes through Penrith, the nearest town, which is twelve miles from the mine by road. Windermere and Keswick are a similar distance, while the mearest railway station at Troutbeck, lies on the Keswick road some eight miles from the mine.

The nearby village Glenridding, sited on the shores of the lake, supplied the greater part of the mine labour force. The mine buildings and the main adit are located on the north side of the Glenridding valley at an altitude of approximately 1000 feet O.D. The mine, as can be seen from Fig 1.1, lies on the east side of the Helvellyn range, which separates Thirlmere from Ullswater.

The broad physical features of the region were determined mainly by erosion during the Ice Age, the structure and relative hardness of the underlying Borrowdale Volcanic rocks only being reflected in the minor details of topography. The Helvellyn range shows a marked asymmetry. On the west side, the smooth but steep slopes, cut by small hanging valleys, sweep down to the wooded shores of Thirlmere. On the other side of the watershed, the roughly E-W, U-shaped va leys of Glenridding and Glencoyne, and the NE-SW valley of Grisedale, separate broad ridges which extend to the shores of Ullswater. The flanks of the ridges are cut by several hanging valleys and towards Helvellyn, a few of these

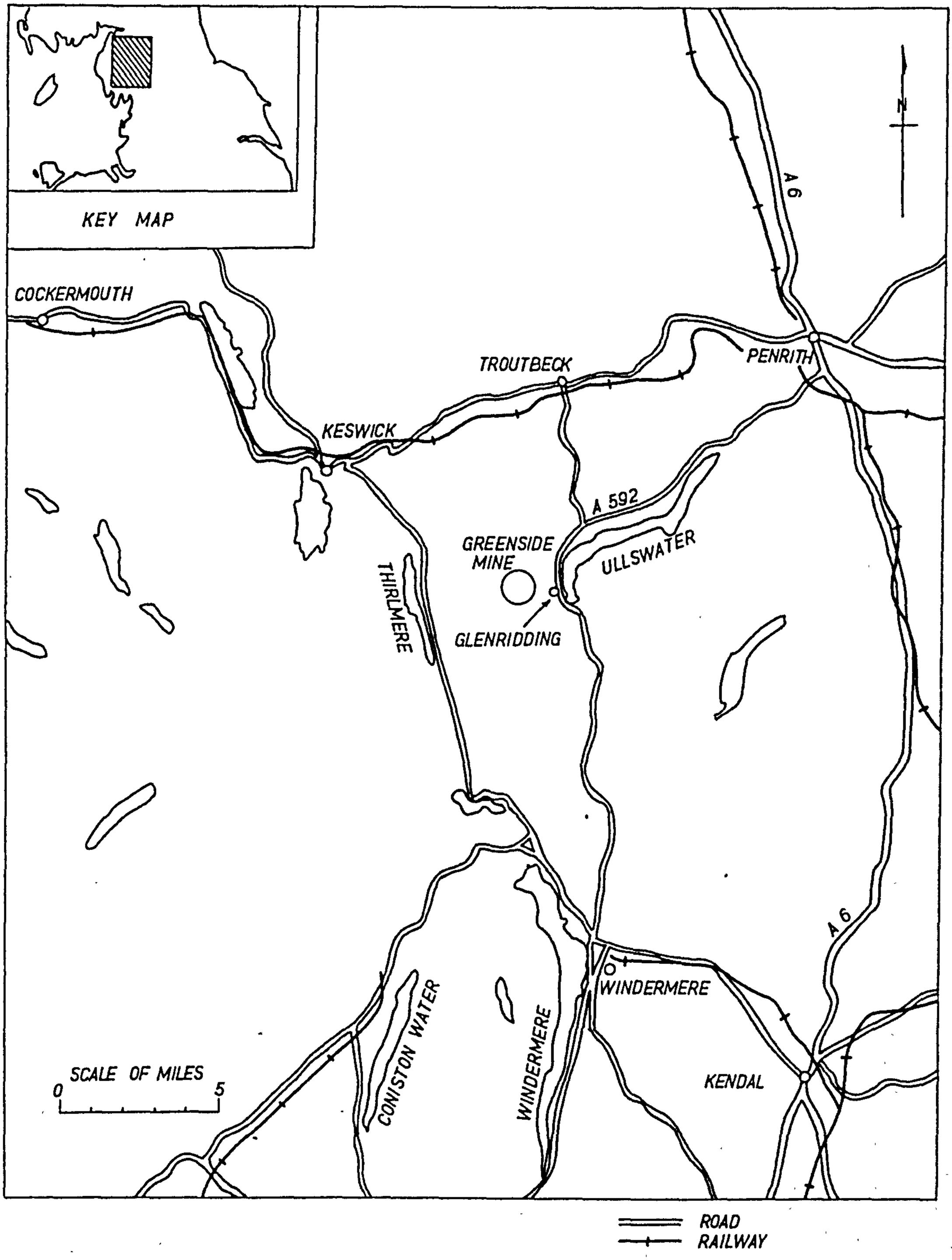


FIG. 1.1 LOCATION OF GREENSIDE MINE

end in corries. The sides of the latter are precipitous and their rear walls, which nearly reach the watershed, face towards the east. The corries of Nethermost Cove, Red Tarn and Brown Cove are separated respectively, by the sharp aretes of Striding Edge and Swirral Edge. The scenery of the northern part of the map area tends to be more subdued and grades northwards into the flat featureless, boggy area of the vale of Threlkeld, which is underlain by the Skiddaw Slates.

The average rainfall is 90 inches per annum. The streams draining Red Tarn, Kepple Cove and Brown Cove, and Top Dam were used as a source of water for the mill, and also for supplying power (initially water power and later electrical power) to the various plant used at the mine.

Over 90% of the area lies above 700 feet O.D. and is non-arable and suitable for sheep only. The vegetation cover is composed mainly of grass, bracken and heather, with sporadic clumps of juniper and gorse. The slopes of the mountains which sweep down to the lake are partly wooded with beech, oak, silver birch and Scots pine. There are also small plantations of spruce. The only arable land is found in the areas of low relief near the shores of Ullswater. The farms in the lower part of the Glenridding valley and at Glencoyne maintain small herds of dairy cattle and have a small acreage of arable land. Both Ullswater and the streams which flow into it, are well stocked with trout. Foxes are common and fox-hunting is a favourite local sport. Rabbits are found in the low-lying areas near the lake, while deer and wild ponies are occasionally seen.

The striking, unspoilt scenery of the area, certainly some of the finest in the Lake District, attracts many tourists. The mountains

although not noted for their rock climbs, are famous. The strict control exercised by various authorities, for the protection of the scenery, has caused many difficulties for the mine, for example, in the camouflaging of the tailings dumps. Generally the work of these authorities is to be commended, but it is felt that in some cases they may have overstepped the mark. The closure of the Hartsop Hall Mine, located in the Patterdale area, caused by the acquisition of the land by the National Trust, is a case in point.

2 History

Many of the mines in the Lake District are of great antiquity. The Romans are thought to have worked copper at the mines near Keswick and at Coniston, and it is conceivable that the Britons worked there before them. In the Elizabethan era copper mining was a flourishing industry in the Vale of Newlands, at Coniston and in the Caldbeck Fells.

The early history of Greenside Mine is obscure and it is uncertain whether in fact it was worked in Elizabethan days. According to local tradition handed down by word of mouth, the mine is said to have been worked by the German miners of Keswick. The only documentary evidence to substantiate this, is entries in the parish register of Patterdale concerning the burial of lead miners in 1713 and 1754.

The earliest authentic evidence of the mine being in existence is contained in an invoice of the Greenside Mining Company, dated 1859, which refers to the working of the mine by various companies since 1784. Clarke in his "Survey of the Lakes", published in 1787, refers to the influx of miners from various parts into the Patterdale area some thirty years previously.

The Greenside Mining Company was formed c.1815, but difficulties in obtaining a lease and disputes over the land ownership prevented the mine from working fully until about 1827. From this year, until 1920 when the company went into voluntary liquidation, the mine was operated almost continuously.

A new company was formed in 1923 but in 1927 the company's reservoir at Kepple Cove burst, causing extensive damage to property in Glenridding. Compensation was heavy and the company never recovered financially.

In 1936 the Basinghall Mining Syndicate took over the property and work at the mine was resumed. 1954 saw the name of the company changed to Greenside Mines Ltd., and under this company the mine operated until very recently. On the 26th. of April,1961, the last ton of ore was milled thus closing the book of the mine's long and fruitful history.

3. Development

A. 18th. Century to 1935

Map 1, Plan 1, and Section 1 (in pocket) show respectively the position of the adits on the surface, the layout of the mine workings, and the areas of the vein stoped.

Prior to 1800 the vein was worked neither extensively nor continuously. The operations were confined to the hillside above the present-day High Horse adit and at an altitude of between 1800 feet O.D. and 2200'O.D. It is probable that the vein was originally worked by means of short levels into the hillside. According to Postlethwaite (1913)* most of the ore was carried over the mountains, through the Vale of St. John and Keswick, to be smelted at Stoney Croft Gill.

The driving of the High Horse level (adit portal at approximately

* refer to bibliography

1780 feet O.D.) was probably initiated between 1800 and1815. Following the formation of the Greenside Mining Company, the level was extended, and then later, a connecting level was driven from the head of Glencoyne Dale. The adit of the Low Horse level, which was started in 1842, lies to the south-east of the High Horse adit, at an altitude of approximately 1580 feet O.D.

In 1853 the Lucy Tongue level was started. The adit portal is located on the north side of the Glenridding valley, at a height of 1082 feet O.D., and is some distance to the south-east of the ore-bearing ground. The first section of the level follows the N-S Lucy Tongue Fault and the second section the E-W Clay Fault. In 1871 the level was completed after eighteen years of work. The total distance driven was just over one mile and like all the previous workings, was drilled entirely by hand, with "black powder" as explosive. Dynamite and compressed air drills were only introduced in 1874.

The vein above the High Horse level had been worked to a great width and fairly close to the surface. In 1862 the ground above collapsed and an immense quantity of ore and rock, estimated at 900,000 tons, filled the stopes below. This fall was known as the "Big Crush", and although ore was recovered from it for several years, much had to be left as it became too dangerous.

By about 1855, most of the ore above the Lucy Tongue level had been exhausted and operations were subsequently confined to the ground below. At this juncture, it may be noted that the Lucy Tongue level is used as a datum level to which all the lower levels are referred. In 1891 the sinking of the vertical Smith's shaft, in the sole of the Lucy Tongue

level, about one mile from the adit, was started. When completed it extended down to the 105 fm. level and opened up four intermediate levels. The vein was found to continue in depth and subsequently, during the First World War, a new shaft was started at a position just south of the Smith's shaft on the 90fm. level. This inclined shaft, know as Murray's, was sunk on the vein down to the 200 fm. level, and opened up four intermediate levels.

The original ore-dressing equipment, sited near the adit of the High Horse level, was of a very primitive nature and was not workable during the winter months. Better equipment was installed in 1842 and then, following the completion of the Lucy Tongue level, a mill was built in the Glenridding valley, near to the adit. The plant installed operated with modifications, until 1934.

During the period from 1800 to 1835, the concentrates were transported to Alston to be smelted. Subsequently a smelt mill was built at the mine and operated until 1919.

Originally water-power, supplied from turbines and water-wheels, was used to drive the hoists, compressors, pumps, crushers and other equipment. Horses and ponies were used for the tramming. 1891 saw the introduction of electricity generated from hydro-electric plants, and the electrical winding gear later installed in Smith's shaft was the first of it's kind in a British metal mine.

B. <u>1936 to 1961</u>

When the Greenside Mining Company wound up their operations in 1934 there only remained small ore reserves. The large block of ground at the south end of the mine was apparently pinching out in depth and

to the north the stopes ended near a cross fault (the North Fault). The new company, Basinghall Mining Syndicate, concentrated exploration in this latter region, on and below the 90 fm. level. The vein was found to continue to the north of the North Fault and furthermore, a branch vein, known but not worked by the old company, was developed and found to be payable. The production from the extension of this block (1000 to 1700 N) below the 90 fm. level proved to be greater than any other single block worked by the company.

In 1943 the New shaft was sunk in order to develop the 1000 N to 1700 N block below the 200 fm. level. The shaft intersected Skiddaw Slates and subsequently this rock was encountered in the levels below. The vein was found to pinch out when it reached the rock, and a diamond drilling programme to explore the continuation of the vein in depth proved unsuccessful. Ore reserves in this area of the mine were thus limited.

In 1940 the driving of the 120 fm. level to the north of the 1000 N to 1700 N block had proved a continuation of the mineralisation to 2700 N. Blocks in the 1700 N to 2700 N region were worked at the same time as the 1000 N to 1700 N block, but by 1948 the reserves of both blocks had dwindled and the continuation of the former in depth seemed unlikely. However, in 1949, the mine was given new life when ore-bearing ground was found at 2100 N on the 175 fm. level. Subsequently this discovery led to the extension of the northern part of the 1700 N to 2700 N block from the 120 fm. level, down to the 217 fm. level.

During the period from 1950 to 1957 exploration was carried out between the Alma and the 120 fm. levels with the view to locate possible

branch veins associated with a quartz-porphyry dyke. The work proved to be unfruitful, as also did the exploration of the continuation of the vein at the north end of the mine.

By 1957 the ore reserves had again seriously diminished, and therefore the last line of attack - the search for the southerly extension of the Greenside Vein south of the Clay Fault - was launched. An extensive amount of work was carried out but no payable mineralisation was found. Further exploration in any part of the mine was not justified, and so in 1961 the company was forced to wind up its operations.

4. Methods of Mining

The Greenside production has been almost entirely from a single vein which has however, several important branches. The vein varies in width from a fraction of an inch up to some thirty feet. The ore has chiefly been won by shrinkage stoping, the average stope-width below the Lucy Tongue level, being about 8.5 feet. In narrow parts of the vein, necessitating a stope-width of less than 6 feet, underhand stoping was employed. Stope widths of fifty feet were recorded in the old workings above the Lucy Tongue level, but here the ore-bearing ground probably comprised several stringers in the country rock rather than a single vein. The stope walls are generally hard and silicified; slabbing-off was seldom a problem and pillar supports were not required.

Levels driven in the vein or in the country rock which is unaffected by faulting, seldom needed support. However the levels along the barren sections of the Greenside Fault often needed to be timbered.

All the ore produced from below the Lucy Tongue level was raised via Murray 's and Smith's shafts. Both shafts had three compartments, two of which were used for hoisting, the other containing a manway. The Lucy Tongue level, from it's completion in 1871 until the closing down of the mine in 1961, has been the only haulage-road to the surface.

5. Production

The total production of Greenside Mine was approximately 2,400,000 tons of ore, which yielded 200,000 tons of PbS concentrates and nearly 2,000,000 ounces of silver. The mine may thus be ranked with the eight other mines in Great Britain which have produced more than 200,000 tons of PbS concentrates (Dunham (1959) I.M.M. Symposium). Although no accurate production figures are available for other Lake District mines, it is probable that Greenside Mine accounts for at least 60% of the total production from this area. Table 1.1 shows the production during various periods of the mine's history.

Records of production were not kept prior to 1835 but it is certain that the quantity of concentrates produced up to this time, formed only a small percentage of the total recorded production. From 1835 to 1919, when the lead was smelted at the mine, the production was recorded in terms of pig lead. The figures have been converted, for uniformity with later production, to 78% Pb concentrates and 7% Pb ore, using respectively a 90% and 100% recovery in the milling and smelting. The grade of the concentrates and the percentage recovery during this period were however, certainly lower than the above figures. Records of the silver production were kept from 1836 to 1919 but the figures quoted for the later periods have been calculated from assay values.

Table1.1 Production

Company	Period	Ore: tons	Concs: tons	Ag: oz
Various	pre 1835	60,000?	5,000?	50,000?
Greenside Mining Co.	1835-1922	1,454,000	117,443	1,230,000
Greenside Mining Co.	1923-1935	130,000	12,991	130,000
B.M.S.and Greenside Mines Ltd.	1936-1961	794,914	65,630	541,000
Total recorded production		2,379,000	196,064	1,901,000
Total production (approx.)		2,439,000	201,000	1,951,000

When Basinghall Mining Syndicate took over the property, a new mill and crushing section were built. The mill operated until the mine closed and treated on average 120 tons of ore per eight-hour shift. From 1936 to 1961 the average grade of ore was 7.2% Pb, with a silver content of 8.5 oz. per ton of concentrates. The recovery and the grade of the concentrates averaged respectively, 85-90%, and 75-79% Pb.

Power for both surface and underground equipment was supplied by the mine's hydro-electric plant, initially supplemented and then later replaced by electricity from the North Western Electricity Board.

6. Previous Work

Prior to 1900, several mining engineers visited the mine and some of their private reports are still in existence. These contain useful data on the width and value of the vein in the older workings but

very little geological information.

In 1878 the Geological Survey published maps of the area. These are at a scale of 6 inches to 1 mile and although the positions of faults were accurately plotted, the rock-types were not clearly distinguished. It is uncertain whether the Survey geologists J.C. Ward and E.J. Herbert examined the underground workings, but certainly they obtained data, probably from the mine-manager, which was used in the compilation of the geological map and also in the Survey Memoir (1876). A brief account of the mine geology also appears in Borlases' paper (1894) and in Postlethwaites book "Mines and Mining in the Lake District" (1913).

Eastwood (1921) described the geology in greater detail in the Geological Survey publication "The Lead and Zinc Ores of the Lake District", and more recently in the I.M.M. Symposium on the "Future of Non-Ferrous Mining in Great Britain and Ireland" (1959). The only other publication specifically concerning the mine is a brief account by Connor (1951). Hartley (1941) covered the area during his surface mapping of the Helvellyn region, but failed to visit the mine and his map shows little relation to the underground geology.

In the early years of the operations of Basinghall Mining Syndicate and more especially from 1947 to the closure of the mine, the development and exploration have been carried out under the excellent supervision of Major H.R. Kerr. Several geologists including G.A. Schnellman, W.R. Jones, W.C.C. Rose, and S.E. Hollingworth have all submitted reports to the company. The majority of these reports were based on short underground visits, the only systematic work being carried out by J.D.Wilson who mapped most of the

accessible workings in 1939.

Existing views on the geology of the mine prior to the present author's work, may be summarised as follows:

The northerly-trending Greenside Fault cuts andesites and andesitic tuffs, which are low in the Borrowdale Volcanic succession. The structural relation between the Skiddaw Slates, found in the lower levels of the mine, and the overlying volcanics and the Greenside Fault was not fully understood. The Greenside Vein, a simple fissure-infilling which follows the Greenside Fault, shows well defined mineral zoning. The localisation of the ore-shoots are controlled primarily by two factors : firstly, the angle of dip of the fault-plane - a steep dip being more favourable, and secondly, by the presence of cross faults. In the northern part of the mine the Greenside Fault follows, for part of it's length, the margins of a quartz-porphyry dyke. The role played by the dyke in the structural control of the branch veins and ore-shoots was a vexed problem, as also was the effect of the Clay Fault on the continuation of the Greenside Fault to the south. Both the Clay and Greenside faults were held to be wide fracture zones, the vein along the latter swinging from one side of the zone to the other.

7. <u>Present Investigation</u>.

This Thesis is based on data collected during the period from September 1959 to August 1961. A total of five months was spent on the underground geological mapping, and two months on the surface mapping of an area of twelve square miles in the vicinity of the mine. The underground mapping was carried out at a scale 1" = 50 feet but where greater detail was required a scale of 1" = 20 feet was employed.

The surface geology was plotted on aerial photographs, the scale of which was approximately 6" - 1 mile.

Shortly after the cessation of production in April 1961, the adits were sealed so that now all workings are inaccessible. Many sections of the levels, especially those above the Lucy Tongue level have been inaccessible for many years, while others, though only abandoned during the last ten years or so, were inaccessible as a result of the "robbing out" of the roofs and soles.

All the accessible parts of the mine were examined and mapped. Table 1.2 shows the accessiblity of each level in September 1959.

Table 1.2 Accessible Sections of the Greenside Mineworkings. Sept. 1959.

Level	Accessible Sections
High Horse	1040 N - 2620 N
Low Horse	1535 S - 575 S, 1020 N - 2000 N
36 fm., 48 fm.	inaccessible
Alma	1390 N - 1560 N
Lucy Tongue	2760 S - 3030 N
20 fm.	570 N - 840 N
40 fm.	40 S - 1600 N
60 fm., 75 fm.	inaccessible
90 fm.	1000 S - 1465 N
105 fm.	inaccessible
120 fm.	320 S - 1560 N
135 fm.	400 S - 340 N
150 fm.	330 S - 320 N
175 fm.	1920 S - 2080 N
200 fm., 217 fm., 221 fm., 237 fm.	inaccessible.

CHAPTER 2 GENERAL GEOLOGY OF THE LAKE DISTRICT

1. Introduction

This chapter, in addition to describing the basic geology of the region, has been expanded so as to include an outline of several problems of Lake District geology, some of which are encountered in the Greenside Mine area.

The Lake District includes parts of Cumberland, Westmorland and Lancashire. The striking scenery of the mountains and lakes are too well known to need description.

This region, and that of the adjacent Howgill Fells to the south-east, are comprised of Lower Palaeozoic rocks which are girdled by Carboniferous and Permo-Triassic strata, (Fig 2.1).

The succession of the Lower Palaeozoic rocks is also shown in Fig.2.1. Basically there is a three-fold system - two thicknesses of geosynclinal sediments, predominantly argillites, being separated by a series of volcanic rocks. The total thickness of the rocks exposed is of the order of 35,000 feet. The extension of these Lower Palaeozoic rocks beyond the limits of the Lake District Inlier is proved by the similar succession found in the Cross Fell Inlier, located on the edge of the Pennines.

The broad distribution of the rocks is relatively simple. The oldest rocks, the Skiddaw Slate Series of lower Ordovician age, occupy a wide anticlinal belt which trends roughly NE - SW. The belt is flanked on both sides by the overlying Borrowdale Volcanic Series, the outcrop on the south flank occupying much the greater area and forming the central mountainous mass of the Lake District. Further south the

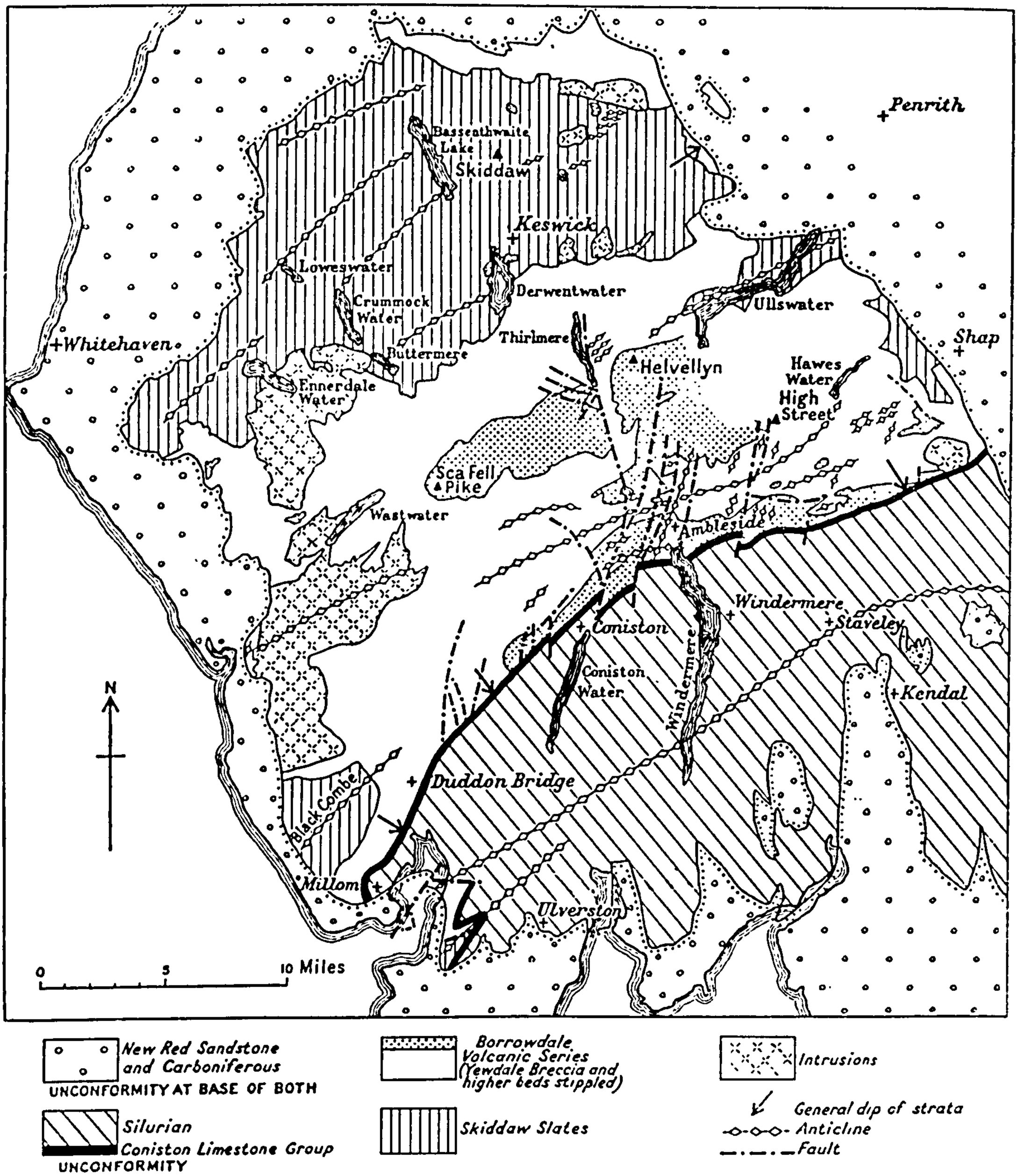


FIG. 2.1 GEOLOGICAL MAP OF THE LAKE DISTRICT (REPRODUCED FROM MITCHELL, 1956)

Coniston Limestone Group, of upper Ordovician age, and the Silurian strata underlie a great area which extends to the south-west almost to the shores of Morecambe Bay, and south-east to the Howgill Fells. Large areas of the Lake District are composed of intrusive rocks, probably of Devonian age. Acid to intermediate types predominate but taking the rocks as a whole there is a wide range of composition.

The rocks have been subjected to four periods of earth movements, viz. pre-Bala, Caledonian, Hercynian, and post-Triassic. The distribution and major structures of the rocks were determined primarily during the Caledonian orogeny.

The Lake District mining field has yielded lead, copper, zinc, iron, tungsten and barite. The ore deposits are all hydrothermal veins which have been formed by the infilling of fissures along steeply dipping, usually normal faults. In general, the veins seldom form a plexus but tend to have a sporadic distribution, occuring in both the Skiddaw Slate Series and the Borrowdale Volcanic Series. The veins are clearly the products of several metalogenetic epochs each probably associated with a period of orogenesis. The tungsten veins are associated with a Caledonian granite, the copper is probably of later date while the iron, lead, zinc and barite veins are apparently the youngest ore deposits.

2. Historical Review.

The geology of the Lake District has attracted and intrigued many famous geologists. In a few pages it would be impossible to summarise adequately the voluminous literature on the region, and the following brief account, describing only the landmarks of geological thought, must suffice.

The basic three-fold succession was first recognised by Otley in 1820. This sequence was substantiated by the work of Sedgwick (1848), Harkness (1863), and Nicholson (1866), all of whom paid special attention to the relation of the volcanics to the underlying Skiddaw Slates and the overlying Coniston Limestone Group - topics which have dominated the interpretation of Lake District geology.

Between 1870 and 1900, maps and memoirs were published by the Geological Survey. The work of the Survey geologists Aveline and Goodchild is to be commended but the maps by Ward suffer from his theory that the different types of volcanic rocks merely represented stages of alteration.

In 1916 Marr's book, "The Geology of the Lake District", was published. The work, in addition to expressing his own views and those of his contemporaries, incorporates the findings of many earlier geologists. Although Marr's contributions on the Lower Palaeozoic sedimentary rocks and the geomorphology of the region are probably more important, he is chiefly remembered for his coining of the term "lag-fault" - a type of thrust, he believed, separating the Borrowdale Volcanic Series from the sedimentary rocks above and below. His views on the upper junction differed from those of the officers of the Geological Survey who held that the junction showed an unconformable relation. A conflict of views also existed between Marr and his contemporary Green, who believed that the junction between the Skiddaw Slates and the Borrowdale Volcanics Series was, for the most part, conformable and unfaulted.

Green (1915),(1919) was also mainly responsible for the recognition of flow-breccias, rocks which had been generally mapped by the Survey geologists as "rough coarse ash". His belief that the great thickness of volcanic

rocks was due to isoclinal folding of a much thinner series, has however,been largely discredited.

The foundation of our knowledge of the petrology of the volcanic and intrusive rocks was laid down by Harker (1891 et seq.) and Rastall (1906 et seq.) both of whom paid particular attention to the latter rocks.

Mention must also be made of Postlethwaite (1913) who collected much material, which otherwise might have been lost, concerning the mines of the Lake District.

A new phase in the understanding of the Lake District geology was initiated by Mitchell (1929 et seq.) and Hartley (1955 et seq.) who remapped in detail areas composed of the Borrowdale Volcanic Series. Their work has paved the way for all later geologists who include Eastwood, Hollingworth, Rose, Trotter, Firman, Oliver and Moseley. All recent research has shown that the Borrowdale Volcanic succession is more variable both laterally and vertically than was previously supposed.

3. Ordovician Rocks.

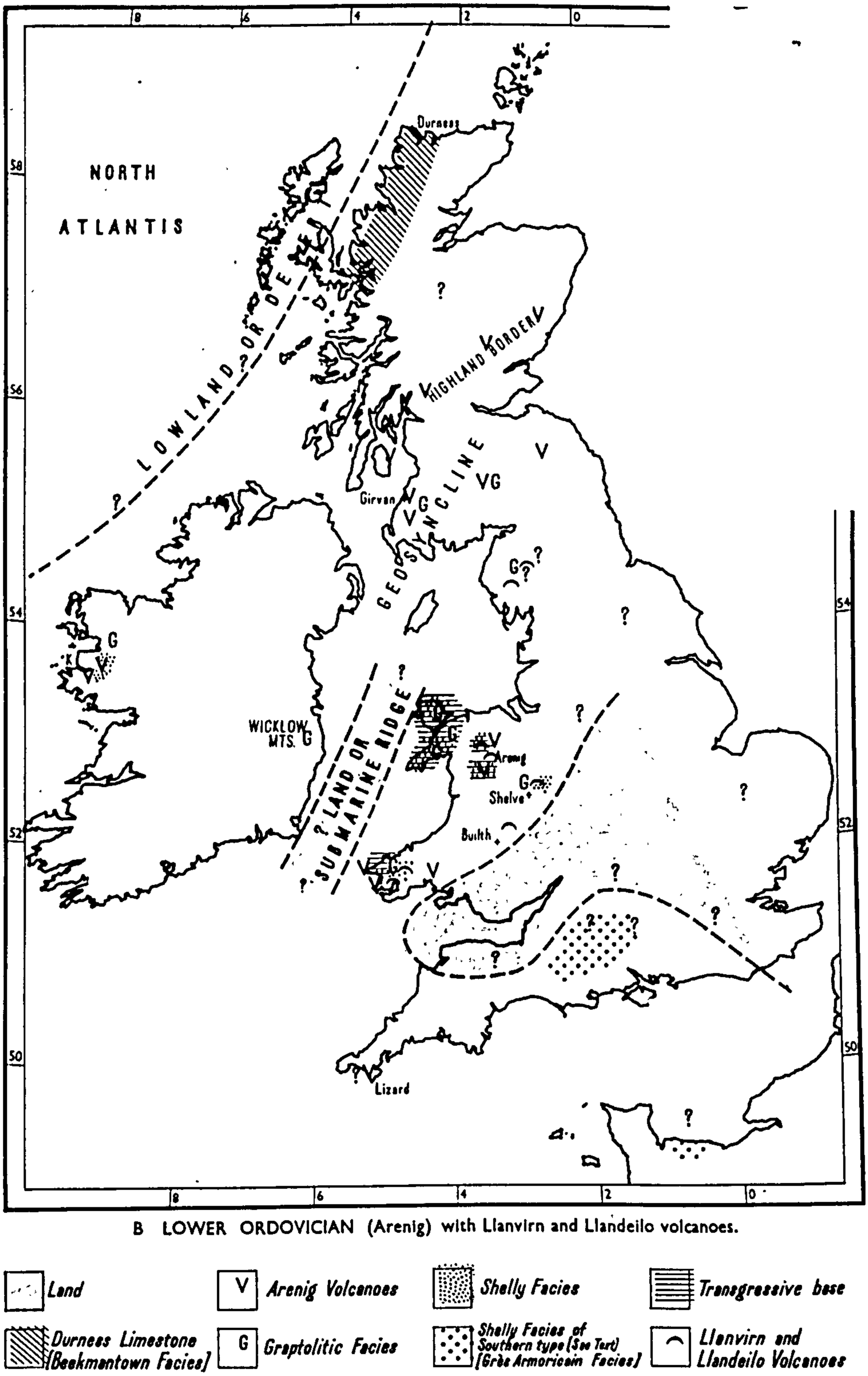
A. Introduction.

The Ordovician rocks of the Lake District are divisible as follows:-

3. Coniston Limestone Group.
2. Borrowdale Volcanic Series.
1. Skiddaw Slate Series.

A palaeogeographic map of Great Britain in Lower Ordovician times is shown in Fig.2.2. The Anglo-Welsh geasyncline was supposedly separated by a land mass or a submarine ridge from the Moffat geosyncline, to the north.

The Skiddaw Slates, ranging in age from Tremadocian to Llanvirnian



B LOWER ORDOVICIAN (Arenig) with Llanvirn and Llandeilo volcanoes.

Land

Arenig Volcanoes

Shelly Facies

Transgressive base

Durness Limestone (Beekmantown Facies)

Graptolitic Facies

Shelly Facies of Southern type (See Text) (Grès Armoricain Facies)

Llanvirn and Llandeilo Volcanoes

FIG. 2.2 LR. ORDOVICIAN PALAEOGEOGRAPHY (REPRODUCED FROM WILLS, 1951)

were formed probably towards the centre of the geosyncline, but the depth of formation was variable. Some of the argillites bear resemblance to the "deep water" graptolitic shales of Wales, while the sandstones and conglomerates indicate more shallow deposition.

This tranquil period of sedimentation was followed by a cataclysmic period of vulcanicity. Similar outbreaks of vulcanicity broke out contemporaneously in Pembrokeshire, Carmarthenshire, central Wales and Shropshire. The Lake District eruptions, however, completely dwarfed the latter eruptions as well as all other Crovician eruptions in the British Isles. Whether this Ordovician vulcanicity can be compared with the present day island festoons of volcanoes, in the orogenic zones of SE Asia, it is impossible to say. The petrography of the British Ordovician rocks suggests a tentative reference to the ophiolitic and Pacific suites found respectively in the foredeep and geanticlinal volcanic inner arc of present day orogenic zones.

When volcanic activity waned at the end of the Llandeilian, mild earth movements - the pre-Bala movements - took place. The volcanic rocks were uplifted, slightly folded and concomitantly eroded before the floor of the geosyncline subsided and marine sedimentation began again. The earliest rocks of this period of sedimentation, the Coniston Limestone Group, are here defined as including both the Caradocian and the Ashgillian. The group is predominantly composed of limestone, sandstones and shales which were clearly laid down in fairly shallow depths as the floor of the geosyncline gently subsided. However, latent vulcanicity, evidenced by tuff bands and one band of rhyolite persisted until the close of the Ordovician.

B. Skiddaw Slate Series

The base of this series of rocks is unknown, and strong folding makes an accurate estimate of the exposed thickness difficult. Rose (1954) who studied the Keswick - Buttermere area gives a minimum thickness of 6,500 feet.

The Series is composed predominantely of shales, siltstones, sandstones, and grits. Attempts have been made, in the main area of outcrop, to establish a general succession by means of the lithology. Thus in the Ennerdale area, Eastwood et al.(1931) have recognised the following threefold succession:

Latterbarrow Sandstone
Mosser/Kirkstile Slates (including Watch Hill Grit)
Blakefell Mudstones and Loweswater Flags

This succession, like others recognised elsewhere, has only a local application since one lithological group may pass laterally into another.

Rose (1954) from a study of the Keswick - Buttermere area, concluded that the Blakefell Mudstone is not a stratigraphical group but in fact represents thermally metamorphosed Mosser - Kirk Stile Slates. Similar rocks are found within the metamorphic aureole of the Ennerdale Granophyre and other intrusions, thus suggesting that the Blakefell Mudstone forms part of the metamorphic aureole of an unexposed intrusion.

The argillaceous beds of the Skiddaw Slates have yielded, among other fossils, numerous graptolites. It is uncertain whether the fauna can be correlated with that of the Anglo-Welsh geosyncline. Dixon (1931) suggested that the fauna did not bear comparison with that of Wales but

more closely resembled that of the Levis Shales of Quebec. Elles (1931), however, maintained that the Welsh faunal succession was definitely applicable to the Skiddaw Slates and she recognised various zones and subzones; the former are shown below :-

Zone of Didymograptus bifidus (ss)
Zone of Didymograptus hirundo
Zone of Didymograptus extensus
Zone of Dichograptus
Zone of Bryograptus kjerulfi

On the above basis Elles concluded that the lowermost beds of the Skiddaw Slates were Tremadocian in age, while the succeeding beds ranged up to Lower Llanvirian. Both Hollingworth (1954) and Rose (1954), however found that in their map-areas this zonal scheme could not be satisfactorily applied.

C. Borrowdale Volcanic Series.

(a) Introduction.

The relationship between the Skiddaw Slate Series and the overlying Borrowdale Volcanic Series has stimulated much controversy, as indicated in the Historical Review, p16. The evidence produced to date strongly suggests that the original relationship was essentially conformable but that later earth movements caused thrusting and faulting along or near the contact in some areas. This subject is treated in greater length in Chapter 3 and Chapter 4.

The Borrowdale Volcanic Series is composed of an alternate succession of pyroclastic rocks and lavas which have a total maximum thickness of between 10,000 and 20,000 feet. The compostion of these lavas varies from basaltic to rhyolitic, but andesitic types form by far the greatest

thickness. The pyroclastic rocks, which in most areas occur in roughly equal proportions to the lavas, generally have an andesitic to rhyolitic composition.

Except near the base of the Series, normal marine sedimentary rocks are completely absent and no fossils, except certain tracks, perhaps made by arthropods, have ever been recorded. The time spanned by this volcanic episode can thus only be estimated from the ages of the fossiliferous rocks above and below. If the zones recognised in the underlying Skiddaw Slate Series by Elles (1931) are valid, then the topmost beds which are sometimes interbedded with the Borrowdale Volcanic Series, belong to the Didymograptus bifidus zone. As explained later, there is some doubt as to whether the Coniston Limestone Group, which overlies the volcanics is Caradocian or Ashgillian in age. Assuming arbitrarily, that the former age is more accurate and that the pre-Bala earth movements and the accompanying erosion only occupied a relatively short time, the Borrowdale Volcanic Series is roughly equivalent to the Upper Llanvirnian and Llandeilian strata of Wales.

(b) Lavas.

The rock-types which have been recognised include basalt, andesite, dacite, rhyodacite and rhyolite. On account of the ubiquitous alteration of the Borrowdale Volcanic Series the recognition of precise rock-types is frequently difficult.

In many areas where there is a large area of outcrop, it has been possible to map individual lava flows. The thickness of the flows varies from a few feet to units several hundred feet thick which show no trace of being composed of a number of flows. The viscosity of the original

lavas is reflected in the form and structure of the flows: rhyolite flows tend to be short and stubby, the more fluid basaltic lavas formed thinner and longer flows, while the andesites are intermediate with respect to these two extremes.

Flow-brecciation, although not invariably present, is nevertheless widespread in all lava types. Vesicularity is probably best shown in the andesites. The primary joints recognised in the lava flows include flat platy joints parallel to the flow banding, and less commonly, polygonal, columnar joints perpendicular to the flow margins.

The conditions of formation of the lavas is uncertain. The absence of pillow lavas and the presence of reddened flow tops points to subaerial eruption, but intercalations of finely banded,presumably water-lain tuffs between some flows seems contradictory to this origin. It is probable that throughout the volcanic episode lavas (and also pyroclastic and epiclastic rocks) were formed under both subaerial and subaqueous conditions, often simultaneously in adjoining areas.

(c) Pyroclastic and Epiclastic Rocks.

The fragment size of these rocks varies from a fraction of a millimetre to several metres. Apart from material derived from the Skiddaw Slate Series, found in the tuffs near the base of the series, all the fragments are of volcanic origin: andesite and andesitic tuff fragments predominate but rhyolite fragments are also important.

Of the various types of deposits distinguished, the most easily recognised are those of well bedded lithic tuffs. The deposits of the finest grain-size frequently form flinty compact rocks. The slightly coarser tuffs are often well cleaved and provide the well known green slates.

The latter may show current bedding, graded bedding, ripple marks and pene-contemporaneous slump structures, features which clearly indicate their subaqueous deposition. Other types, in which the bedding is less perfect or impersistent, may have been deposited subaerially. Volcanic bombs are found in some bedded tuffs but seldom occur in great profusion. The bedded tuffs probably have a pyroclastic origin; the possible presence of epiclastic material must not however be excluded. Evidence of large scale contemporaneous erosion of units of the Borrowdale Volcanic succession has not been shown, but would be difficult to prove due to the inherent impersistence of the units.

The poorly bedded tuffs which are generally coarser than the bedded tuffs , are composed predominantly of angular and subangular fragments. However, in some coarse tuffs near the base of the succession, round fragments are found. The coarse breccias, which in some cases are composed of fragments of a single rock-type, are the most likely rocks of pyroclastic origin.

Streaky rocks, predominantly of rhyolitic composition, have for a l long time puzzled geologists who have studied the Borrowdale Volcanic Series. Opinion has vacillated as to whether they should be described as tuffs or lavas. In many ways they resemble flow-banded rhyolite but contain much foreign material, especially flat chloritic fragments. Oliver (1954) has suggested that the rocks are ignimbrits and could be compared with the well known recent examples of nuee ardente deposits.

(d) Succession.

The Officers of the Geological Survey, and many of the workers prior to about 1920 who studied the region, tried to draw up a succession applic-

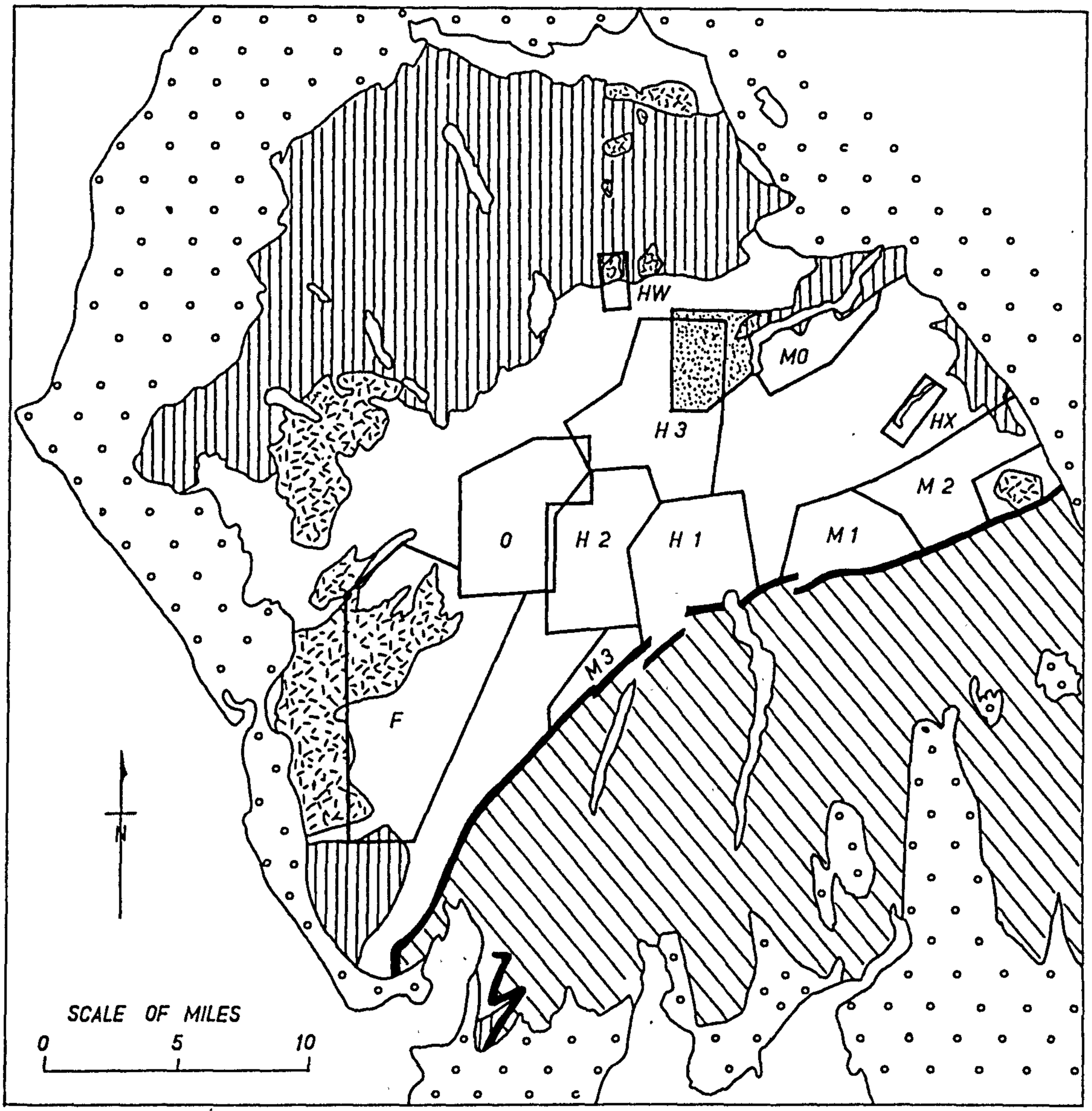
able to region as a whole. As more areas are remapped, especially in the light of the new knowledge of some rock types, it is becoming increasingly obvious that the formulation of such a general succession is very difficult, if not impossible. Correlation of the rocks, because of the absence of fossils, must necessarily be based on lithology. Recent subaerial andesite flows generally do not exceed 10 miles in length, and rhyolite flows are much shorter. The groups of more fluid lavas - basic andesites and basalts - which have greater extents will therefore be of more use for correlation purposes. Some recent ignimbrites have an areal extent of several hundred square miles, but it is uncertain whether the Lake District ignimbrites are strictly comparable, and correlation on such a basis should be made tentatively. Well-banded lithic tuffs undoubtedly occur at several horizons throughout the succession, and it is thus by no means certain that the group name 'Middle Tuffs'is strictly valid.

Figs 2.3 and 2.4 show respectively the areas remapped during the last 35 years or so, and the correlation of the successions found in some of these areas.

D. Coniston Limestone Group

The above term is here defined as including all those rocks which succeed the Borrowdale Volcanic Series but which are themselves overlain by Silurian strata.

The relation of the Borrowdale Volcanic Series to the overlying Coniston Limestone, like it's lower counterpart the Skiddaw Slates, has for a long time stimulated much controversy. It has now, however, been proved beyond all doubt that the Coniston Limestone Group rests



NEW RED SANDSTONE & CARBONIFEROUS

BORROWDALE VOLCANIC SERIES

INTRUSIONS

SILURIAN CONISTON LIMESTONE GROUP

SKIDDAW SLATES

AREAS OUTLINED :—
F — FIRMAN 1957
H 1,2,3 – HARTLEY 1925,32,42
HW — HADFIELD & WHITESIDE 1936
HX — HANCOX 1934
M-1,2,3 — MITCHELL 1929, 34, 40
MO — MOSELEY 1960
O — OLIVER 1961
PRESENT AREA — STIPPLED

FIG. 2.3 AREAS OF THE LAKE DISTRICT REMAPPED DURING THE LAST 35 YRS.
(MAIN OUTCROP OF BORROWDALE VOLCANIC SERIES ONLY)

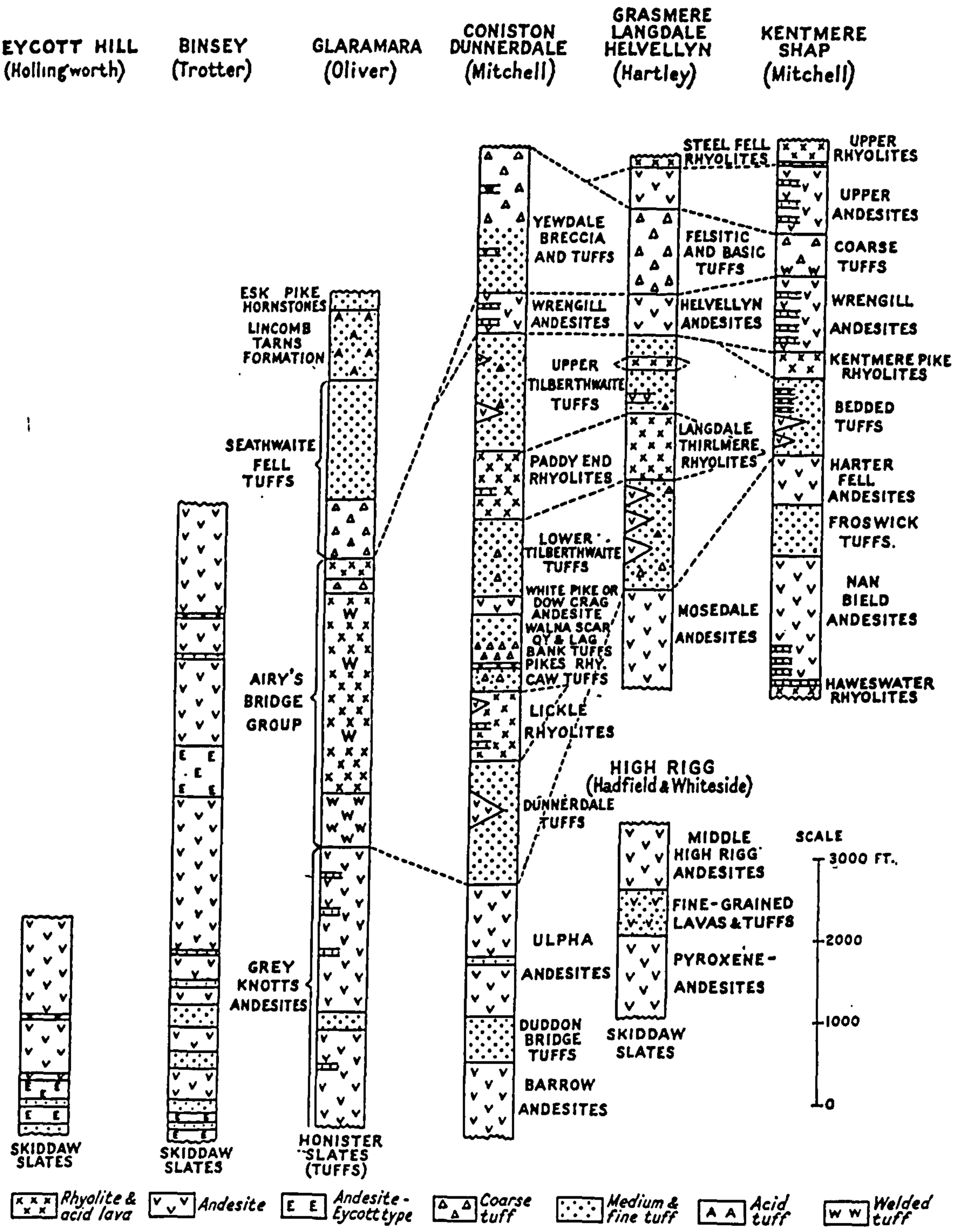


FIG. 2.4 BORROWDALE VOLCANIC SERIES SUCCESSION (REPRODUCED FROM MITCHELL, 1956)

unconformably on the volcanic rocks. The strata of this group progressively transgress, from east to west, 8000 feet of Borrowdale Volcanic rocks, and at Greenscoe, Dunham (in Mitchell, 1956) has shown that the basal beds rest on the Skiddaw Slate Series.

The general succession is as follows :-

		Thickness
4.	Ashgill Shales: shales, some ashy, with a limestone band at the base.	up to 450'
3.	Applethwaite Beds: shales, sometimes ashy, with limestones; basal conglomerate in places.	
	UNCONFORMITY	
2.	Stockdale Rhyolite.	0-450'
1.	Stile End Beds: stratified fine and coarse calcareous ashy beds; impersistent basal conglomerate.	up to 250'
	UNCONFORMITY	
	(Borrowdale Volcanic Series)	

The conglomerate which occurs impersistently at the base of the Stile End Beds is probably diachronous and tends to fill hollows in the surface of the unconformity. In the Kentmere area Mitchell (1925) has detected a second conformity at a higher level in the group. To the west of this area the Stile End Beds are overstepped by the Stockdale Rhyolite and the Applethwaite Beds, the latter coming to rest directly on the Borrowdale Volcanic Series.

Little recent palaeontological work on the Coniston Limestone Group has been carried out, and the lower zones represented are not known with any degree of certainty. Formerly it was thought that the group included both the Caradocian and the Ashgillian but recent work by King and Williams (1948) in the Cautley area suggests that the greater part of the

group may be of Ashgillian age. According to Elles and Wood (1895) the small outlier of shales, completely surrounded by Borrowdale Volcanic rocks, at Drygill in the Caldbeck Fells, is, however, of Caradocian age.

4. Silurian and Later Rocks.

A full description of these rocks is not pertinent in this context and thus a brief outline must suffice.

Silurian strata suceed, conformably as far as can be determined, the Ordovician rocks. The Coniston Limestone Group, as described previously, was laid down in fairly shallow depths, during the gentle subsidence of the geosynclinal floor , which followed the pre-Bala earth movements and erosion. Silurian geosynclinal sedimentation, initially probably at a greater depth than that of the underlying rocks, continued uninterrupted until the close of the period. The rocks are predominantly shales, mudstones, sandstones and grits, but thin beds of limestones also occur; the total thickness is approximately 13,000 feet.

No Downtonian rocks are known in the North of England. Rocks, probably of Old Red Sandstone age, occur at Mell Fell (south of Ullswater) and at Millom. Apart from these isolated examples there is a large gap in the succession, marking the Caledonian orogeny during which the rocks were uplifted, folded and eroded.

In the central mountainous mass of the Lake District there are no solid rocks younger than these Devonian rocks. The inlier of Lower Palaeczoic rocks is completely surrounded by Carboniferous Limestone on all but the western side, where New Red Sandstone overlaps the Carboniferous to rest on the older rocks. The basal beds of the limestone

group are comprised of conglomerates, with sandstones and shales. They are probably diachronous and were formed on a gently subsiding surface shortly after the dying phases of the Caledonian orogeny. Near Cockermouth, basalts were erupted between the formation of the conglomerates and the lowest limestones. Capewell (1954) has suggested a similar age for basic dykes and a small volcanic neck located near Mell Fell. The Millstone Grit Series rests unconformably on the limestone group and in the Whitehaven and Maryport area the former series are succeeded by the productive Coal Measures. Upper Carboniferous strata are also developed in this area. Minor earth movements occurred throughout the Carboniferous period especially during the Namurian, and culminated later in the Hercynian orogeny.

During this orogeny the region once more became a landmass, the erosion of which produced coarse breccias - the Brockrams - formed of fragments, often reddened, of pre-existing rocks. According to Dunham and Rose (1949), the Brockrams were developed along the margins of an upland landmass occupying the present area of the Lake District. The rocks pass laterally, in places, into the Magnesian Limestone and also into the St. Bees Shale and the St. Bees Sandstone. The latter formation passes upwards into the red Stanwix Shales which are believed to be the equivalent of the Keuper Marls of the Midlands.

Marine Jurassic and Cretaceous rocks were probably deposited in the region but were completely removed by the extensive erosion which accompanied the Tertiary earth movements. The latter caused the region to be uplifted to form a great dome upon which the consequent radial drainage pattern was imposed.

During the Glacial period, this drainage system was modified to various extents but it's basic pattern was still preserved. There were at least three periods of glaciation, each separated by a milder interlude. The ice movement was generally radially outwards from the centre of the region, but in the western parts, the ice was deflected south by the southerly moving Irish Sea Ice. Many glacial features are well shown in the Lake District, for example, U-shaped valleys, hanging valleys, truncated spurs, corries, aretes and roches moutonees. Besides the Boulder Clay, there are other glacial deposits such as moraines, eskers, and outwash-fans. There are also examples of glacial lakes and associated overflow channels.

The most important post-Glacial deposits are peat and lake sediments.

5. Intrusions.

Intrusive rocks, predominantly of acid composition, occupy a large area of the Lake District, (see Fig.2.1). Intermediate, basic and ultra-basic rocks are also found but generally form only minor intrusions. In the North of England, the Caledonian, Hercynian and Tertiary progenies all had associated phases of igneous activity. The relations of some of the Lake District intrusions to these orogenies are not fully known.

The major intrusions include the Shap Granite, the Eskdale Granite, the Skiddaw Granite, the Ennerdale Granophyre, the Carrock Fell Complex and the Threlkeld Microgranite. Except for the latter they are all probably stock-like. The extent of the contact metemorphic aureole of the Skiddaw granite suggests that unroofing is in an early stage, while the other intrusions are further advanced in this respect. The Threlkeld

Microgranite, intruded at the junction of the Skiddaw Slate Series and the Borrowdale Volcanic Series, probably has a laccolithic form.

All the intrusions have metamorphosed to varying degrees, the surrounding rocks. The intrusion of both the Shap and the Skiddaw granite masses was followed by the formation of the aplite and pegmatite dykes and later by pneumatolytic and hydrothermal activity. During the two latter phases small amounts of sulphides and other minerals were formed at Shap, while wolframite-bearing veins were formed in the Skiddaw area.

Minor intrusions occur chiefly in the form of dykes and small bosses. Many of the former are clearly related to the major intrusions but a well defined radial or linear pattern is seldom exhibited. Small intrusions associated with the Ordovician vulcanicity have been recognised but it is certain that the majority of the minor intrusions have no such relationship.

The evidence accumulated to date suggests a Caledonian age for the major intrusions. A fragment of the Eskdale Granite and of the Ennerdale Granophyre have been found respectively in the Millstone Grit, and in conglomerates below the Carboniferous Limestone. These two intrusions cut the Borrowdale Volcanic Series and thus their age can be determined within broad limits. A more precise date can be obtained for the Shap Granite. Radial dykes associated with the latter, cut rocks which range in age from that of the Borrowdale Volcanic Series to that of the Upper Ludlow. The basal conglomerates of the Carboniferous contain felspars derived from the granite so that the emplacement must be Devonian. The age of the Skiddaw Granite, based on rubidium-strontium dating (Dodson and Moorbath, 1961), is younger than the ShapGranite(Kulp et al,1960).

The Skiddaw Granite is also younger than the Carrock Fell Complex as evidenced by the wolframite-bearing veins, associated with the former, which cut the gabbro of the Carrock Fell Complex.

6. Structural Geology.

The present distribution of the rock groups and their primary structural elements were determined during the Caledonian orogeny. The older and younger earth movements - the pre-Bala, Hercynian, and post-Triassic - although important, played relatively minor roles.

A. Folding, Cleavage and Jointing.

Fig. 2.1 illustrates the structure of the region. The trend of the Caledonian fold axes is arcuate, swinging from a north-easterly direction in the west to a more easterly direction in the east of the region. The basic structure is an anticlinal belt composed of the Skiddaw Slate Series which are flanked both to the north and south by the Borrowdale Volcanic Series. Within the larger southerly outcrop of the latter there is a less important anticlinal structure extending from Black Combe to Shap, and a complementary synclinal structure extending from Scafell, through Helvellyn, to the east of Ullswater. The large outcrop of Silurian strata to the south has received little attention, but an anticlinal structure apparently stretches across the whole area, from Duddon Estuary, in the west, to beyond Staveley in the east.

The marked contrast in the competency of the Borrowdale Volcanic rocks and those of the Skiddaw Slate Series is reflected in the type of folding developed: the former showing broad, open structures and the latter much tighter folds.

In the main outcrop of the Skiddaw Slate Series, the major Caledonian folds as determined by Rose (1955), Eastwood et al (1931), and Trotter et al (1937), are shown in Fig. 2.1. The numerous smaller and minor folds present are frequently overturned and isoclinal; associated thrusting is also common. Usually these folds are parallel to the main structures but instances of divergence have also been recorded. The structural relations of the Skiddaw Slate inliers at Ullswater, west of Shap and at Black Combe are difficult to determine but they all appear to have a basic anticlinal structure.

The competent Borrowdale Volcanic rocks generally show broad open folds. Green,Mitchell and Hartley, as mentioned previously, have postulated tight or isoclinal folds in some areas. The most important belt of such folding, according to Mitchell (1956) extends from Coniston to Shap. Hartley (1925 et seq) has described similar folding in the Langdale, Grasmere and Helvellyn areas. Recent work in some of the areas mapped by Mitchell and Hartley has, however, revealed only broad, open structures.

Pre-Bala folding along NNE trends has also been recognised by Mitchell (1929 et seq) in the Coniston- Shap belt. His main line of evidence is based on the variations in pitch of the Caledonian folds, which, he believes, reflects the older folds.

In addition to the main anticline in the Silurian rocks, numerous other parallel folds were recognised by the Survey geologists. These folds and minor folds, which are often isoclinal, tend to become more gentle to the south.

The effects of the Hercynian and later earth movements are best

studied with reference to the structures developed in the younger rocks which surround the Lake District inlier. The Carboniferous rocks of West Cumberland show gentle, open folding generally along NE-SW lines, as for example in Whitehaven and Maryport areas. These Hercynian folds are thus roughly parallel to the Caledonian folds in the older rocks, and it is probable that the latter structures in part controlled the location of the younger folds, and were at the same time themselves modified and accentuated by the Hercynian movements. The gentle dome-like structures of the Alston and Askrigg blocks trend ENE-WSW and again,are perhaps related to underlying Caledonian structures,

The dates of the minor earth movements, which took place after the main Hercynian movements, are difficult to determine with precision. All these later earth movements will therefore be referred to as "post-Triassic". Their general effect, in both West Cumberland and the Northern Pennines, was to cause uplift, tilting, and in places, gentle warping of the rocks. The latter is best developed in West Cumberland where a broad E-W trending anticline has been recognised near Harrington. Minor parallel folds occur to the south, one of which is apparently related to the Caledonian Dent anticline. NW and NE trending minor folds have also been recorded.

The argillaceous Lower Palaeozoic rocks and more especially the fine grained bedded tuffs of the Borrowdale Volcanic Series, are frequently well cleaved. The steeply dipping or vertical cleavage planes of the latter, which have a regional ENE strike, are essentially parallel to the axial planes of the Caledonian folds, thus suggesting a common origin. However in the Coniston - Shap belt, and more especially in

Dunnerdale Fells, Mitchell (1956) has noted a divergence of the trends of the cleavage and axial planes, a result, he suggests of later earth movements. The cleavage of the Caledonian intrusions, developed locally in a few cases, is perhaps of similar origin.

Most workers have recognised two dominant groups of joints: steeply dipping joints which strike between NW-SE and NE-SW, and low angle joints which have a variable strike. The former group is often composed of two sets of joints which differ in strike by 60 to 90 degrees. It seems probable that these sets represent conjugate shear directions, related to the NNW-SSE Caledonian compression. The origin of steeply dipping joints with other strike directions, however , is not clear. Some of the low angle joints are perhaps of tensional origin, and again of Caledonian formation. Joints associated with the other periods of earth movements suffered by the region are undoubtedly present but are difficult to recognise.

B. Faulting and Mineralisation.

All four earth movements, which affected the region, in addition to folding the rocks, caused concomitant faulting. The ages of many of the faults are difficult to determine and it is probable, in the case of older faults, that renewed movement has taken place during subsequent orogenic periods. The relation of the mineral veins to the overall structural pattern forms an essential part of the structural analysis of any region. It is therefore unfortunate that many of the workers in the Lake District, officers of the Geological Survey excepted, whilst carefully mapping lithological units, folds, and faults have tended to disregard mineralisation along the faults. A full dicussion of the structural relations

of the Lake District veins, their age and also their relation to the veins of the Northern Pennines, forms Chapter 8. In this introductory chapter, only a brief summary will be given of these topics.

The major faults of the Lake District trend between NNE and NW. Several of the faults are powerful fractures, and extend for several miles. The most noticeable effect of these faults is the displacement of the Coniston Limestone Group , which forms a marker horizon. The direction and the amount of movement along the faults is uncertain, but the large shift of the Coniston Limestone Group in places, suggests that there is an important tear component. South of the Coniston Limestone outcrop, several of these faults are said to end at an important strike fault within the Stockdale Shales (Mitchell , 1956).

The age of the faults is uncertain; in many areas the faults form a conjugate pattern suggesting that they are tear fractures related to the Caledonian compression. On the other hand, several of the NW-SE trending faults are probably post-Triassic in age, since a group of faults with this trend are very well developed in the Carboniferous and later rocks of West Cumberland.

Faults of other trends are also present, but their age and origin are also uncertain. Thrusting has been postulated in some areas of the Lake District, and, as noted previously, the Skiddaw Slates/Borrowdale Volcanic Series contact has suffered thrust movement locally, especially in the northern part of the region.

The veins of the Lake District, except for those in the Vale of Newlands (Keswick) area and in the Caldbeck Fells tend to have a scattering distribution. They occur in both the Skiddaw Slates and the

Borrowdale Volcanic Series, as well as occasionally in the intrusive rocks. All the ore deposits are simple fissure infillings, probably along normal faults. However, the localisation of the faults is obscure, since there is no straightforward relation to the stratigraphy or folding of the region.

There is direct evidence of the age of several groups of the Lake District veins. As mentioned previously, the tungsten veins are genetically associated with Caledonian Skiddaw Granite. The lead veins are clearly later in age, since at Carrock, an E-W lead vein cuts the tungsten veins. Several of the copper veins are also displaced by the lead veins. Recent isotope data on the galena of the Lake District (Moorbath, 1962), suggests that the majority of the veins have a basically Hercynian age. However, the sources of the mineralising solutions from which the lead veins, and also the copper veins, were derived, are obscure. The iron veins are the youngest ore deposits, and are clearly related to the post-Triassic iron deposits of West Cumberland.

Except for some of the iron veins which are associated with NW-SE faults of probable post-Triassic age, the majority of the veins in the Lake District occur along impersistent faults, suggesting that the associated downthrow is relatively small. Although several of the lead veins are parallel to the major faults, they do not appear to be associated with them, and the absence of similar mineralisation along the major faults testifies to a different age of formation. The copper and tungsten veins also show no clear relation to the major faults.

CHAPTER 3

GEOLOGY OF THE GLENRIDDING AREA

1. Introduction.

The environs of Greenside Mine which were geologically mapped by the author are here termed the 'Glenridding Area' (Fig. 3.1). The area was first mapped by J.C.Ward and J.J.Herbert of the Geological Survey in the eighteen-seventies. Since that time the only work on the area has been by Hartley (1942) who covered part of the western section of the map-area. The area south-east of Ullswater has recently been described by Moseley (1960), while the results of an examination of the area to the north of the present map-area remain unpublished. The location of the areas mapped by Hartley and Moseley has been illustrated previously (Fig. 2.3 ,p. 24.).

2. Rock Classification and Nomenclature.

Because of the widespread alteration of the Borrowdale Volcanic rocks the precise rocks-types could not be determined. The terms used here, viz. 'basalt', 'basic' andesite, 'acid' andesite and 'rhyolite', and the complementary volcaniclastic rock-types, are therefore broad divisions which are probably to some extent overlapping. The terms 'felsite' and 'felsitic', because of the variation in their usage, have been avoided in this thesis. The terms employed in describing the textures of lavas are those suggested by Williams, Turner and Gilbert (1954).

The alteration of the rocks is described briefly in this chapter, but is considered in greater detail in the introduction of the chapter concerning the hydrothermal alteration associated with the Greenside Vein. The terms 'chlorite', 'leucoxene' and 'carbonate' therefore include several mineral species. The composition of the plagioclase was determined by

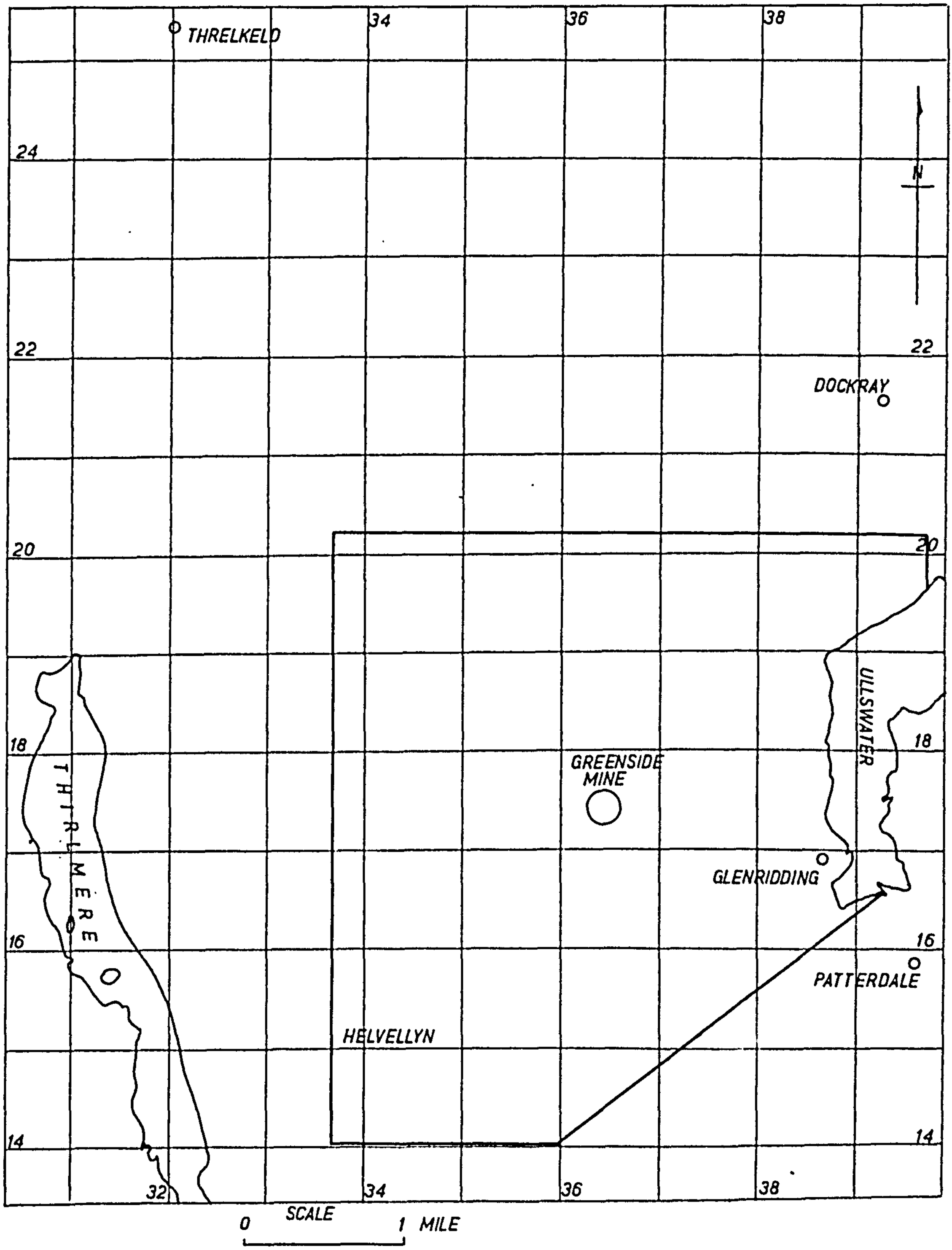


FIG. 3.1 LOCATION OF THE MAP AREA

the maximum extinction method, where necessary using the R.I. method as a check.

The recent classification of volcaniclastic rocks by Fisher (1961), is employed in this Thesis. The most important autoclastic rocks in the area are flow-breccias. For mapping purposes these rocks were included as a part of the lava flows, and thus a rigorous classification on the basis of fragment size was not necessary. It is believed that the remaining volcaniclastic rocks in the area are predominantly of pyroclastic rather than epiclastic origin. Except for coarser material, where a non-genetic term is employed, the fragment size classification used here is that applicable to pyroclastic rocks, although this does not imply the absence of epiclastic material. The classification is as follows :-

Term	Predominant Fragment Size - mm.
volcanic breccia	> 64
tuff breccia	2 - 64
coarse tuff	1/16 - 2
fine tuff	< 1/16

It should be noted that the term 'tuff breccia' is preferred to Fisher's term 'lapillistone'.

3. Succession.

A. Correlation with Adjoining Areas.

The geology of the area is illustrated in Maps 1 & 2 (in pocket). The succession and structure elucidated, differ markedly from that deduced by Hartley (1942), much of which was found to be erroneous.

The group names adopted by the latter have therefore been largely discarded. The succession in the map-area is divisible as follows (in descending stratigraphical order) :-

	Thickness - feet
Borrowdale Volcanic Series:	
1. Red Tarn Group	2000
2. Glenridding Group...	600 - 1300
3. Ullswater Group.....	2000 - 5000
Skiddaw Slate Series.....	500
Total Thickness.....	5100 - 8,300

The thickness of 4,600 - 8,300 for the Borrowdale Volcanic Series compares with a thickness of 3,800 - 4,850 feet proposed by Hartley (1942). Figures 3.2 and 3.3 show respectively, the variation of the succession from east to west across the map-area, and a suggested correlation with adjoining areas. Because of Hartley's erroneous succession, the correlation, given here between the succession of the map-area and that of the Scafell and the south eastern Ullswater areas differs from that proposed respectively by Oliver (1961) and Moseley(1960). The succession in all three areas is now seen to have a greater similarity than was previously envisaged.

It should be noted that the lavas which outcrop on the south side of Grisedale (outside the map-area) must lie above the Red Tarn Group and are probably equivalent, in part, to the Place Fell Group and Angle Tarn Andesites of S-E Ullswater (Moseley, 1960).

B. Skiddaw Slate Series

In the Glencoyne area, and on the footwall (west) side of the Greenside Fault in the lowest levels of the mine, Skiddaw Slates are found. The Greenside Vein was found to die out on encountering these rocks and

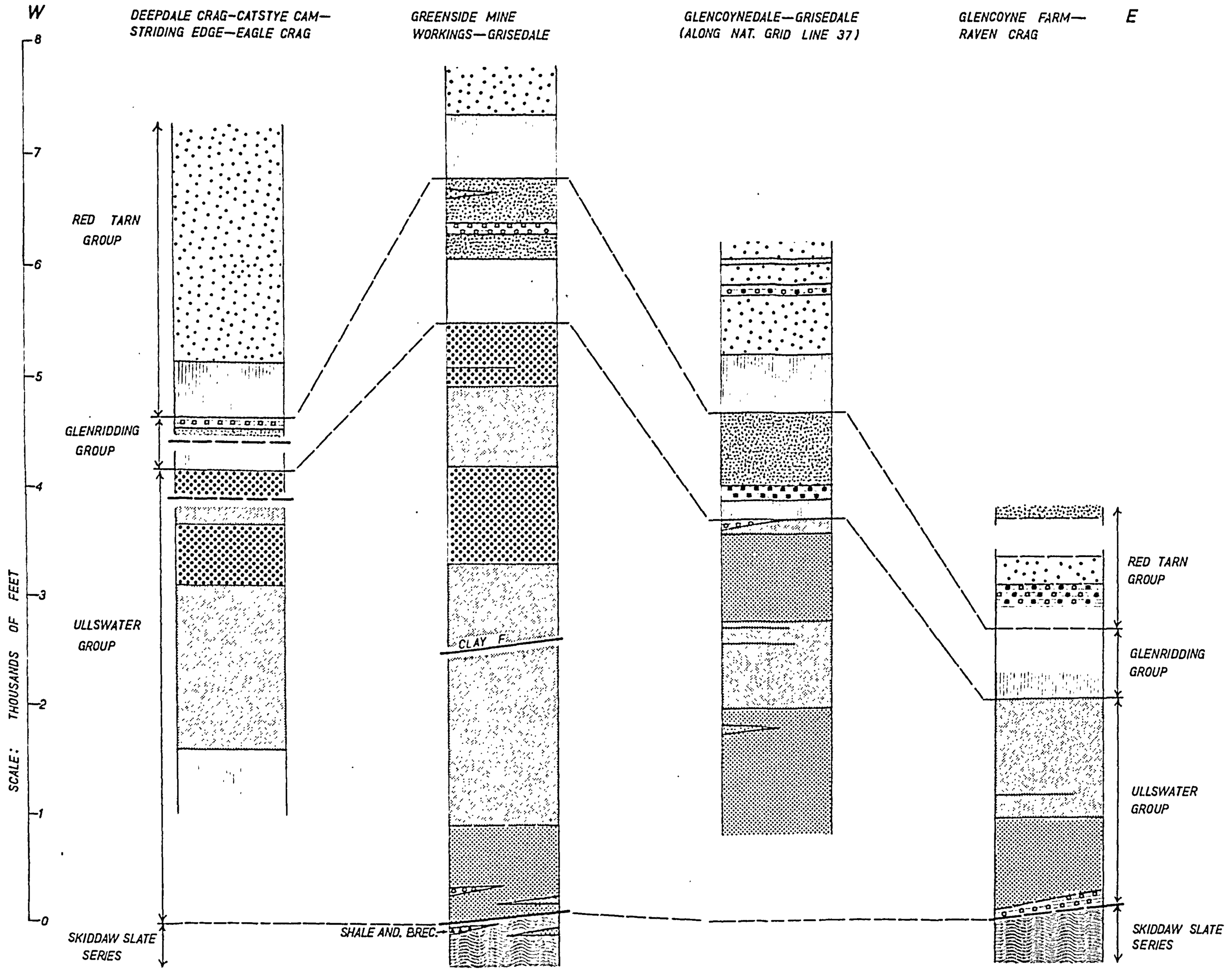
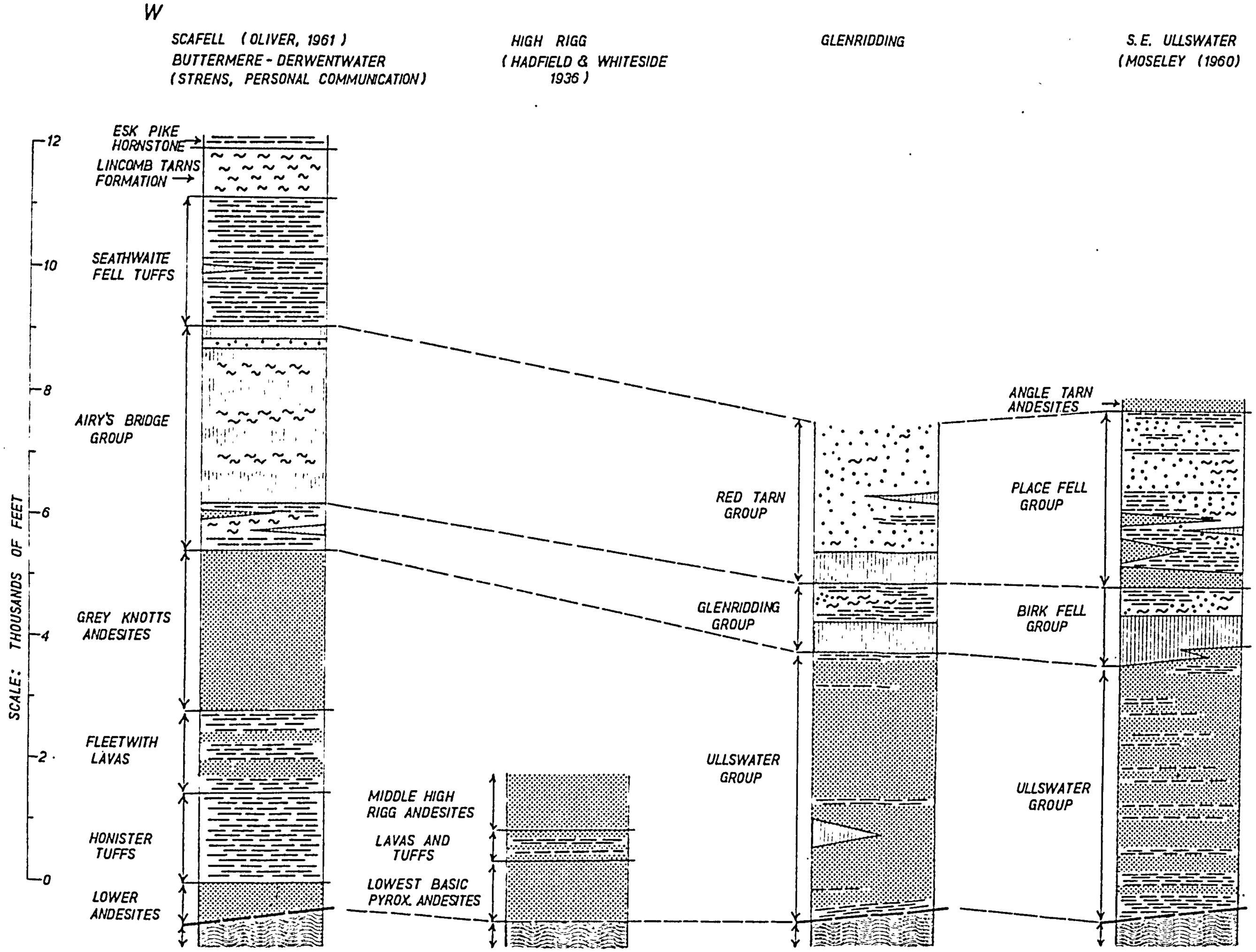


FIG. 3.2 STRATIGRAPHICAL SUCCESSION OF THE GLENRIDDING AREA



EXPLANATION

BORROWDALE VOLCANIC SERIES

- ANDESITE AND BASALT
- RHYOLITE AND RHYODACITE
- ANDESITIC TUFF AND BRECCIA
- ANDESITIC-RHYOLITIC (≡ 'FELSITIC' AND 'RHYODACITIC') TUFF AND BRECCIA
- IGNIMBRITES

SKIDDAW SLATE SERIES

FAULT

FIG. 3.3 CORRELATION OF THE SUCCESSIONS IN THE GLENRIDDING AND ADJOINING AREAS

extensive exploration on the possible continuation of the vein at greater depths proved unsuccessful. These lowermost workings were therefore abandoned and gradually became flooded so that at the time of the author's underground geological mapping the levels were inaccessible. The north end of the 120 fm. level where Skiddaw Slates were cut in diamond drill holes, was also inaccessible. The following account is therefore based mainly on limited exposures in the Glencoyne area, and on diamond drill cores and logs.

The Skiddaw Slates are composed predominantly of dark coloured shales. Bands of andesite and breccias, composed of shale and andesite fragments, are found near the top of the series, while bands of similar breccia and also of shale are found at the base of the overlying Borrowdale Volcanic Series.

The shales are bluish-black or dark grey in colour but lighter coloured laminations are common and may give the rock a banded appearance. Breccia structures which were probably formed penecontemporaneously with deposition may also be present (Fig. 3.4).

The following graptolites were recorded by Bulman (Geological Survey records) from the shales intersected by diamond drill holes R.C.E. 3 and 4 (collar on the 214 fm sub-level, co-ordinates 1365 N, 370 E).

Didymograptus cf leptograptoides, Monsen

Didymograptus Nicholsoni (?) , Lapworth

Didymograptus cf filiformis, Tornquist

Didymograptus climacograptoides, Holm M.S.

Glyptograptus cf dentatus, (Brong)

Cryptograptus tricornis, (Carruthers)

Glossograptus sp. or possibly acanthus, Elles and Wood

Recorded from the Glencoyne farm area :-

Didymograptus bifidus, Hall (immature form)

The graptolites from the shales in the mineworkings were collected within 130 feet of the contact with the Borrowdale Volcanic Series. The amount of movement along or near the contact is believed to be small (see Chap. 4) and therefore the cutting out of an extensive thickness of Skiddaw Slates seems unlikely. Whether or not this is so , the presence of andesite flows within the shales indicates that the strata are essentially the topmost of the series. Bulman has suggested that the shales are within the lower part of the bifidus zone.

Thin flows of andesite are found in the shales, especially near the junction with the Borrowdale Volcanic Series. The flows are 2 to 11 feet in thickness but their lateral extent could not be determined. The andesite may be of 'acid' or 'basic' type and has a similar petrography to that of the overlying andesites of the Borrowdale Volcanic Series. The contact of the flows with the underlying and overlying shales may be sharp, or be marked by a band of breccia composed of andesite scoriae and shale fragments set in a matrix of similar shale (Fig. 3.5). Green (1917) has described similar breccias, and his suggestion that the rocks were formed by the pouring out of lava on the sea floor seems reasonable.

Other shale-andesite breccias, not apparently associated directly with lava flows, are found both at the top of the Skiddaw Slates and at the base of the Borrowdale Volcanic Series. The thickness of the bands varies from a few inches to five feet. The andesite fragments are not scoriaceous but are angular or slightly rounded (Fig. 3.6); more than



Fig. 3.4 D.D.H. core composed of shale from the Skiddaw Slates. The breccia structure (emphasised by the colour contrast of the fragments and matrix) is a tectonic, or possibly a sedimentary feature.
At 223', R.C.E.2, 1365 N, 214 fm. level. X 1.

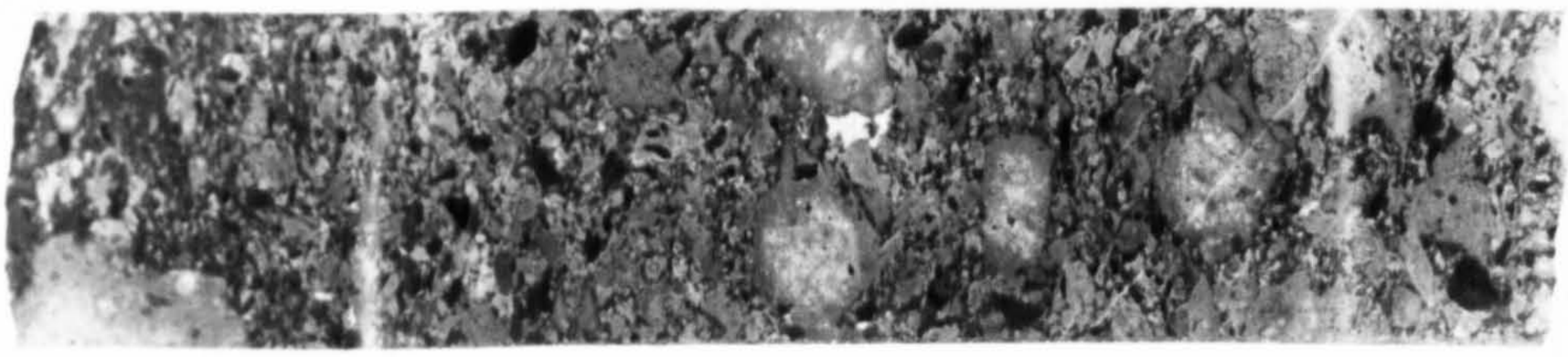


Fig. 3.5 D.D.H core composed of scoriaceous andesite with interstitial shale material (Skiddaw Slates). Note the highly irregular shapes of the andesite scoria, and the occasional fragments of shale. At 108', R.C.E.6, 3120 N, 120 fm. level. X 1.

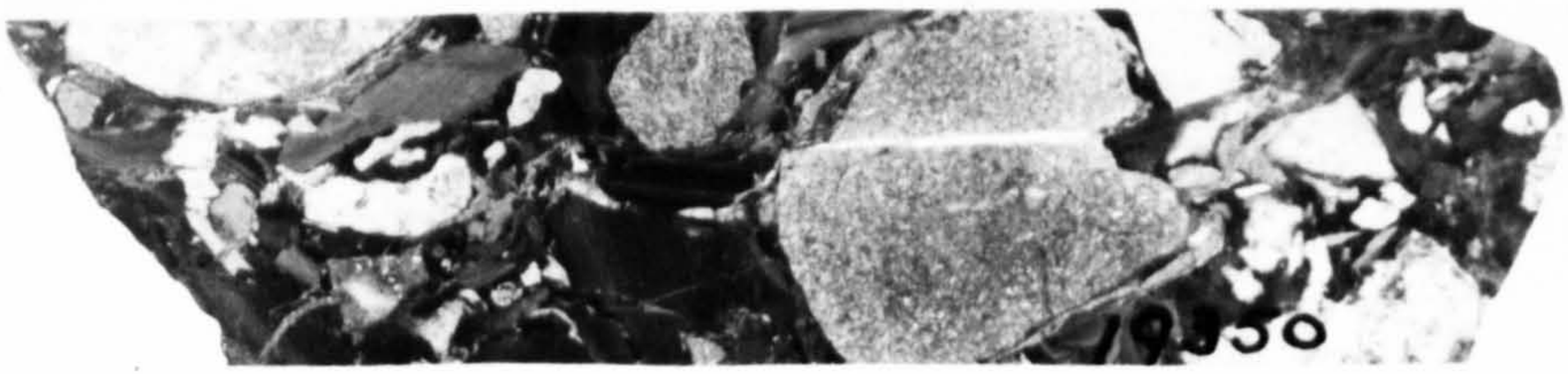


Fig. 3.6 D.D.H. core composed of fragments of andesite and shale (Skiddaw Slates). Note the variation in the degree of alteration of the andesite. Later movement has caused fracturing of the large andesite fragment. At 25', R.C.E. 4, 1365 N, 214 fm. level. X 1.

one type of andesite may be found in a single breccia band. The breccias are apparently similar to the "mottled tuffs", which are found near the boundary of the Skiddaw Slates and the Borrowdale Volcanic Series in many parts of the Lake District (Green, 1915, 1917). However some of the breccias , which are found at the junction of the two series and also at the contact of andesite flows within the shale, are probably the result of faulting.

The presence of andesite flows within the Skiddaw Slate Series, shale bands within the Borrowdale Volcanic Series, and of shale-andesite breccias in both series, is strong evidence of an original conformable relation. Fault movements along or near the junction are considered in a later section. (Chap 4).

C. Ullswater Group

The intermediate and basic lavas and subsidiary tuffs which overlie the Skiddaw Slates on the southern flanks of Ullswater, were referred to by Marr (1900) as the Ullswater Group. The term was retained by Moseley (1960) and is again used here in preference to Hartley's approximately equivalent group, "Bedded Tuffs and Lava Flows", which implies a minor proportion of lavas.

The central massive parts of the lava flows of the Ullswater Group tend to form ridges, while the more easily eroded flow-brecciated lava and tuff intercalations which are found between the flows, form grassy depressions or ledges. These topographic features are well shown on aerial photographs, and enabled the lava outcrops to be divided into a series of units, each unit probably representing a single flow. In poorly exposed areas, however, supplementary evidence is necessary to

delineate the relation between units and the flows. In some cases thick units are probably composed of several flows.

The small areal extent and complex interdigitation of the lava flows or groups of lava flows has caused the succession to be very variable from place to place. The Ullswater Group is therefore not described in stratigraphical order but in terms of the rock-types composing the group.

(a) Basalts

The two groups of basaltic lavas in the area occur towards the top of the Ullswater Group. The thickest and lowermost group, termed the Stang Basalt by Hartley (1942), extends from the western boundary of the map-area to Stang End, where the flows die out. The units, where observable, exceed one hundred feet in thickness, suggesting that the flows are of a similar order of thickness.

Flow banding and platy joints are rare in the basalts, while flow-brecciation is developed locally, for example north of Kepple Cove, where a fine example of 'aa' lava is exposed (Fig. 3.13). The lava unaffected by flow-brecciation is massive, seldom cleaved and generally has a dark green or black colour: flow-brecciated lava is often purplish or reddish in colour.

Augite is the predominant phenocryst mineral and forms well shaped lustrous crystals, up to 4 mm. in length. In thin section the crystals show lamellar twinning and are frequently zoned (Fig. 3.14); partial alteration to chlorite and minor epidote is common. Pseudomorphs, up to 3 mm. in length, composed of fibrous chlorite with a 'bastite' structure, probably represent an orthopyroxene (Fig. 3.14). The quantity of phenocryst plagioclase is small, and the laths which are generally less than



Fig. 3.13 Flow-brecciated 'aa' basalt. Note the clinkery, jagged surfaces. North of Kepple Cove.

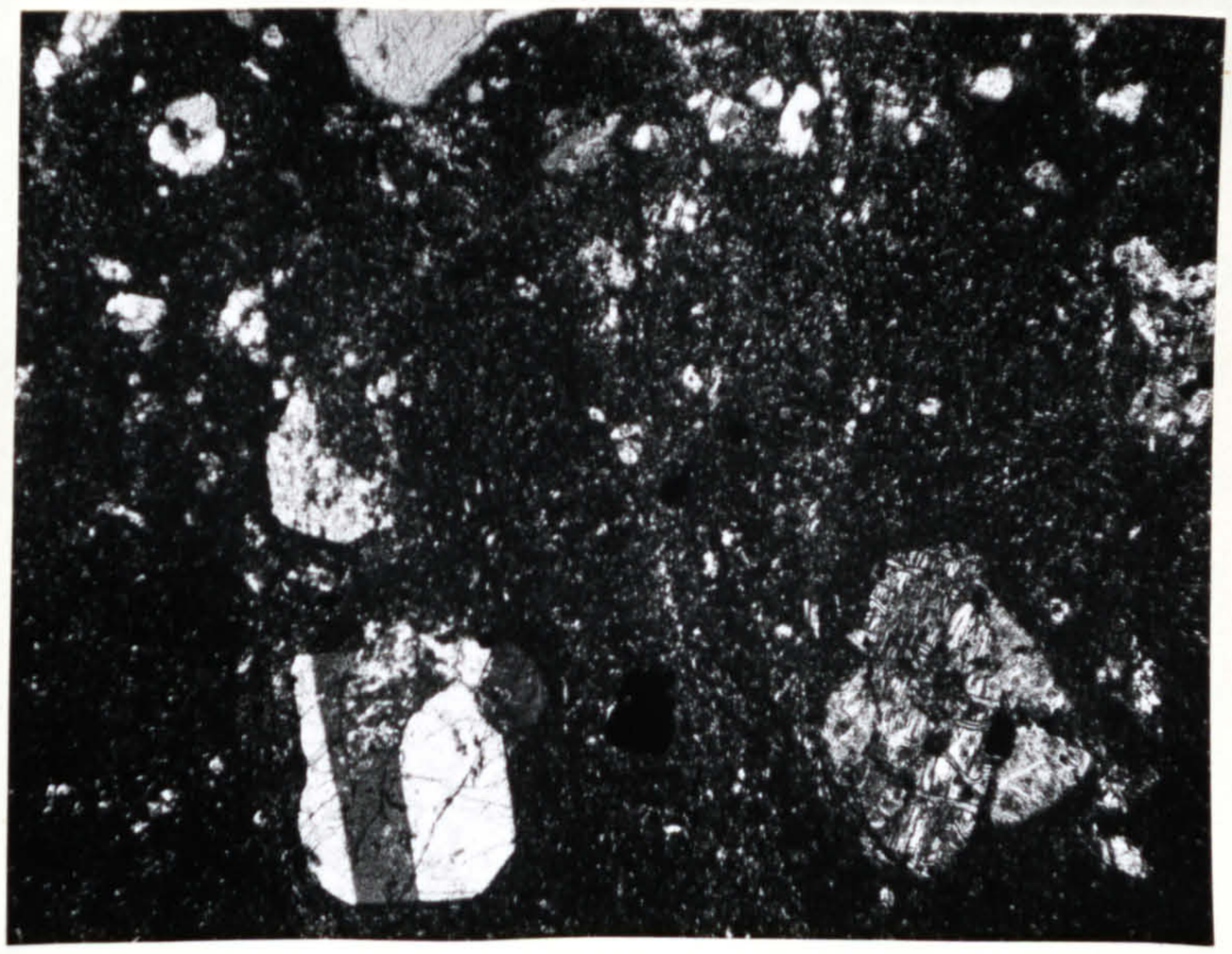


Fig. 3.14 Basalt: euhedral augite (showing lamellar twinning), and 'bastite' pseudomorphs set in an intersertal groundmass. Dumps from adit south-west of Shaw's Vein. X 20. Crossed nicols.

1.5 mm. long, are commonly completely altered to sericite. The texture of the groundmass is intersertal and the plagioclase microlites have a composition of An_{49} (andesine-labr dorite). Disseminated and granular magnetite occurs in the interstitial chloritic material. The Stang End lava contains 49.62% SiO_2 (Hartley, 1942) which justifies the term basalt for this group of rocks. This silicia percentage is the lowest recorded in any Lake District lava.

(b) 'Basic' Andesites

The dark coloured lavas which are found at the base of the Ullswater Group are best described as 'basic' andesites. The rocks are exposed in Glencoyne and are the dominant wall rocks of the Greenside Vein below the 90 fm. level. Similar flows also occur towards the top of the Ullswater Group.

The lava is frequently homogeneous and non-flow-brecciated throughout a vertical thickness of one hundred feet or more, suggesting that the flows are of a similar order of thickness.

Outcrops of andesite which apparently cut across the local strike direction are perhaps burrowing flows or shallow intrusions. Some fine grained rocks which are associated with the lavas, have a fairly good cleavage, show no definite lava texture, and are therefore possibly tuffs. For mapping purposes, however, such rocks have been included with the lavas.

The 'basic' andesites are generally aphanitic, or show only small scattered phenocrysts. The groundmass is dark green in colour and has an intersertal or cryptocrystalline texture when fresh (Fig. 3.7). The plagioclase microlites when present, are partially altered to sericite and calcite and their composition could not be determined. The interstitial

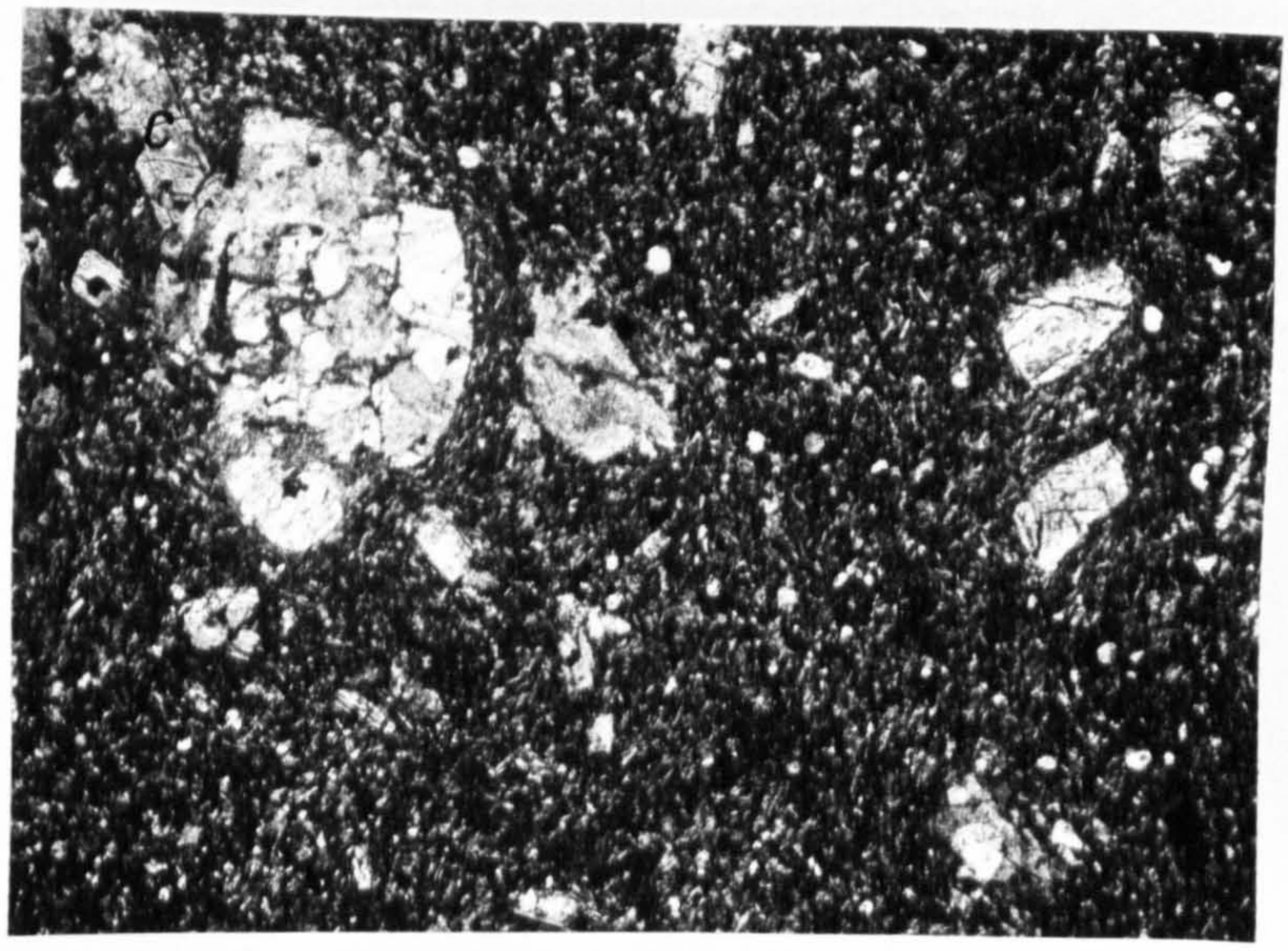


Fig. 3.7 'Basic' andesite: laths of calcitised, albitised plagioclase, and euhedral clinopyroxene pseudomorphs (composed of chlorite (C)) set in an intersertal groundmass. The small white spots are quartz amygdales. Latterbarrow Gill, Glencoynedale. X 20. Crossed nicols.

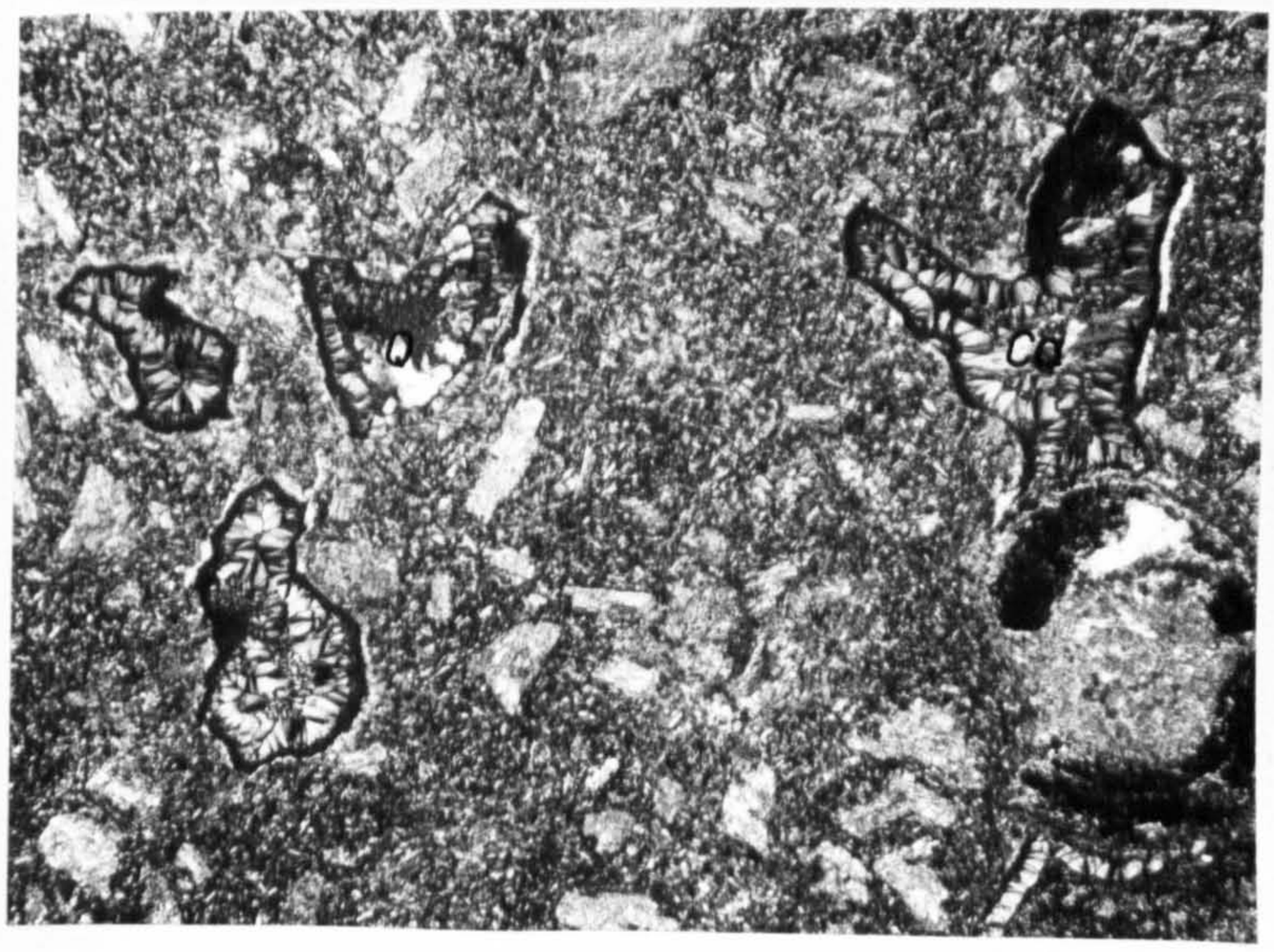


Fig. 3.8a Amygdaloidal 'basic' andesite: small laths of calcitised plagioclase set in an intersertal groundmass. Chlorite amygdales, a few with calcite(Ca) or quartz centres (Q). South of Glencoyne Farm. X 20. Crossed nicols.

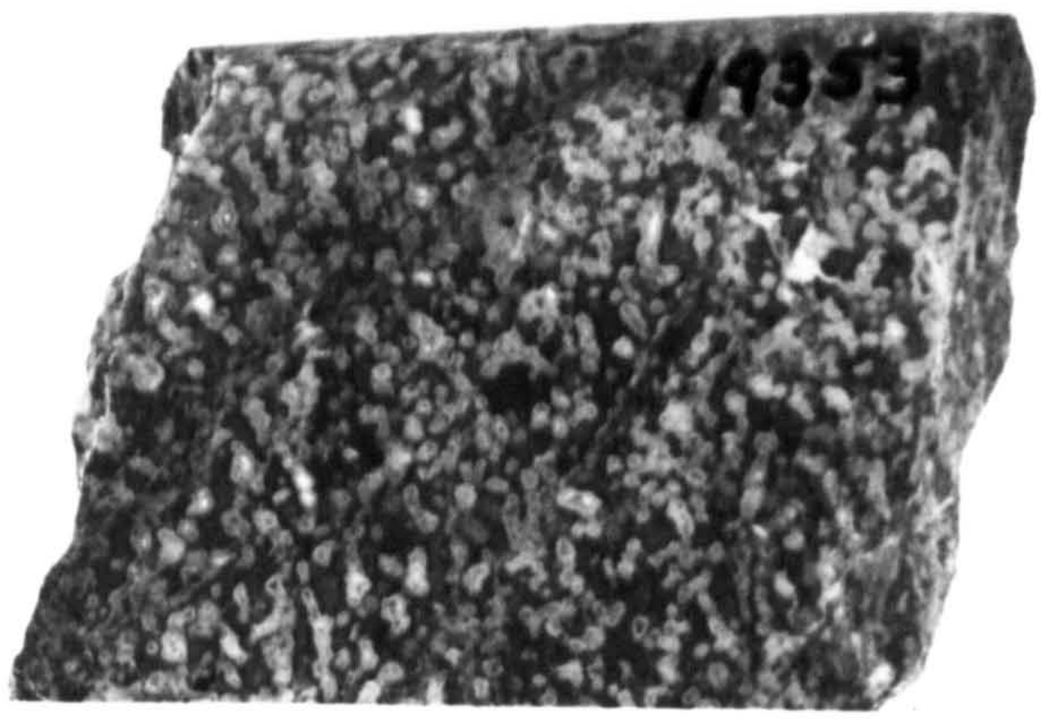


Fig. 3.8b D.D.H. core composed of amygdaloidal, 'basic' andesite. Quartz-calcite amygdales. At 74', D.D.H. 191, 470 N cross-cut, 221 fm. level. X 1.

material, where determinable, is composed of chlorite, sericite, calcite, 'leucoxene' and magnetite. The plagioclase phenocrysts generally do not exceed 1 mm. in length, and where unaltered to sericite and calcite, are seen to be andesine. Phencrysts composed of chlorite, 'leucoxene', and calcite, and calcite represent an original pyroxene, probably clinopyroxene. Garnets, partially altered to chlorite, occur locally. Amygdales of chlorite are often conspicuous (Fig. 3.8) while similar infillings of quartz, chalcedony and calcite also occur.

The flow-brecciated 'basic' andesite is frequently reddened due to the presence of finely divided hematite. Oliver (1956) attributes such hematisation to subaerial weathering of the exposed lava surfaces. Hematisation of non-flow-brecciated basic andesite was observed on the 90 fm. level of the mine workings. The hematite occurs as :-

(a) finely divided particles,
(b) narrow veinlets,
(c) peripheral zones surrounding original clinopyroxene.

Bright green chlorite is associated with the hematite. It seems likely that this alteration was not associated with the weathering of the lava surfaces,but was later in date.

(c) 'Acid' Andesites

The lavas which form the middle and upper portions of the Ullswater Group are very variable in petrography but are best described as 'acid' andesites. The northern part of the map-area and the wall rocks of the Greenside Vein above the 90 fm. level are predominantly composed of such andesites.

The mapped units varied from fifty feet to units several hundred feet in thickness which are perhaps composed of several flows. Flow-brecciation is well developed and sometimes extends throughout a thickness of fifty feet or more. On weathered surfaces the breccia texture is often well exhibited (Fig. 3.9). Hematisation of the flow-breccias is again a common feature. Rocks composed of scattered unoxidised lava fragments enclosed in almost identical lava, probably represent fragments of the lava from the solidified margin of the flow, which have become incorporated in the liquid lava, in contrast to the oxidised flow-breccias which represent the actual crust of the flow. In Glenridding Beck homogeneous 'acid' andesite is cut by irregular fractures infilled by very fine grained pale-coloured lava which has probably penetrated from a source below the lava flow.

Flow-banding, and associated platy jointing is common especially towards the margins of the flows. Vesicles also tend to be concentrated near the margins and are filled with either quartz, chalcedony, calcite or chlorite or combinations of these.

The 'acid' andesites are distinguished from the 'basic' andesites by their lighter colour and by their numerous plagioclase phenocrysts. Several distinct types of 'acid' andesite can be recognised. The most easily distinguished has a grey-blue, grey, or sometimes purplish-grey groundmass which has a somewhat flinty fracture. The lavas are porphyritic with numerous pale green plagioclase laths, not exceeding 2 mm. in length, and smaller scattered ferromagnesian phenocrysts (Fig. 3.10). The groundmass is cryptocrystalline but sometimes a hyalopilitic texture



Fig. 3.9 Flow-brecciated 'acid' andesite. Note the absence of lava enclosing the fragments. Kepple Cove.

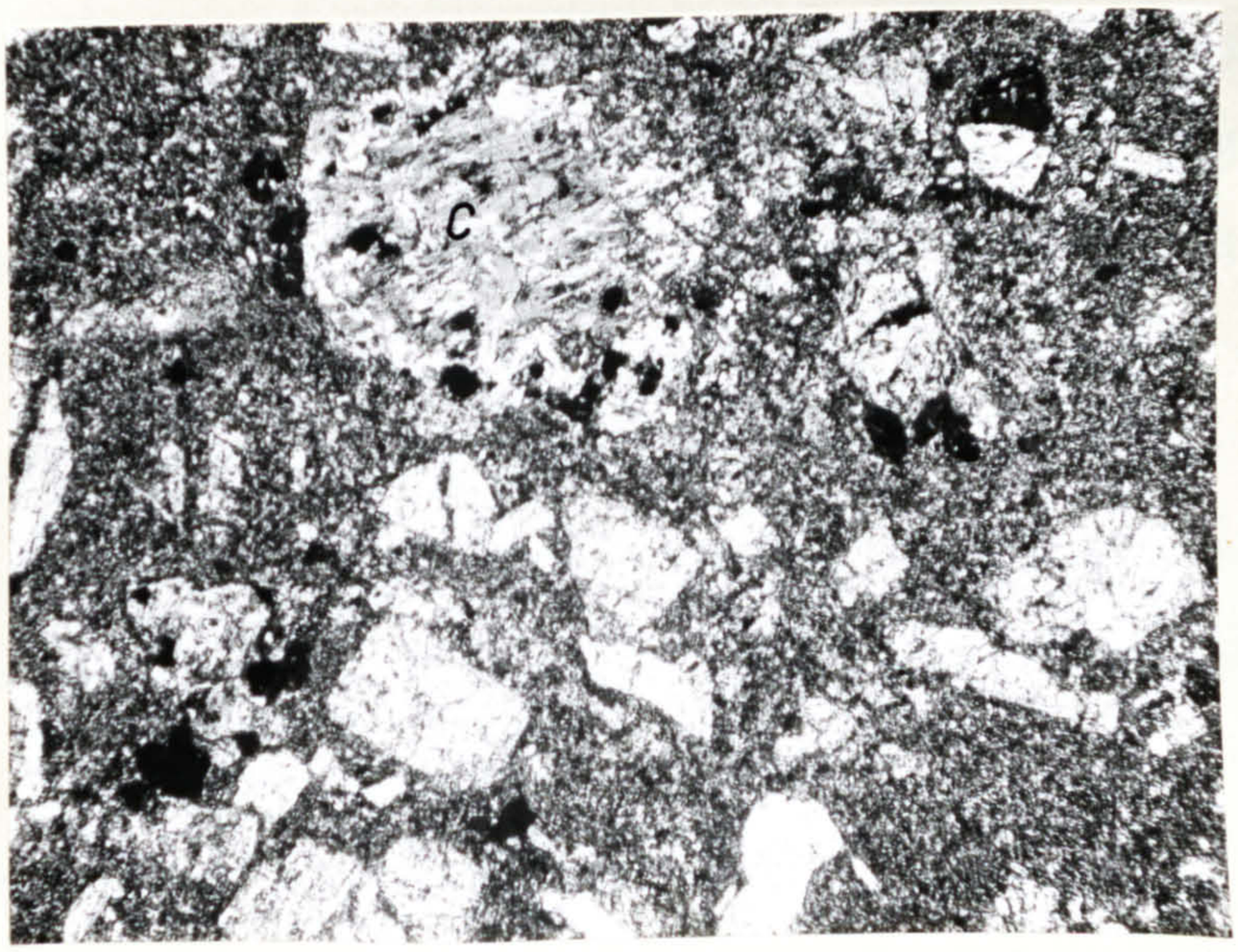


Fig. 3.10 'Acid' andesite: laths of sericitised plagioclase, and subhedral clinopyroxene pseudomorphs (composed of chlorite (C) with minor calcite and 'leucoxene') set in a hyalopitic groundmass. The small dark patches are 'leucoxene' after ilmenite. Top Dam. X 20. Crossed nicols.

is recognisable. The cryptocrystalline material may be partially isotropic or may show a patchy, mosaic extinction. Scattered grains and finely divided 'leucoxene' (after ilmenite) occur throughout the groundmass while flakes of carbonate and minor quantities of apatite, magnetite, pyrite and quartz are also present. The plagioclase phenocrysts are frequently strongly zoned, and where not extensively altered to sericite, calcite or epidote, are seen to be andesine. Areas composed of chlorite, carbonate, 'leucoxene' and epidote represent an original clinopyroxene; other similar pseudomorphs were perhaps originally orthopyroxene, while altered biotite is occasionally present. An unusual feature found sporadically in these lavas is the intimate 'mixing' of two types of lava , one of which has a darker coloured and coarser groundmass thsn the other (Fig. 3.11).

Andesites characterised by biotite as the principal ferromagnesian mineral are perhaps better described as dacites, and approach the rhyolites in appearance and petrography. These andesites form a narrow band on the north side of Glencoynedale, and are also found at the north end of the Lucy Tongue level. A similar andesite occurs in the Lucy Tongue adit, but here pyroxene and garnet are present in addition to biotite.

Other 'acid' andesites are darker coloured and more porphyritic than the types described above. The groundmass is grey-green to brownish-grey in colour and in thin section exhibits a cryptocrystalline, hyalopilitic or intersertal texture. In hand specimen, the numerous plagioclase laths are whitish in colour and may reach 3 mm. in length; a glomeroporphyritic texture is found occasionally. The plagioclase is

andesine and is partially altered to sericite and calcite. Some plagioclase phenocrysts, which are only slightly altered to sericite and calcite, are cloudy, unzoned, and show very simple albite twinning. These phenocrysts, often occuring alongside those of normal zoned andesine, are clearly secondary albite. Similar felspars are found sporadically in other types of acid andesites and have been recorded in lavas of the Borrowdale Volcanic Series by several workers e.g. Oliver, 1961.

The original pyroxene forms phenocrysts, or groups of phenocrysts, up to 2 mm. across, which are altered to chlorite, calcite, 'leucoxene' and sericite. In some lavas, mainly those which are flow-brecciated, hematite, and other iron oxides, form a rim round the pyroxene phenocrysts. Curious small six-side phenocrysts with corroded outlines, now composed of mosaic of quartz with a rim of hematite, were observed in the lava south of Glencoyne Cottage (Fig. 3.12). The hematite suggests the earlier presence of an iron-rich mineral , very possibly garnet.

(d) Rhyolites

The most important group of rhyolite flows in the Ullswater Group is exposed in the north-west corner of the map-area. The lavas are fairly low in the succession, but their absence in the Glencoyne area and in the Greenside Mine workings indicates that the flows become thinner and die out to the south.

Lack of exposure in this northern part of the area prevented the mapping of the individual flows which probably compose this group of lavas. Flow banding (with associated platy jointing), and flow brecciation, are common features. Cleavage, as in the andesites, is poorly developed and is noticable only in the exposures on the tops of hills,

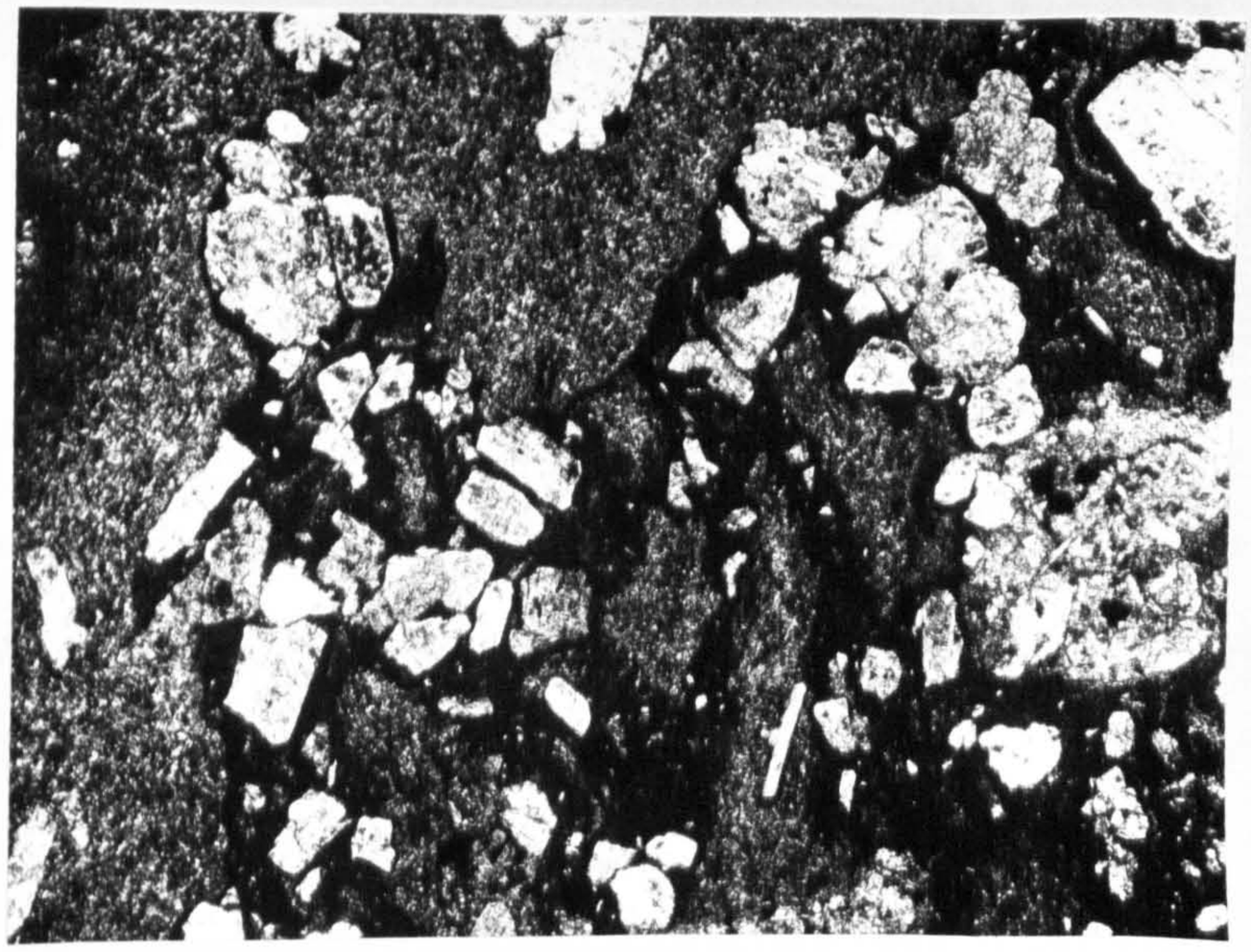


Fig. 3.11 'Acid' andesite: irregular areas of porphyritic lava with a dark, fine-grained groundmass enclosed by feebly porphyritic lava with a coarser-grained, lighter-coloured groundmass. Hartside. X 20. Crossed nicols.

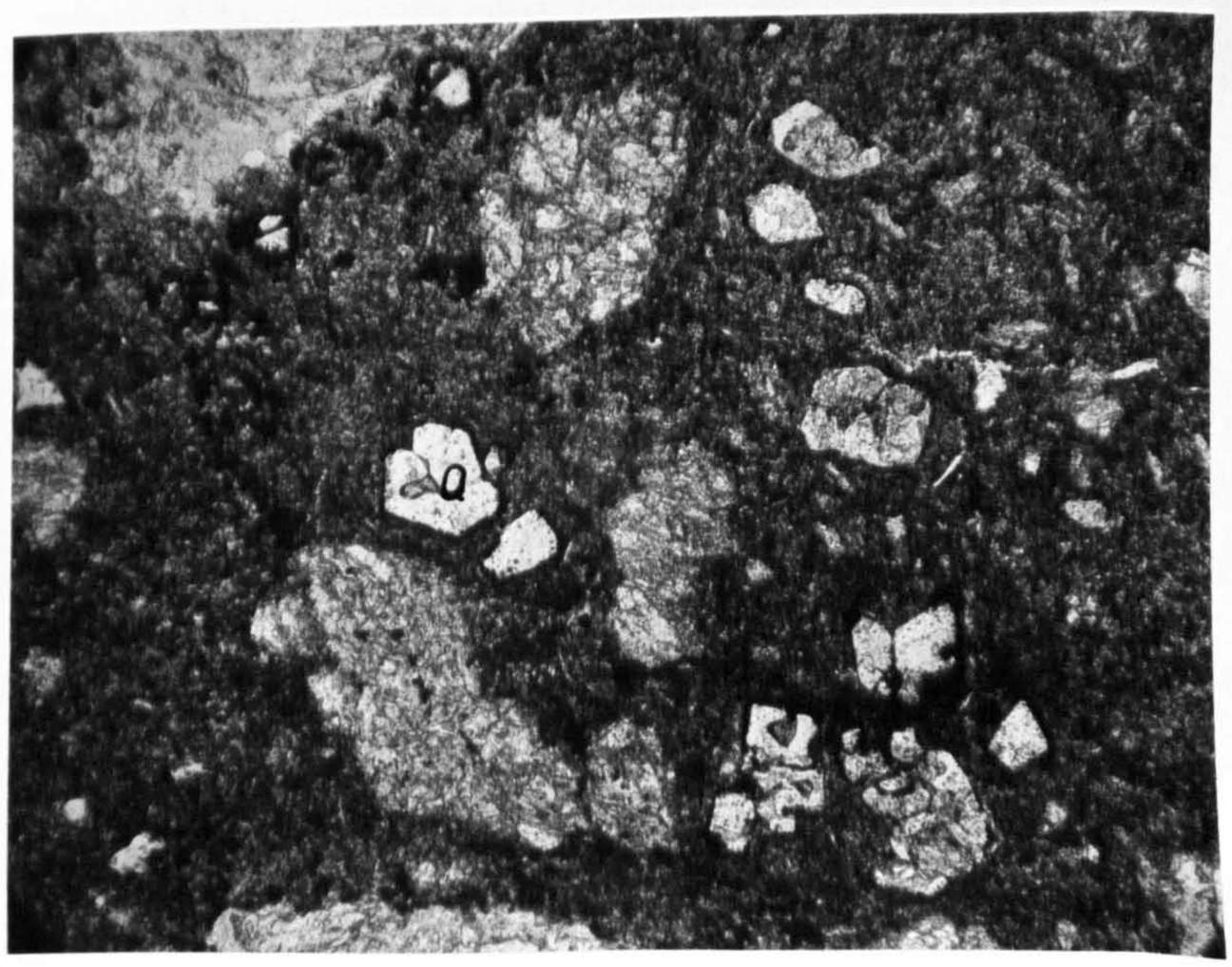


Fig. 3.12 'Acid' andesite: euhedral garnet (?) replaced by quartz (Q) and outlined by iron oxides. Intersertal groundmass. South of Glencoyne Farm. X 50. Ordinary light.

where in conjunction with irregular closely spaced joints, it often facilitates weathering of the rhyolite to a crumbly mass. The weathered surfaces are commonly cream or pinkish in colour, but a coating of limonite on exposed surfaces often gives the rock a mustard-brown colour. The fresh rock is compact and has a flinty conchoidal fracture.

The groundmass of the rhyolite, when fresh, is commonly pinkish-buff in colour but may be various pale shades. Scattered slender laths, up to 1 mm. in length, of greenish-white felspar are present, but their extensive alteration to a fine-grained aggregate of sericite and calcite precluded their determination. An analysis of this rock given by Hartley (1942) shows that soda is completely absent, suggesting that the rock is perhaps a potash rhyolite and that the original felspar was orthoclase. Small rare phenocrysts composed of epidote represent an original ferromagnesian mineral, probably biotite. The groundmass is completely devitrified and composed of quartz, sericite , calcite, chlorite and indeterminable cryptocrystalline material. Flow structure is emphasised by thin seams and lenticles of quartz, which parallel the structure, and by changes in the colour and grain size of the groundmass in successive bands. The latter features are a result of devitrification and alteration, but must, however, reflect slight changes in the composition of the lava. The accessory minerals include ilmenite (altered partially to 'leucoxene'), sphene, apatite,and zircon.

Hartley (1942) included the lavas described above in his "Thirlmere Rhyolite". In the text of his paper it is implied that the group occurred at or near the top of the "Bedded Tuffs with Lava Flows", but reference to the map accompanying this paper shows the rhyolite group occuring at two

or possibly three horizons, each separated by a great thickness of strata. Furthermore it was stated that the Thirlmere Rhyolite was intruded parallel to the bedding of the volcanic rocks and has caused alteration probably solfataric, in the adjacent rocks. In the area re-examined by the author, the rhyolite, designated "Thirlmere Rhyolite" by Hartley, supplied no evidence to suggest an intrusive origin, while the alteration of the volcanic rocks is widespread and shows no relation to the distribution of rhyolite masses. These conclusions also apply to all other rhyolite groups in the map-area. The more convincing intrusive relations of the Thirlmere Rhyolite in the Langdale area (Hartley, 1932) can probably be attributed to shallow burrowing flows rather than deep seated intrusions.

(e) Tuffs and Breccias

Volcaniclastic rocks, excluding flow-breccias, form only a small part of the total thickness of the Ullswater Group. The rocks are discontinuous in distribution and except near the base of the group, where breccias and tuff breccias reach a thickness of one hundred feet or more, form only thin lenses and intercalations between the lava flows.

The flow-breccias have been described previously and will not be further considered. In general, the tuffs and breccias are composed of andesitic material which is closely comparable with the lava of the flows immediately underlying or overlying them. Frequently flow-breccias are transitional with the tuffs and breccias and a division between the two types is often immpossible.

Tuff breccias and breccias are found mainly in the lower levels of the mine, e.g. the southern section of the 175 fm. level, and are

also exposed south of Glencoyne Farm. Except for breccias containing Skiddaw Slate fragments (previously described, p. 40) the rocks are composed of fragments of lava and occasional tuff. Fragments of 'basic' andesite usually predominate but fragments of 'acid' andesite, pinkish rhyolite and occasionally banded dark-coloured andesitic tuff may also be present (Fig. 3.15). The matrix is composed of similar components, but is frequently altered, thereby obscuring the original texture and composition. The fragments are invariably angular and are poorly sorted; bedding is seldom visible. The predominance of a single component in the breccias which is similar to the lava of nearby flows, and the angularity of the fragments suggest that the rocks have a pyroclastic origin. Volcanic bombs, pumice fragments and glass shards, typical pyroclastic material, are however absent. The source of the rhyolite fragments is obscure as no flows of that rhyolite are known below these breccias, and similarly no examples of comparable banded tuff were observed which could account for the fragments contained in the breccias. The tuff breccia cut in the diamond drill hole R.C.E. 5 (collar on the 214 fm. level) contains numerous garnets (Fig. 3.16), the origin of which is obscure since the closely associated lava is garnet-free.

The tuffs of the Ullswater Group form thin intercalations between the lava flows. They are generally coarse in grain-size and are composed generally of andesitic material although buff-coloured tuff found on the 175 fm. level, south of the Clay Fault, probably contains ryholitic material. Both broken and complete crystals of plagioclase are plentiful, while fragments of quartz are occasionally present.



Fig. 3.15 Andesitic breccia. Note the fragment of banded andesitic tuff, and also the chloritised rim of the fragment in the centre of the plate. 180 S, 150 fm. level.

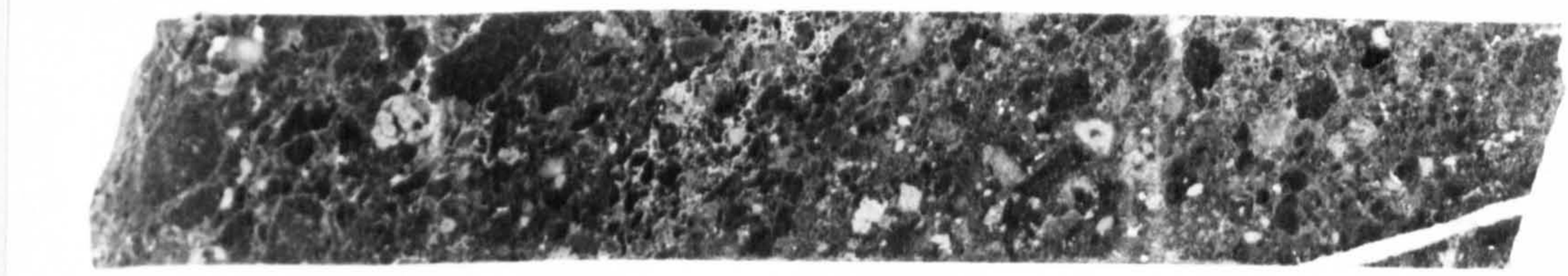


Fig. 3.16 D.D.H. core composed garnetiferous, andesitic tuff breccia. The occasional light-coloured fragments are rhyolite. At 75', R.C.E. 5, 2720 N, 120 fm. level. X 3/4.

The fragments are angular but in some cases are subangular. Some tuffs consist of an alternation of fine and coarse material and thus show conspicuous bedding; slump structures, current bedding and other sedimentary features were not observed and therefore a subaqueous origin cannot be pronounced with certainty. Other tuffs are poorly sorted and do not show bedding structure. A concretionary or pellet structure was observed in the tuffs on the west side of Blea Cove. Similar structure have been described by Hartley (1932) and other workers on the Borrowdale Volcanic Series, and can probably be attributed to volcanic hailstones. The pellets which are composed of similar material to the surrounding tuff, are ellipsoidal and have their long axes, which are up to 1.5 cm. long, roughly parallel to the bedding.

D. Glenridding Group

This group of rocks, and also the Red Tarn Group are not found in the immediate mine area, and therefore are described in less detail than the Ullswater Group. The lower limit of the Glenridding Group is defined by the junction of a series of rhyolites with the underlying basalts and andesites of the Ullswater Group. The junction of the bedded tuffs with the overlying rhyolites of the Red Tarn Group marks the upper limit.

(a) Rhyolites.

These rocks extend from Kepple Cove in the west to the shores of Ullswater in the east. The small patch of this rhyolite which is perched on the basalt flows east of Kepple Cove, indicates the uneven topography during this volcanic episode. Thin intercalations of andesite occur locally at the base of the rhyolites.

In general, these rhyolites are very similar to the rhyolites developed in the Ullswater Group. The flows are apparently at least 50 feet in thickness. Flow lines and flow banding, often strongly contorted, are well developed, while flow-brecciation is common along both the upper and lower flow margins. At Blea Cove the rhyolitic tuff-breccia, which overlies the rhyolites, is probably genetically associated with these flows.

The dominant phenocrysts in the rhyolite are of plagioclase and have a composition of An_{0-9} (albite). Many of the albite phenocrysts are cloudy and unzoned thus suggesting that they have a secondary origin. Partial alteration of the felspar to sericite and calcite is common, as it is in the few phenocrysts of perthite present. Chlorite flakes which form small patches, sometimes exhibit pleochroic haloes, and thus indicate that the original mineral was biotite. The groundmass is similar to that of the rhyolites described previously.

(b) Tuffs and Tuff Breccias

The rhyolites are succeeded by a series of essentially andesitic tuffs and tuff breccias. The fine grained tuffs are frequently well bedded, sometimes showing 10 - 20 laminae to the cm. (Fig. 3.17). Alternations of fine and coarse grained laminae, graded and current bedding, slump structures and load casts testify to a subaqueous deposition (Fig. 3.18). Cleavage is often very well developed, and at Blea Cove a band 10 - 15 feet thick has been worked for slate.

The components of the tuff include:

(a) fine grained recrystallized material (probably volcanic dust originally)

(b) Fragments composed largely of chlorite (originally andesite)



Fig. 3.17 Cleavage blocks of delicately-banded, fine-grained andesitic tuff. Slate Quarry in Blea Cove.



Fig. 3.18 Fine-grained andesitic tuff. Note the contorted bedding, probably a penecontemporaneous sedimentary structure.

(c) altered plagioclase and pyroxene crystals.

The fragments are invariably angular or subangular.

A remarkable 'spotted' fine-grained tuff occurs at Blea Cove and can be traced westwards to Catstye Cam. A similar rock was described by Hartley (1925) from the Grasmere area. The spots are roughly spherical, white in colour, and average 1 mm. in diameter, although they sometimes coalesce to form larger irregular patches or lenticles. The minerals composing the spots are either chalcedony, epidote and 'leucoxene', or sometimes calcite. A metamorphic origin is unlikely and some process of recrystallisation of the tuff components at several scattered centres, probably shortly after deposition, seems more probable.

Other coarser tuffs composed largely of whole and broken crystals of plagioclase and pyroxene were mistakenly mapped by Hartley (1942) as andesites - the "Helvellyn" andesites. Spots similar to those found in the fine grained tuffs are also present.

The very fine grained tuffs which have a pale blue colour are perhaps better termed hornstones. They have a conchoidal fracture and weather to a cream colour.

The band of tuff breccia which extends from Blea Cove to Catstye Cam is very hard compact rock and often forms a small topographic feature. The junction with the underlying bedded tuffs is often irregular and it is significant that Hartley (1932, 1942) has described coarse breccias on a similar horizon, which in some cases are locally unconformable The fragments composing the tuff breccia include rhyolite, dark fine-grained chloritic material, andesite, plagioclase crystals, and occasionally blocks of 'spotted' tuff (Fig. 3.19). The rock exhibits poor sorting



Fig. 3.19 Andesitic tuff breccia. Note the large fragments of 'spotted' andesitic tuff (T). Beneath the north face of Catstye Cam.

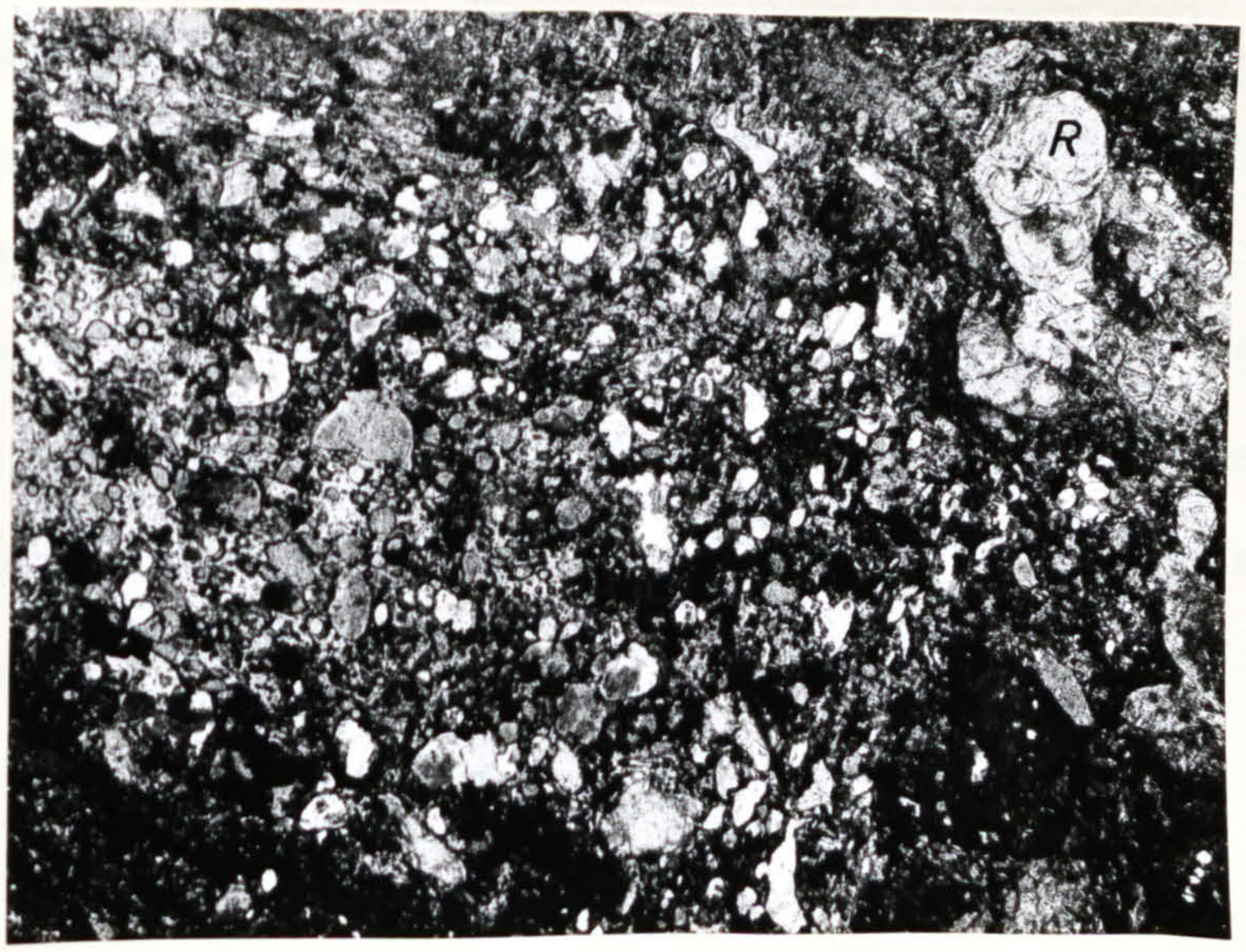


Fig. 3.20 Andesitic tuff breccia: fragments of pumice and perlitic rhyolite set in a matrix composed of glass shards and micro-crystalline material. South-west of Blea Cove. X 20. Ordinary light. (rhyolite - R)

and is seldom bedded. The rhyolite fragments often show a pumice structure, while the chloritic fragments are pumice, in which the spaces have been infilled with chlorite (Fig. 3.20). The matrix of the rock is composed of devitrified glass shards, and recrystallized volcanic dust. The compact nature of the rock and the presence of glass shards and pumice fragments probably indicate that the rock is an ignimbrite. However, the pumice fragments are not collapsed and the shards not bent or moulded upon each other thus indicating only incipient welding.

E. Red Tarn Group

(a) Rhyolites

In contrast to the rhyolite flows which occur in the Ullswater and Glenridding Groups, the rhyolites of the Red Tarn Group seldom show flow-banding and flow-brecciation. The basal rhyolites extend from the head of Blea Cove to the north face of Catstye Cam, and are apparently composed of a single flow.

The groundmass, which has a pale grey-green colour, was probably originally glassy but is now completely devitrified and composed largely of a mosaic of quartz. The chief phenocrysts are of plagioclase (albite), but except near the base of the flow, they form only a small percentage of the volume of the rocks. The plagioclase laths, usually less than 2 mm. in length, are partially altered to sericite and calcite. Smaller phenocrysts composed of epidote and 'leucoxene', probably represent original biotite (Fig. 3.21). Grains of garnet, invariably less than .5 mm. across and usually altered to chlorite and 'leucoxene', occur sporadically. Magnetite and zircon are present in accessory amounts.

The topmost beds in the Helvellyn area according to Hartley (1942)

are the Steel Fell Rhyolites. Exposures of this so-called group on the summits of Catstye Cam and Helvellyn, and on Striding Edge were not confirmed, while other exposures located north of Catstye Cam and at the head of Blea Cove must be the basal rhyolites of the Red Tarn Group.

In addition to the basal rhyolites, a single flow of small extent, is found within the overlying tuff group. The physical features of the flow and the petrography of the rock composing it, are very similar to the rhyolites of the Glenridding and Ullswater Groups.

(b) Tuffs and Tuff Breccias

The basal rhyolites are overlain by a thick group of tuffs and tuff breccias. Catstye Cam, Swirral Edge, and Striding Edge are largely composed of these rocks, which must in these areas reach a thickness of at least 2000 feet. The rocks are greyish or greenish in colour and weather to grey-brown shades. Irregular columnar joints are developed locally while cleavage is apparent on most outcrops.

The material composing these rocks ranges from very fine volcanic dust to fragments 3 cm. across, but the majority of the rocks have a predominant grain size of between .5 mm. and 3 mm. Because of the difficulty of gauging the exact predominant grain size in the field, all rocks with the latter range have been termed 'coarse tuff'. The components of the tuffs and tuff breccias may be listed as follows :-

(1) volcanic dust

(2) broken or whole plagioclase crystals, .5 mm. to 3 mm. in length,

(3) angular fragments of rhyolite,

(4) lenticular or angular fragments of dark green chloritic material,

(5) angular fragments of andesite.

The matrix of most of the tuffs and tuff breccias has been altered to a fine grained aggregate composed of quartz (often in mosaic form), chlorite, sericite, calcite, and 'leucoxene', as well as cryptocrystalline indeterminable material. It seems likely that the original matrix was fine grained and thus probably composed of fine dust. Patches of 2° albite are occasionally found.

The plagioclase crystals are generally whole (Fig. 3.22) but are altered to calcite, chlorite and sericite. Their composition - oligoclase - andesine - shows that they could be derived either from rhyolitic or andesitic lavas. The petrographic features of the rhyolite fragments are very similar to the rhyolites of the underlying strata. Andesite fragments are rare, but again are similar to the underlying andesite flows.

The origin of the fragments composed of dark green fine grained material is difficult to determine. The complete absence of phenocrysts is characteristic , and, excepting some lavas of 'basic' andesite which are of local distribution, there are no comparable rocks in the area.

The variable percentage of each of these components and the lack of knowledge of the origin of the fragments makes the definition of the rocks in terms of composition very difficult. Rocks which are neither composed predominantly of rhyolitic nor andesitic material have therefore been termed'andesitic-rhyolitic'. Rhyolitic rocks tend to be found at the base of the group; the andesitic component of the mixed types increases towards the east and is associated with a diminution of the grain size, perhaps indicating a south-westerly source.

The lenticular chloritic fragments, when present, are generally

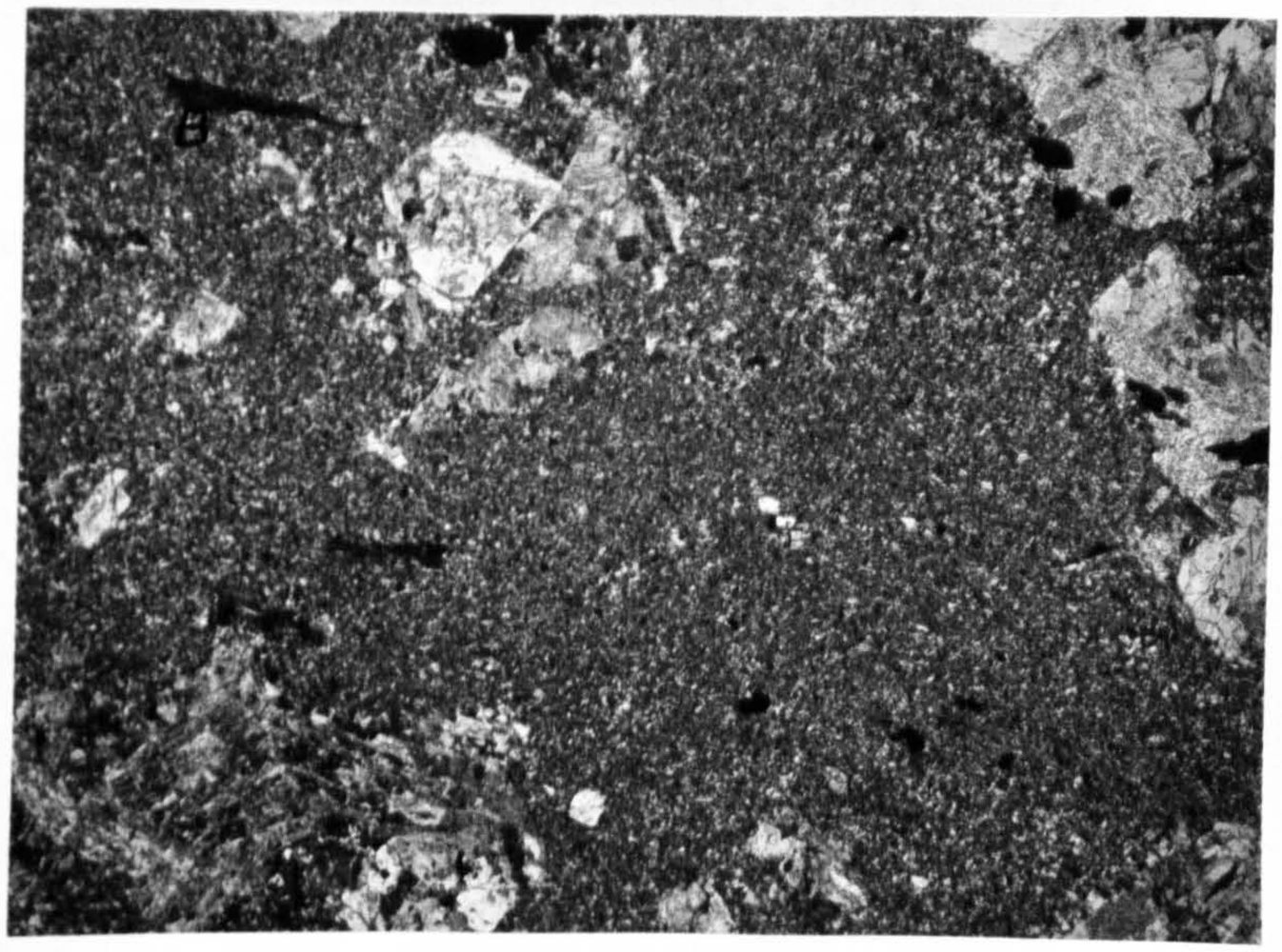


Fig. 3.21 Rhyolite: cloudy, unzoned albite, and flakes of biotite(B) (partially altered to chlorite) set in a devitrified groundmass. East of Catstye Cam. X 20. Crossed nicols.



Fig. 3.22 Coarse andesitic-rhyolitic tuff: whole and broken plagioclase crystals and fragments of rhyolite and andesite enclosed in a microcrystalline matrix. North-east of Eagle Crag. X 20. Crossed nicols.

aligned parallel to the bedding, thus giving the rock a streaky appearance. Oliver (1954) has suggested that similar rocks in Scafell are ignimbrites. However, in contrast to the probable ignimbrites of the Glenridding Group the rocks here are generally poorly welded, show no glass shards and are sometimes well sorted and bedded. It therefore seems probable that most of the Red Tarn tuffs are the products of normal ash showers.

4. Intrusions

A. Introduction

The intrusive rocks in the Glenridding area range from acid to basic in composition and occur in the form of small dykes and bosses. The intermediate and acid rocks show approximately the same mineralogy but the proportions of each mineral, the texture, and the colour of the groundmass are very variable, so that the division into the three classes used here, viz. quartz-porphyry, 'granite-porphyry' and 'porphyrite' is somewhat arbitrary.

B. Dolerites

The narrow basic dykes, which are similar to the basic andesites and basalts of the Ullswater Group, are probably genetically associated with these lavas. The rocks are dark green in colour, invariably fine-grained, and have a similar petrography to the basalts and 'basic' andesites.

In the southern section of the the Greenside mine-workings, composite dykes composed of dolerite and quartz-porphyry are found. The dolerite outcropping on Swirral Edge is probably part of similar composite

intrusion, but in this case the other component is 'granite-porphyry'. Similar composite intrusions from the Scafell area have recently been described by Oliver (1961).

The dolerite of the composite intrusion shows a typical doleritic or sub-ophitic texture (Fig. 3.23). The plagioclase of the dolerite from the mine-workings is rather sodic (An_{34}) while that of the rock from Swirral Edge is extensively altered to sericite and calcite. The interstitial minerals are clinopyroxene (partially altered to epidote and chlorite) and magnetite. Secondary quartz occurs in small patches and also in the form of veinlets containing epidote. Apitite occurs in accessory amounts.

Rocks which resemble the dolerite of the composite intrusions, but which form normal dykes, are found in the mine-area and on Catstye Cam. One dolerite dyke in the mine-area contains large amygdales composed of calcite and chlorite.

C. 'Porphyrites'

This group includes all porphyritic dyke rocks which are approximately dioritic in composition. The rocks form small dykes and also a much larger intrusion west of Lanty Tarn; east of Lanty Tarn the field relations of an outcrop of coarse-grained intermediate rock with the surrounding volcanics are indefinite, but the general similarity of the rock with that of the 'porphyrite' dykes suggests an intrusive origin.

The rocks have a reddish or greyish-brown groundmass and contain conspicuous phenocrysts of plagioclase and ferromagnesian minerals, (Fig. 3.24). The original groundmass has largely been replaced by a mosaic of quartz with chlorite and sericite flakes, calcite, magnetite,

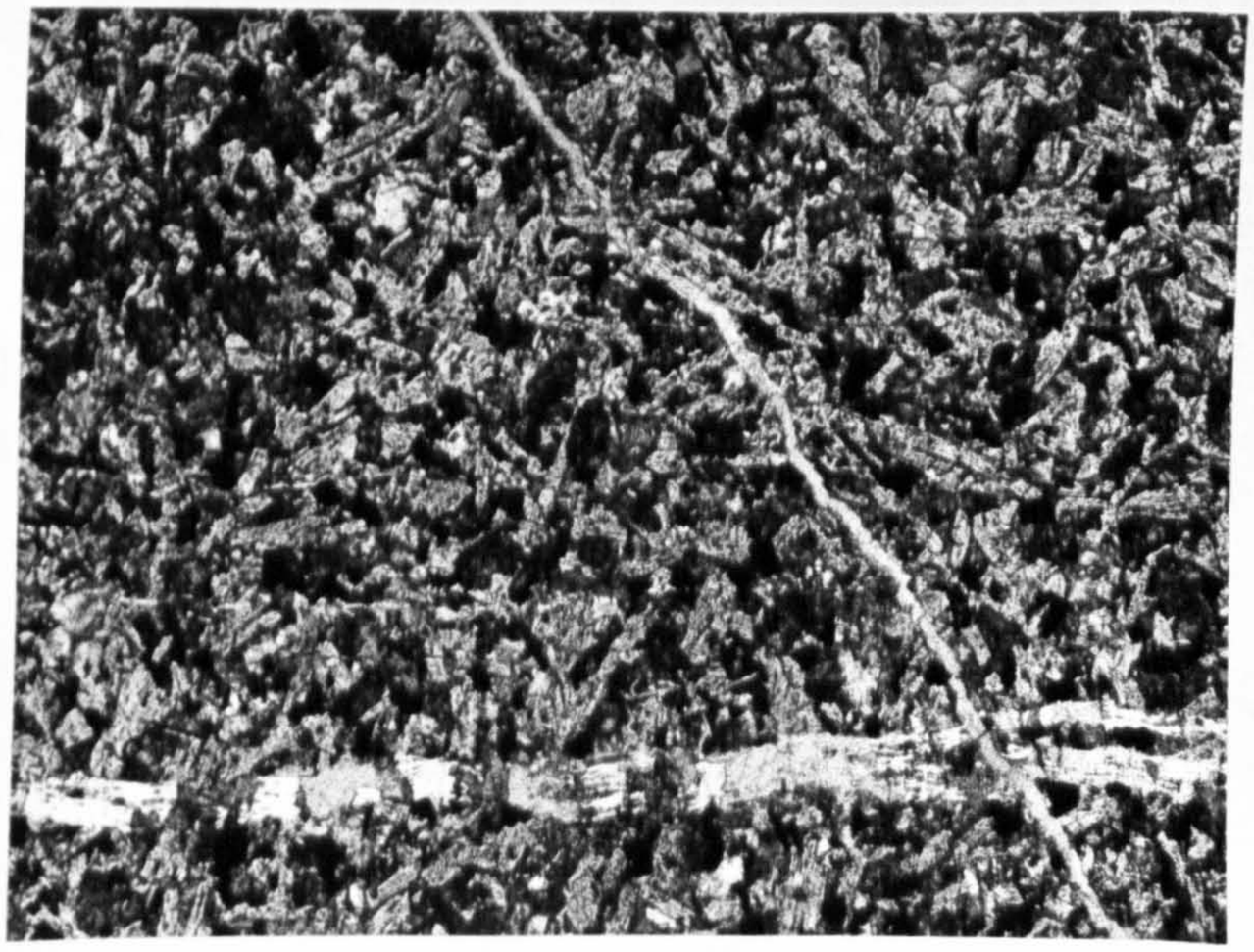


Fig. 3.23 Dolerite: laths of andesine with interstitial augite, magnetite, and chlorite. Veinlets composed of quartz, calcite and epidote. 218 S, 175 fm. level. X 20. Ordinary light.

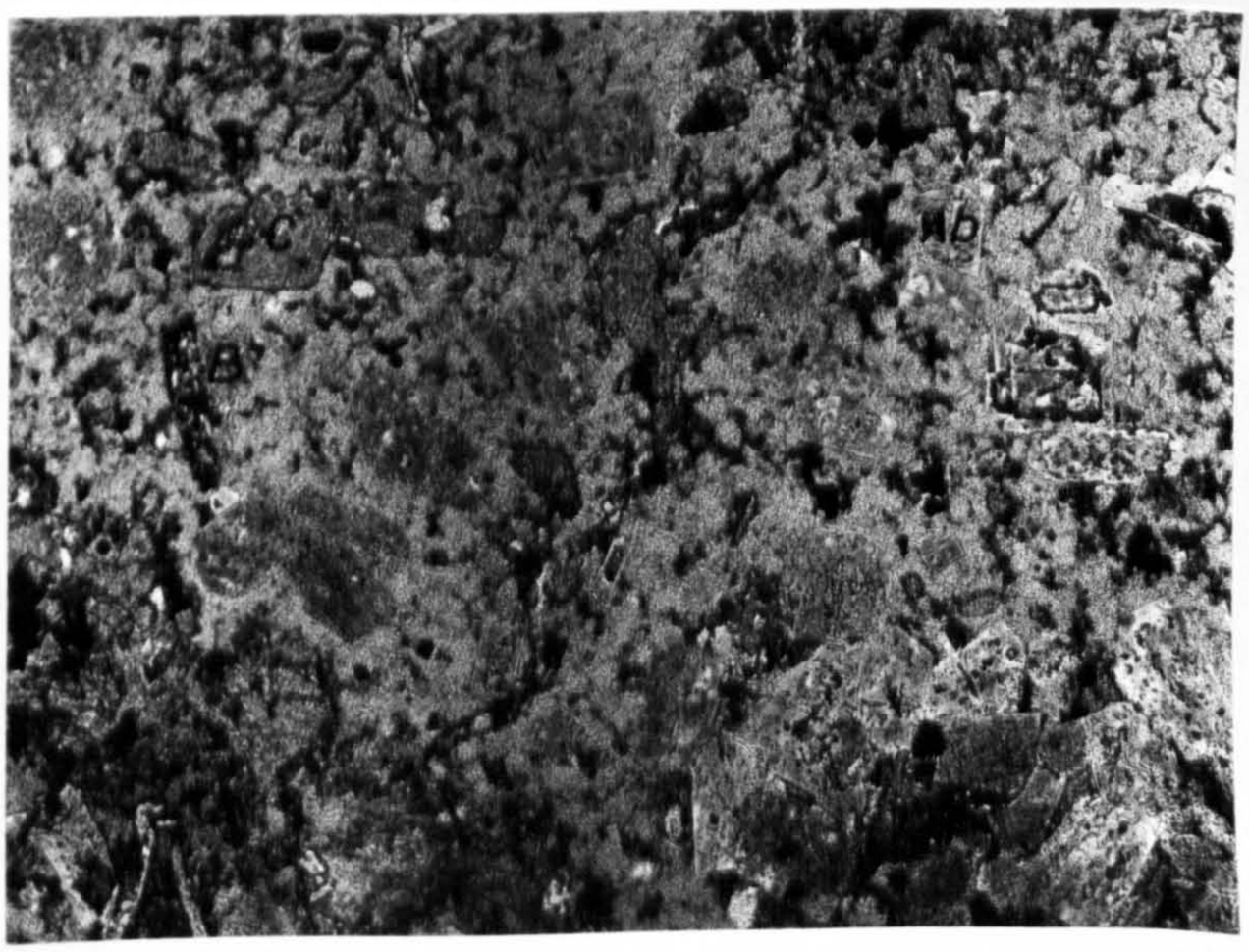


Fig. 3.24 'Porphyrite': laths of cloudy albite (Ab), plates of chlorite (C) after clinopyroxene, and flakes composed largely of 'leucoxene' (after biotite (B)) set in a fine-grained groundmass. West of Lanty Tarn. X 20. Ordinary light.

'leucoxene',and cryptocrystalline material. The zoned and slightly corroded plagioclase crystals are albitised or partially altered to calcite, sericite and chlorite; when fresh the phenocrysts are seen to be andesine (An_{30-35}). The ferromagnesian minerals - pyroxene, biotite, and probably amphibole - are completely altered to chlorite and minor 'leucoxene'.

Apatite, quartz, magnetite, zircon, rutile, and garnet are the accessory minerals. Garnet is partially altered to chlorite and forms rounded grains up to .5 mm. in diameter. Occasionally plagioclase laths enclose an irregular garnet phenocryst which is associated with grains of iron oxide. Similar enclosed garnets have been recorded in both intrusive and extrusive rocks of the Lake District and have been interpreted in various ways, but the suggestion by Oliver (1956) that the garnet is pyrogenetic, seems the most reasonable.

The appreciable amounts of pyroxene, biotite and amphibole as phenocrysts, and the large content of apatite, indicate that the porphyrites have lamprophyric affinities. However, the porphyrites which are lighter in colour, and which contain biotite as the principal ferromagnesian mineral, are probably associated with the 'granite-porphyries'.

D. 'Granite-porphyries'

The division of the acid intrusives into 'granite-porphyries' and quartz-porphyries is based mainly upon the amount of phenocryst quartz - the mineral forming small scattered phenocrysts in the former group, but large numerous phenocrysts in the latter. Large laths of plagioclase and flakes of chlorite (after biotite) are found in both groups.

The groundmass of the 'granite-porphyries' may be various shades of

grey and green; it is now composed of a mosaic of quartz, occasional small plagioclase laths, flakes of sericite and chlorite, patches of calcite, and cryptocrystalline material. As in the porphyrites, the original texture and composition have been altered.

The phenocryst plagioclase is albite or oligoclase (An_{7-12}), and is partially altered to sericite and calcite. Perthite is occasionally found. Quartz forms scattered bi-pyramidal crystals which have been rounded and embayed by corrosive magmatic processes (Fig. 3.25). Flakes and plates of chlorite and 'leucoxene' represent the original biotite. Garnet, zircon, apatite and rutile are the accessory minerals.

E. Quartz-porphyries

There are two types of quartz-porphyry : firstly, a pale-green type characterised by numerous, large plagioclase and quartz phenocrysts, and secondly, a darker coloured type containing fewer plagioclase phenocrysts. The latter type occurs as part of a composite intrusion in the southern section of the mine-workings, and also on the 175 fm. level, south of the Clay Fault. The remaining quartz-porphyry in the Glenridding area, including the dyke whose contacts are followed by the North and Greenside faults, is the pale-coloured type.

The groundmass of both types of quartz-porphyry is similar to that of the 'granite-pophyries' except that the dark-coloured type contains a large amount of chlorite and 'leucoxene'. The plagioclase phenocrysts of the pale-coloured type are albite or oligoclase (An_{7-12}), but alteration to sericite and calcite is common. The similar but more extensive alteration of the plagioclase in the dark-coloured type precluded a determination of composition. The biotite of both types is

altered to chlorite, sericite and 'leucoxene', while the quartz forms large embayed bi-pyramids (fig. 3.26). Garnet is absent from the quartz-porphyries. but otherwise the accessory minerals are similar to those of the granite-porphyries.

Lens-like fissures filled with vuggy quartz are very common in the quartz-pophyries and also in the 'granite-pophyries' (Fig. 3.27). Minor amounts of chlorite, carbonates and pyrite are found in the quartz veins associated with the main quartz-porphyry dyke found in the Green-side mine-workings. The veins are irregular in orientation but are essentially flat-lying, and often extend beyond the margins of the dyke into the wall rock. The length of the veins seldom exceeds five feet, while the maximum thickness is about one foot. The plexus of veins within the dykes points to a genetic relation with the intrusions, the quartz probably being formed from late-stage solutions. The fissures are perhaps too wide and numerous to be cooling cracks, and were probably formed by tensional tectonic forces which acted immediately after consol-idation.

The quartz veins of similar type which are found sporadically in the volcanic rocks throughout the map-area, are probably not associated with the intrusions, but were formed from residual solutions derived from the lavas.

F. Age and Sequence of the Intrusions

The intrusions show no definite trend in relation to the tectonics of the map-area. Some of the 'porphyrite' dykes appear to be parallel to the cleavage but the other dykes have a random orientation. 'Granite-porphyry' occurs at the contact of the Skiddaw with the Borrowdale

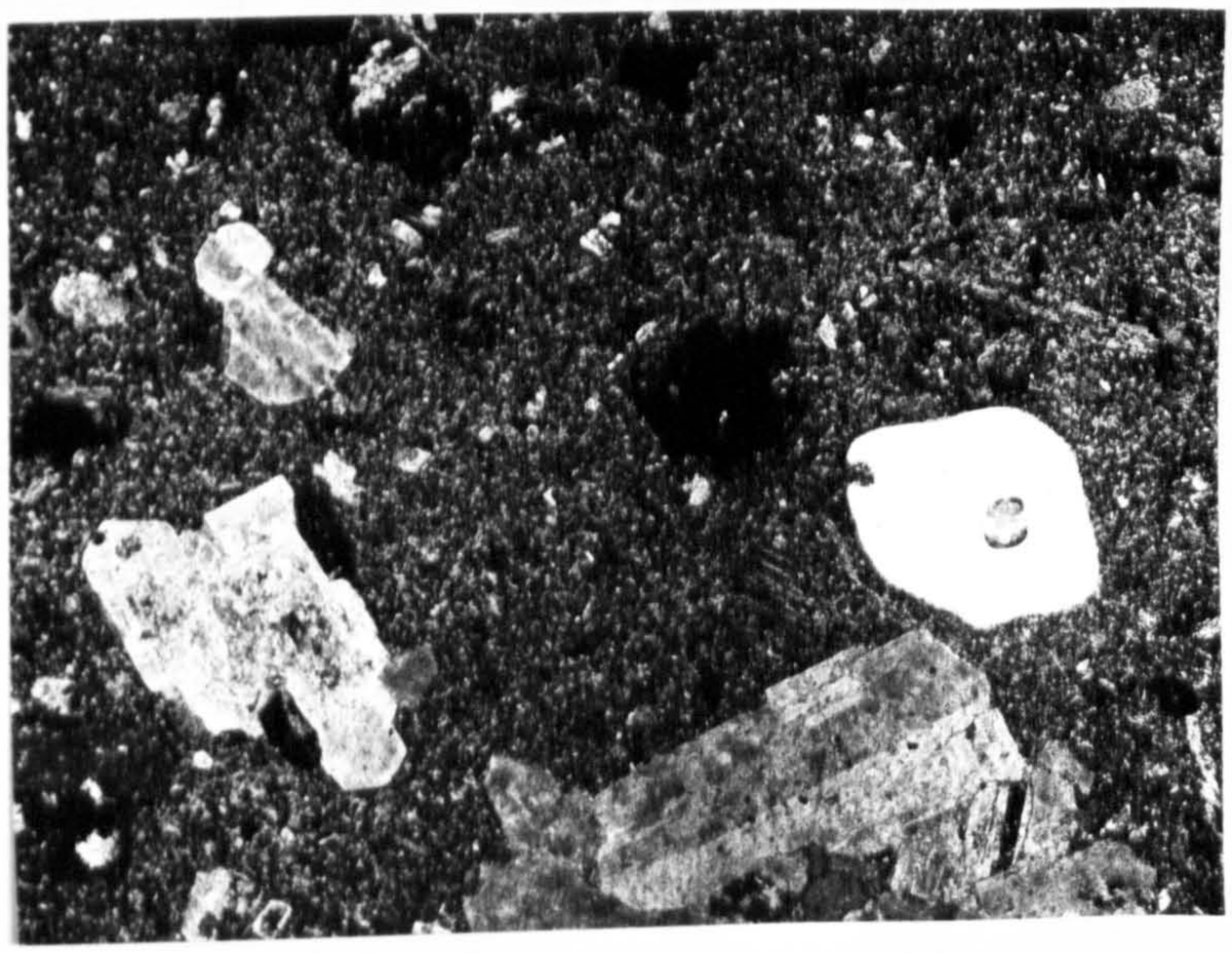


Fig. 3.25 'Granite-porphyry': laths of cloudy albite, corroded subhedral quartz, and plates of biotite (altered to chlorite and 'leucoxene') set in a quartz-sericite groundmass. Stream north of Catstye Cam. X 20. Crossed nicols.

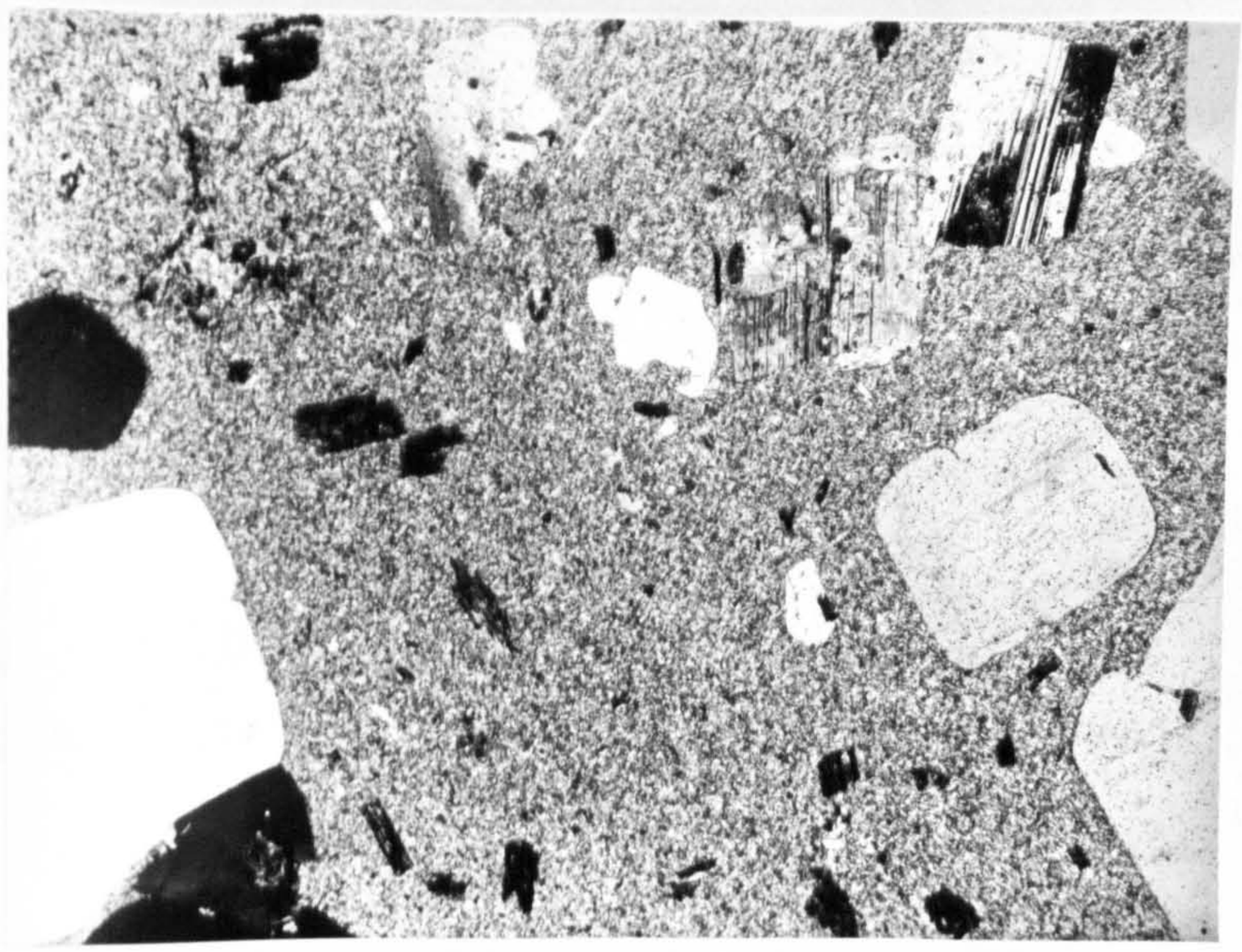


Fig. 3.26 Quartz-porphyry: corroded euhedral quartz, laths of albite, and flakes of biotite (altered to chlorite and 'leucoxene') set in a quartz-sericite groundmass. 1453 N, 90 fm. level. X 20. Crossed nicols.



Fig. 3.27 Tensional quartz veins in quartz-porphyry. Veinlets of barite (Ba) and fractures which are associated with the Greenside Fault, cut and displace the tensional veins. 1425 N, 40 fm. level.

Volcanic Series at Gloncoyne Farm, but the intrusion appears to be plug-like rather than laccolithic. Except for the large'porphyrite'intrusion west of Lanty Tarn, none of the intrusive rocks are cleaved. There is no evidence that any dyke was intruded along or near an older fault. The contention of Oliver (1961) that dykes which outcrop along fracture zones, or which lie parallel and near to them, are " at least as late as that of the faulting" is suspect, and careful examination of the dyke fault relationship must be made before judgement is cast. The relation of dykes and faults is considered in greater detail in a later section .

The intrusions have a narrow chilled margin, often with small felspar laths aligned parallel to the contact; no examples of intrusive breccia were observed. The contact metamorphic effects are almost negligible - usually a slight induration and sometimes bleaching of the rocks. The contact metamorphic effects of the Threlkeld Microgranite is also very slight (Hadfield and Whiteside, 1936). However the contact metamorphism of a xenolith of shale in the quartz-porphyry at Greenside is very noticeable. The rock is bleached, as a result of seriticisation, and exhibits small dark spots which are perhaps due to the segregation of fine carbon.

The sequence of the intrusions appears to be as follows :-

1. Fine-grained dolerite probably associated with the basic lavas of the Borrowdale Volcanic Series.
2. 'Porphyrites'.
3. Composite intrusions of dolerite/'granite-porphyry' and dolerite/quartz-porphyry.
4. Pale-coloured quartz-porphyry.
5. Dolerite.

The intrusive history of the area is undoubtedly more complicated than has been indicated above. However, the sequence of intrusions in the Scafell area, as outlined by Oliver (1961), agrees reasonably well with the sequence given here.

Dykes of 'serpentine' were apparently cut in the workings of the Helvellyn Mine and were recorded on the Geological Survey Sheet (6 inches to 1 mile series). This area was not studied and no serpentine dykes were observed in the map-area.

The quartz-porphyries, 'granite-porphyries',, 'porphyrites' and some of the dolerites are apparently related and can possibly be referred to a single intrusive suite. The Greenside quartz-porphyry closely resembles the Threlkeld microgranite which is three miles distant. The latter intrusion occurs along the Borrowdale Volcanic Series/Skiddaw Slates junction and probably has a laccolithic form, (Hadfield and Whiteside,1936).

A xenolith composed of folded Skiddaw Slates in the Threlkeld Microgranite suggests that the intrusion has a Caledonian age and is post-folding, (Rastall, 1941). At Holghyll, near Penruddock, Capewell (1955) has recorded fragments of quartz-felsite and mica-lamprophyre in the Mell Fell Conglomerate, a post-orogenic deposit of probable lower Old Red Sandstone age. The fragments apparently resemble intrusive rocks of the Cross Fell Inlier (Hudson, 1937), but can be also be compared with the intrusive rocks of the Lake District, a point overlooked by Capewell. The source of fragments of tourmalinised siltstones and mudstones (probably Skiddaw Slates) and a "flood of little-worn(tourmaline) grains" in the conglomerate at Holghyll were not satisfactorily

explained. The Threlkeld Microgranite which contains tourmaline in accessory amounts (Rastall and Wilcockson ,1915), and xenoliths of Skiddaw Slate with introduced tourmaline (Rastall,1941),is the most obvious source of these components thus substantiating a Caledonian age for this intrusion. The possibility that some of the tourmaline was derived from the Skiddaw Granite must also be considered. It is suggested that the suite of intrusive rocks in the map-area have a similar age, although some fine-grained dolerite dykes are apparently contemporaneous with the Borrowdale Volcanic Series.

5. Initial Structure of the Area

It seems very probable that the initial structure of a volcanic region influences the folding and faulting caused by later tectonic forces. The structure of modern volcanic provinces is very complex and therefore the interpretation of ancient areas of vulcanicity which have suffered one or more orogenies, is extremely difficult. In the area under consideration,no volcanic centre nor any other major conduit of lava could be found. However, the thickness of the strata increases westwards, suggesting that the source lay in this direction. The effect of this increase in the thickness on the later structures developed could not, however, be determined.

Most of the geological mapping of the volcanic rocks of the Lake District has been made on the tacit assumption that initial dips are small and may be neglected. The initial dips of modern subaerial lava flows may reach 30° and there is no reason to suppose that the lavas of the Borrowdale Volcanic Series are exceptional in this respect.

Initial dips in the ignimbrites,and the tuffs deposited under subaqueous conditions may be small., but subaqueous lava flows(if present), like subaerial flows, must have a limited lateral extent and must therefore form lens-like accumulations which necessarily have initial dips. The rapid thinning of the lava groups in the Glenridding area indicates that such dips are definitely present.

In addition to the unknown initial dip component of measurements made in the field, other factors must also be taken into account. Dip measurements in flow-banded and flow-brecciated lava tend to be erratic and often bear little relation to the inclination of the surface of the flow. Bearing these considerations in mind, the interpretation of dip and strike readings and the delineation of fold axes must be made with caution.

It seems probable that some of the postulated tight, isoclinal folding of the volcanic rocks can be attributed to such erratic initial dips. According to Mitchell, the most important belt of isoclinal folds extends between Coniston and Shap; it is significant that recent remapping by Konig (personal communication) has revealed only open folds.

The contrast in the competency of the Skiddaw Slates and the Borrowdale Volcanic Series has clearly influenced the effect of later tectonic forces. The plane of junction of the two series is an important zone of weakness along which fault movement is to be expected. The structure of the Skiddaw Slates at Greenside has an important effect on the localisation of the ore-shoots. This subject is therefore not considered in this chapter and is treated in detail in Chapter 4.

6. Folds.

The recorded dip and strike readings in the Glenridding area are shown in Map 1 ; Map 2 shows the position of the axes of the folds.

Folding in the Glenridding are is gentle. Two main fold structures have been delineated :-

(1) the Helvellyn Syncline

(2) the Glencoyne Anticline.

Both folds have a ENE -WSW trend and therefore are assumed to be Caledonian structures.

The Helvellyn Syncline is perhaps better described as a monocline, since the southern limb of the fold is only developed in the west of the area, near the summit of Helvellyn. Eastwards the fold becomes monoclinal, and finally this structure too dies out and the strata have a uniform southerly dip. There is no clear evidence of the plunge of the fold.

The Glencoyne Anticline is also limited in extent. The fold has caused the Skiddaw Slates to be exposed in the lower part of the Glencoynedale and in Glencoyne Park. Westwards the fold dies out and only southerly dips have been recorded. The disposition of the Skiddaw Slates in the Greenside workings corroborates this conclusion. The plunge of the anticline, as indicated by the strike of the overlying Borrowdale Volcanic Series, is to the west.

The area north of Glencoynedale is poorly exposed. Southerly dips near Dowthwaitehead indicate that a syncline lies between these two areas. The location of the fold axis shown on Map 2 is, however, only approximate. The whole of the Borrowdale Volcanic outcrop

between Glencoynedale and the outcrop of the Skiddaw Slates in the Vale of Threlkeld, is apparently composed of gently rolling strata which have an overall southerly dip.

Both the Helvellyn Syncline and the Glencoyne Anticline are asymmetric- the southerly limb of the Glencoyne Anticline (the northerly limb of the Helvellyn Syncline) being steeper than the complementary limbs of each fold. The Helvellyn Syncline is very probably an extension of the syncline mapped by Oliver (1961) in the Scafell area, and east of the Glenridding area is developed again on the other side of Ullswater (Moseley, 1960). It is noteworthy that the fold in the latter area is also monoclinal in form, and northerly dips are only found locally.

No minor, tight, or isoclinal folding was observed in the Glenridding area. The structure outlined thus differs markedly from that postulated by Hartley (1942). The main zone of postulated minor folding according to the latter, is located along the eastern shores of Thirlmere. The area lies outside the area mapped by the present author, and therefore no comment can be made. The folds, which according to Hartley bring in the two outcrops of 'Steel Fell Rhyolite' near Blea Cove, were not confirmed in the present mapping, and seem to have been based on an extensive flight of imagination. The 'Steel Fell Rhyolite' (according to Hartley the topmost strata of the Borrowdale Volcanic Series in this area) has been shown previously to mark the base of the Red Tarn Group (p. 64).

Pre-bala folding was not observed in the Glenridding area. Such folding has been postulated by Mitchell (1956) in the southern part of the Lake District and is based on the variation in pitch of the

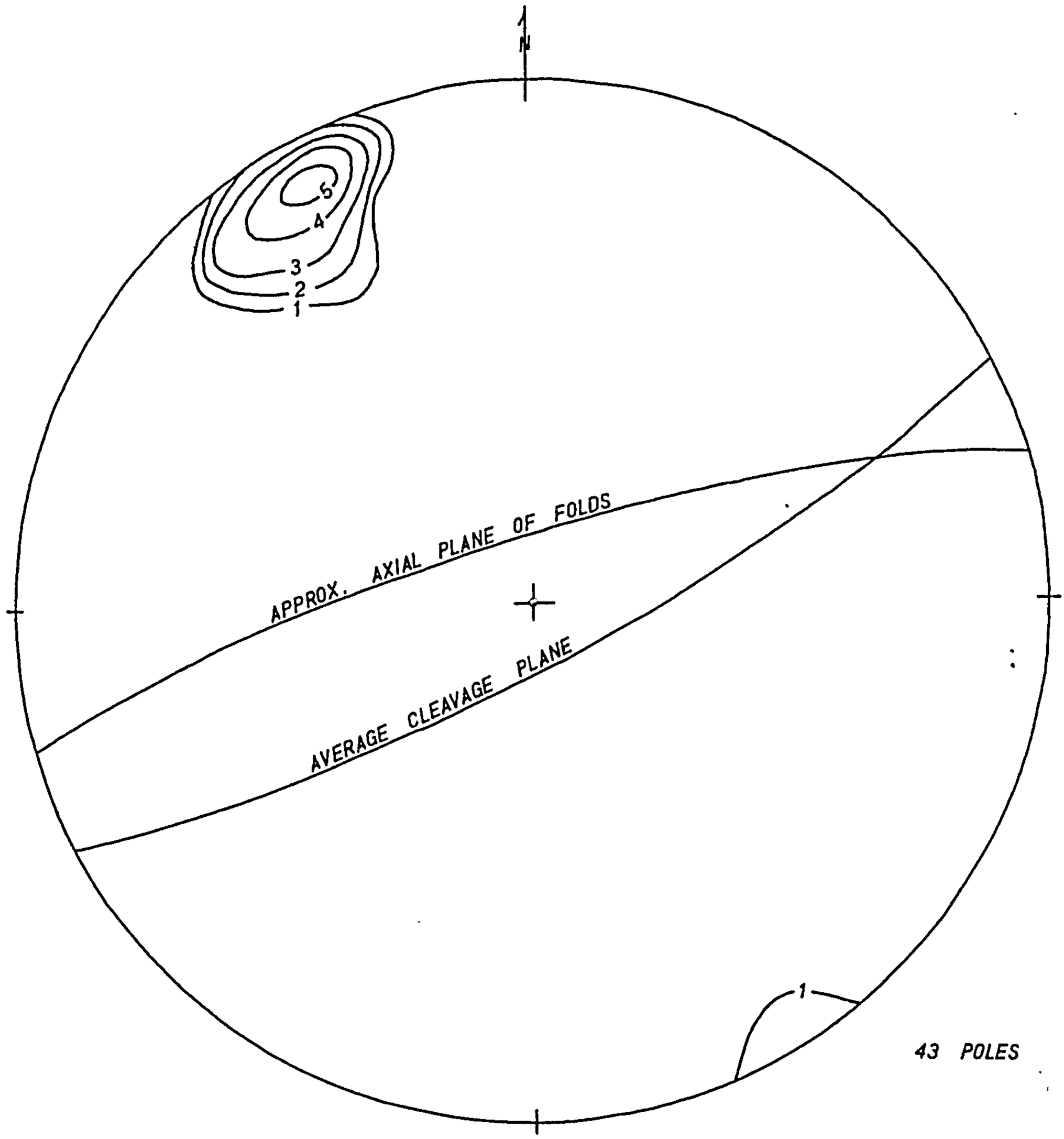


FIG. 3.28 CONTOUR DIAGRAM OF CLEAVAGE POLES

CONTOUR INTERVAL 1%

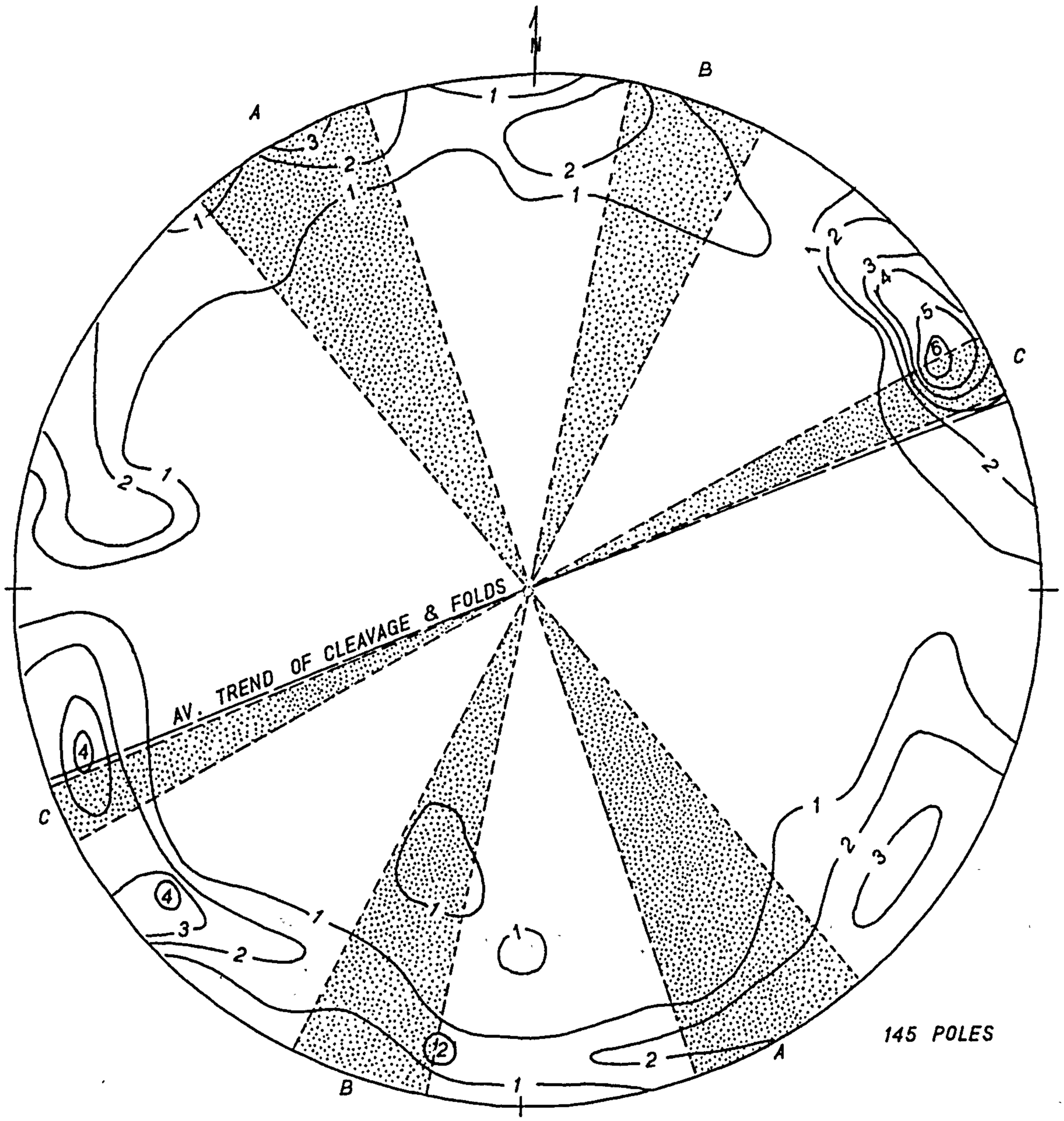


FIG. 3.29 CONTOUR DIAGRAM OF JOINT POLES

CONTOUR INTERVAL — 1 %
STIPPLED AREA — MAJOR TREND

related to the NNW-SSE Caledonian compression; tensional joints parallel to the NNW compression are also possibly represented in trend A. Similar trends to A and B have been observed in the area south-east of Ullswater (Moseley, 1960). It is noteworthy, however , that no NW or NNW trending Caledonian faults have been recognised in the Glenridding area, and therefore the origin of the joints is by no means certain. Trend C is parallel to the cleavage and thus perpendicular to the Caledonian compression, It is suggested that these joints are tensional release fractures.

8. Faults and Veins.

A. Introduction

The tectonic and mineralisation sequence in the area which has been affected by more than one orogeny is often complex, and requires careful analysis. Frequently a single period of orogenesis is characterised by a specific type of mineralisation. The relation between the various faults and episodes of minerlisation in one part of a metallogenetic province can often provide a 'key' which is useful in elucidating the tectonic history and mineralisation sequence in other areas of the province where the relations are not so distinct. Furthermore mineral exploration can be focussed on the most favourable areas indicated.

The failure of many geologists who have worked in the Lake District to take account of the mineral veins is to be regretted. The elucidation of the structural history of the region has undoubtedly been inhibited by this omission.

In the Glenridding area three groups of faults, each with a

characteristic type of mineralisation, can be distinguished. This three-fold division is to some extent an over-simplication since several periods of fault movement and phases of mineralisation may be represented in a single group. The groups are as follows :-

1. E-W to ENE-WSW normal faults. Probable Caledonian age. Quartz-pyrite-dolomite-ankerite-calcite mineralisation.

2. N-S, E-W and NE-SW normal faults. Probable Hercynian age. Galena-sphalerite-quartz-barite mineralisation.

3. NNE-SSW and NW-SE faults. Post-Triassic age (?). Dolomite-barite-quartz-calcite hematite mineralisation.

B. Group 1 Faults (Caledonian)

Details of the faults included in this category are summarised as follows :-

Fault	Av. strike	Av. dip	Throw	Strike slip
Swineside F	N 68°	near vertical	N	?
Clay F	N 88°	76°S	300'S ?	nil ?
North F	N 85°	81°N	N	nil ?
Kepple Cove F	N 79°	80°S	200-300'S	nil ?

(a) Swineside Fault

The Borrowdale Volcanic Series/Skiddaw Slates junction between the Troutbeck road and a point north of Glencoynedale is marked by the Swineside Fault. South-west of this point the fault swings into the Borrowdale Volcanic Series. The fault is poorly exposed. In Glencoyne Park the quartz-veined fault zone has a steep dip, the direction of which could not be determined with certainty. Near the Troutbeck road the dip of the fault varies from vertical to 85° northwards.

(b) Clay Fault

The Greenside Fault is terminated to the south by the Clay Fault. The precise effect of the latter on the Greenside Fault, and the possible continuation of ecomonic mineralisation south of the Clay Fault, has received much speculation during the history of the mine.

On surface the fault has been traced from Sticks Pass to the Greenside Fault outcrop. The extension of the fault beyond the western margin of the area is shown on the Geological Survey map. East of the outcrop of the Greenside Fault, exposures are poor, but a slight topographic depression suggests a possible extension along the south side of Glencoynedale to Glencoyne Farm, where the fault perhaps marks the Skiddaw Slates/Borrowdale Volcanic Series junction.

The Clay Fault takes its name from the associated wide gouge (or clay) zone which may be up to 45 feet in width. On each side of the gouge zone the rocks may be shattered over a distance of up to 50 feet. However, the conception of previous geologists, that the Clay Fault is a gouge zone several hundred feet in width, is completely erroneous.

Veins associated with the Clay Fault are commonly localised in the wall rocks adjacent to the fault rather than the main fault zone itself. This is because extensive movement along a fault plane will cause gouge and breccia, produced by the grinding of the bearing surfaces, to be transported to the open spaces which are therefore filled up as movement continues.

The veins associated with the Clay Fault are composed largely of quartz with minor amounts of pyrite. Similar veins are also found

throughout the mine workings. A sheeted vein-structure - a series of closely spaced stringers rather than a single wide vein - is common.

The most important zone of veins is found on the foot-wall side of the Clay Fault, i.e. to the north of the main fault zone. It was thought, prior to the author's work, that only a single vein occurred north of the Clay Fault; this vein was variously termed "Johnson's Cross-back", "Johnson's Cross-vein" or "Johnson's Ross Vein". It seems that the widest vein immediately north of the Clay Fault was taken as "Johnson's Cross-back", but the discontinuous nature of all the veins indicates that "Johnson's Cross-back" is unlikely to be the same vein on each level.

The quartz-pyrite veins, which may be up to 6 feet in width, generally have a steeper dip than the main fault zone, and sometimes are vertical or even dip northwards, i.e. in the opposite direction to to the main fault zone. The localisation of veins in the steeply dipping fissures is indicative of normal faulting. The amount of throw is uncertain. The variable lithology of the volcanic rocks and the absence of marker horizons make estimations difficult. A tentative estimate of 300 feet to the south is suggested. The fault has suffered minor movement during the later periods of fracturing, and the estimate given includes these later displacements. There is no clear evidence of strike slip.

The sequence of mineralisation along the Clay Fault is summarised below :-

1. Quartz
2. Pyrite
3. Marcasite
4. Ankerite-dolomite and calcite.

Each stage of mineralisation is separated by a period of fracturing. The quartz is semi-opaque, milky white in colour &has a vitreous lustre. The appearance is thus in marked contrast to the sugary and lamellar quartz of the Greenside Vein (Fig. 3.31) . The quartz is invariably fractured and often cemented by later pyrite. Marcasite occasionally overgrows the pyrite. The time relations of the marcasite and the ankerite-dolomite-calcite stages of mineralisation are uncertain, but both phases are clearly later than the pyrite.

(c) North Fault

On surface the North Fault (known at the mine as the "North Cross-back") is not conspicuous , but in the Greenside workings the fault is seen to better advantage. The fault follows the contacts of the E-W trending portion of the quartz-porphyry dyke (Map 3). The intrusion on surface is a simple dyke, but in depth it splits into two or three branches. The fault follows the contacts of these branches and thus becomes a complex zone rather than a single plane of movement (Section3). Below the 120 fm. level, the E-W trending portion of the dyke is absent and the broad complex fault zone gradually converges to form a single zone on and below the 175 fm. level. The North Fault has an important effect in the localisation of the ore shoots; this is considered in the following chapter.

Repeated movement along the fault has occurred during later periods of fracturing, and therefore the earliest movement cannot be easily gauged. In contrast to the Clay Fault, quartz-pyrite mineralisation (and also ankerite-dolerite-calcite mineralisation) is rare and takes the form a narrow stringers. This is suggestive of only minor

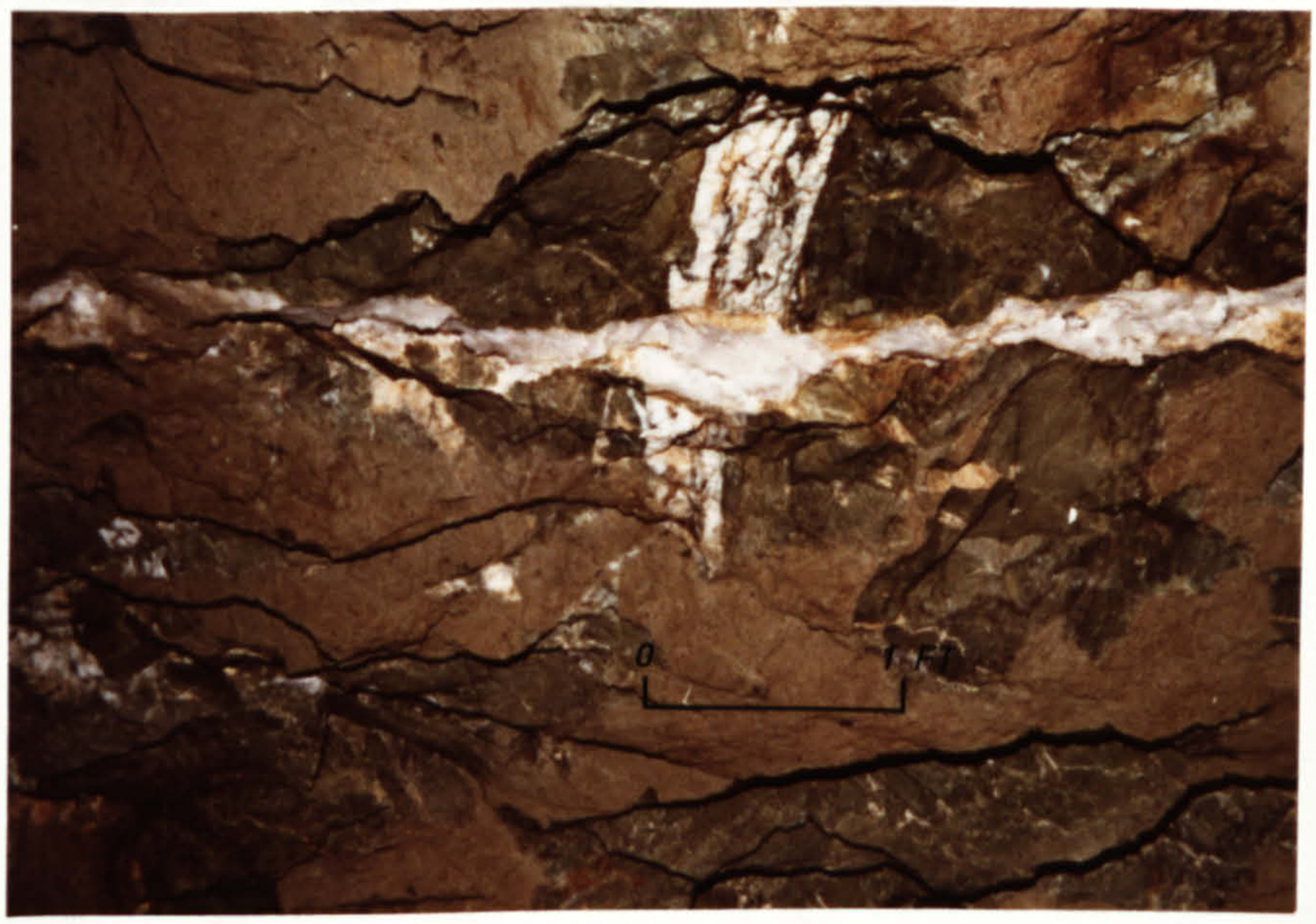


Fig. 3.31 Quartz-pyrite vein, associated with the Clay Fault, cut by a later quartz-galena stringer, associated with the Greenside Vein. 920 S, 175 fm. level.

movement during the Caledonian period.

(d) Kepple Cove Fault

In the western portion of the Glenridding area, a zone of several parallel faults constitute the Kepple Cove Fault. East of Blea Cove the fault cannot be traced with certainty,but an eastward extension along the floor of the Glenridding valley is suggested.

The dip of the Kepple Cove Fault is variable: the average dip is about 80° to the south but vertical and northerly dips have also been recorded. At Blea Cove, the downthrow is 300 feet to the south; near Kepple Cove, rhyolite is faulted against basalt, thus apparently suggesting a northerly downthrow. However, the rhyolite as described previously, has been formed on an irregular unconformable surface and the actual downthrow here is probably similar to that at Blea Cove.

The downthrow of the Moorside Fault is similar to that of the Kepple Cove Fault at Blea Cove, thus pointing to a simultaneous formation.

In contrast to the mineralisation along the Clay Fault, quartz and pyrite are not so common, a fine-grained aggregate of ankerite-dolomite being the more usual mineralisation. The latter minerals are often brecciated, and cemented by later calcite.

(c) Other Faults

Although the evidence is inconclusive, Shaw's Vein (composed of quartz) and the minor fault north of Glenridding Dod are included in Group 1. West of Stick's Pass, beyord the margin of the map-area, is a small copper prospect which is on strike with the Clay Fault. However a direct relation with the latter fault could not be determined. The mineralisation consists of stringers of malachite (probably representing original chalcopyrite),

associated with limonite and pyrite, in silicified volcanics.

C. Group 2 Faults (Hercynian)

Details of the faults included in this category are summarised as follows:-

Fault	Av. strike	Av. dip	Throw (approx)	Strike-slip (approx)
Greenside mine-workings:-				
(1) Main F	N 5°	70° E	50' E	7' (dextral)
(2) Hanging-wall F	N 0°	65-70°E	E ?	nil ?
(3) No. 1 Branch	N 48°	S	S ?	nil ?
(4) 348 W F	N 32°	75° E	E ?	nil ?
(5) S-W F	N 38°	65° E	E ?	nil ?
(6) Dawes Vein	N 8°	70-80°E	E ?	nil ?
(7) Eagle Crag Vein	N 93°	83° S	10-20'S ?	nil ?
(8) (unnamed see text)	N 31°	86° E	?	nil ?
(9) (unnamed see text)	N 62°	85° S	?	nil ?

(a) Faults in the Greenside Mine-workings

Plan 2 illustrates the mineralised faults encountered in the mine-workings. The Greenside Fault (or Greenside Vein) comprises the Main Fault and several branch faults, viz. the Foot-wall Branch , the East Branch, the No. 1 Branch and the No. 2 Branch.

The Main Fault has been traced 3900 feet along the strike and 2600 feet vertically. The ore shoots (Section 1) are simple fissure infillings along the fault , and the vein varies in width from a fraction of an inch to approximately thirty feet; the average width is approximately 6-8 feet.

The barren sections of the fault are composed of a breccia-gouge zone with shattered walls; the mineralised sections have slightly brecciated or shattered walls. The belief of previous geologists, that

the Greenside Fault is a fault zone a few hundred feet in width, which is bounded by a distinct foot-wall and hanging-wall, is erroneous. The maximum width of the breccia-gouge zone along the barren sections is forty feet, and the average width is 5 - 7 feet.

The fault has a downthrow of approximately 50 feet to the east, and a dextral strike-slip of 7 feet. The downthrow has been calculated from the displacement of the dykes (Section 3) and a quartz-pyrite vein. The horizontal displacement of the dykes could, at first sight , be due solely to a dextral strike slip but the dissimilar lithology of the walls of the fault in some places, and the localisation of the ore shoots along the steeper sections of the fault clearly indicate that this horizontal displacement can be mainly attributed to an essentially vertical movement. (The displacement of a vertical quartz-pyrite vein indicates that there is a small horizontal component of movement) The movement along the fault is considered further in the following chapter.

The Main Fault follows, for part of its length, the north-south trending portion of the quartz-porphyry dyke. The Foot-wall and East Branches, and the Hanging-wall Fault, follow the contacts of the dyke, or are controlled indirectly by the latter.

At the south end of the mine the Main Fault swings westwards, splits into a horsetail structure, and finally dies out some distance short of the Clay Fault. The position of dying-out and the shape of the South ore shoot are clearly influenced by the Clay Fault (Section 1). The Dawes Vein (a short vein associated with the horsetail structure) cuts clean through a quartz-pyrite vein associated with the Clay Fault, thus clearly establishing the time relations of the Greenside Fault

with the latter. A quartz-galena stringer associated with the Dawes Vein, which cuts through a quartz-pyrite vein, is shown in Fig. 3.31,(p.88) The Dawes Vein extends south to the Clay Fault; here the vein swings abruptly into the foot-wall of the latter and dies out.

The No. 1 Branch (perhaps better described as cross-fault) lies in the foot-wall of the Main Fault. On the 90 fm. level the mineralisation along the No. 1 Branch cuts through the Main Fault and extends into the hanging-wall. Movement along the branch fault, and perhaps the initial period of fracturing, was therefore later than the mineralisation along the Main Fault. It is suggested that the 348 Fault and S-W fault, which have a similar trend to the No. 1 Branch, can be attibuted to the same period of fracturing.

The mineralisation associated with these faults, described in detail in Chapter 6, is summarised below :-

Stage 1. Ankerite-dolomite, calcite, pyrite, sphalerite quartz, galena, chalcopyrite, barite, calcite.

Stage 2. Galena, sphalerite, chalcopyrite, quartz, barite, calcite.

Stage 3. Calcite, chalcopyrite.

Stage 4. Barite

Stage 5. Ankerite, sphalerite, calcite, quartz

Each stage is separated by a period of fracturing.

The ankerite-dolomite-calcite mineralisation,along the Clay Fault and perhaps other Group 1 faults, can conceivably be attributed to the intial phases of Stage 1 of the lead-zinc mineralisation. However, the complete absence of galena and sphalerite etc. along the Clay Fault is inconsistent with this hypothesis.

(b) Eagle Crag Vein

The Eagle Crag Vein was worked for lead during the last century. Mine-plans and details of production are not available,but judging from the size of the dumps the quantity of ore produced must have been small.

On surface the vein is narrow (1-2 feet in width) and tends to be developed along the steeper sections of the fault, thus suggesting normal movement. The amount of downthrow could not be determined but the dying out of the fault in places indicates that it is small, and probably in the order of a few tens of feet.

The vein structure and mineralisation of the Eagle Crag Vein is very similar to that of the Greenside Vein except that sphalerite and chalcopyrite are more important.

(c) Other Faults

Trials for lead-zinc veins have been made in several places in the Glenridding area. The positions of adits (mainly pre-1900) are shown on Map 1.

Only the upper adit in Brown Cove , and the adit north of Eagle Crag proved any lead-zinc mineralisation. The adit portals of both are now scree covered, as are the areas in their immediate vicinity, so that no mineralisation can be seen on the surface. The dumps of the former adit contain fragments of barite with galena and chalcopyrite, while the dumps near Eagle Crag contain tuff fragments which are cut by sporadic quartz-galena-chalcopyrite stringers; The latter mineralisation is probably along the continuation of one of the NNE-SSW faults (8) which outcrop to the south.

The lower adit in Brown Cove cuts a few irregular calcite veins.

However the dumps contain fragments of quartz-pyrite and ankerite-dolomite similar to that found along the Kepple Cove Fault. A few scattered cubes of fluorite were also found in the dump material. This mineral is not to be found in the Greenside or the Eagle Crag veins, and in the Lake District has only been recorded in the Force Crag and Hartsop Hall veins. It is suggested that the fluorite at Brown Cove is the same age as the lead-zinc mineralisation.

In the stream-bed west of Lanty Tarn, a small vein composed of quartz with scattered specks of galena was found (9). The vein extends only six feet along the strike and is up to one foot in width.

(d) Renewed Movement along Caledonian Faults.

On the old mine-plans, hoppers are shown along the drive on the Low Horse level which follows "Johnson's Cross-back". Therefore this E-W fracture was probably reopened& afforded penetration by the lead-zinc mineralising solutions.

On the 90 fm. level a quartz-pyrite vein associated with the North Fault is brecciated and the fault zone contains narrow quartz-galena stringers which again testify to renewed movement.

D. Group 3 Faults (Post-Triassic)

Details of the faults included in this group are summarized as follows :-

Fault	Av. strike	Av. dip	Throw	Strike-slip
Rake F	N 16°	W	?	?
Brownend F	N 22°	?	?	?
Lucy Tongue F	N 7°	69°E	E	nil ?
Latterbarrow F	N 147°	85°W	?	?
Black Crag F	N 31°	85°E	E	?

(a) Rake Fault

This is not exposed but is marked by a topographic depression, and a line of springs on the north side of Grisedale. The Rake Fault is probably the continuation of the Dunney Beck-Fairfield-Grisedale Fault which can be traced as far south as Coniston, where it displaces the outcrop of the Coniston Limestone for one mile. The downthrow of the fault as estimated by Hartley (1942, 1925) is as follows :-

Grisedale-fairfield section.....1500' to W

Dunney Beck section.....200-800' to W

No horizontal movement was envisaged. However, the displacement of the Coniston Limestone outcrop would require a downthrow of at least 5000 feet if no horizontal movement is assumed.

In the Glenridding area the displacement along the fault could not be determined with certainty - the apparent small horizontal displacement of the beds being equally accounted for by normal (easterly), or sinistral movement. Furthermore the extension of the fault to the north, where it perhaps marks the Skiddaw Slates/Borrowdale Volcanic Series junction, is again uncertain. It is noteworthy that the disposition of the Skiddaw Slates on the eastern side of the fault is not consistent with a possible easterly downthrow.

(b) Brownend Fault

Like the Rake Fault this fault has been plotted from a topographic depression. The movement along the fault could not be gauged.

(e) Lucy Tongue Fault.

This fault has been traced on the surface for nearly two miles. The old miners obviously knew of the fault's existence and the first

section of the Lucy Tongue adit was driven along the soft ground afforded by the fault. The Low Horse adit is driven on a branch of the Lucy Tongue Fault.

The movement along the fault is small: the quartz-porphyry dyke which outcrops along Glenridding Screes shows no horizontal displacement. It is suggested that the fault has a small downthrow to the east.

South of Glenridding Beck the Lucy Tongue Fault cuts through the Kepple Cove Fault; the intersection shows no displacement of either fault. However the Lucy Tongue Fault is clearly later, since otherwise the large downthrow of the Kepple Cove Fault would cause the Lucy Tongue Fault to be displaced to the west (unless the dip slip of the Kepple Cove Fault was exactly similar to the dip of the Lucy Tongue Fault, an unlikely chance). The Lucy Tongue Fault is also apparently undisplaced by the eastward extension of the Clay Fault, and is therefore later.

In places the fault is mineralised: dolomite, barite, quartz and calcite are the vein minerals. In contrast to the pale-coloured barite of the lead-zinc mineralisation the mineral here is deep salmon-pink in colour.

(d) Latterbarrow Fault

There is no clear evidence of the movement along this fault. Veinlets of quartz and calcite occur along the fault, while the wall rocks are hematised.

(e) Black Crag Fault.

This minor fault forms a conspicuous topographic feature even though the movement is small (the quartz-porphyry dyke along the

Glenridding Screes is not displaced).

Several minor faults or master joints which parallel the Black Crag Fault are found along the Glenridding Screes. Except for the minor fault east of Black Crag, these are not shown on Map 1 but have been included in the stereo-plot of the joint planes,p. 82 . The former fault, which lies along the contact of a granite-porphyry dyke, has displaced the afore-mentioned quartz-porphyry dyke. The displacement could be explained by either vertical or horizontal movement. No mineralisation was noted along this fault nor the Black Crag Fault.

(f) Other Faults

The two NW trending faults in the NE corner of the map-area were plotted from air-photographs; they can perhaps be referred to this group.

The minor faults in Nethermost Cove and at Catstye Cam could not be assigned with certainty to any of the three groups of faults.

(g) Renewed Movement along Group 1 (Caledonian)&Group 2 (Hercynian) Faults

Although the Greenside Fault was formed later than the Clay and North Faults, renewed movement along the latter has caused the Greenside Fault to be displaced. Thus the Main Fault has been shifted 5 feet to the west by the North Fault, while the Dawes Vein has been shifted 2 feet to the west by faulting along a quartz-pyrite vein associated with the Clay Fault.(Both displacements given for north side of cross-fault).

The Main Fault is also displaced by the Wynn Fault. The age of the latter is uncertain but the coincidence of the fault with a change of strike of the Main Fault suggests that it is at least the same age as the Main Fault.

Renewed movement also has taken place along the Greenside Fault itself - occasionally the vein quartz has become soft and powdery as a result of shearing. The direction of the net slip has been shown to be to the south; however, slickensides along the fault have an average plunge of 72° to the north (when projected on a N-S vertical plane). It is therefore suggested that renewed movement along the fault took place in this direction.

Hematisation of the wall rocks of the 348 Fault can probably be attributed to the mineralisation associated with the Group 3 faults.

9. Tectonic Sequence and Stress Orientations

The three groups of faults distinguished have been based mainly on the evidence at Greenside. Here the relations of the Clay, Greenside and Lucy Tongue faults, which represent groups 1,2 and 3 respectively, are clear. The faults in the remainder of the Glenridding area, where time relations are not so distinct, have been categorised by employing the characteristic mineralisation along each of the above faults as a 'key'.

Having established the time relations between the groups of faults, the absolute age of each will now be considered. On the basis of lead isotope data, the model age of the Greenside galena is 330 $\pm$90 million years (Moorbath, 1962). The lead veins of south-west England, which are genetically associated with granites of proven Hercynian age, have a model age of 280 $\pm$30 million years (Moorbath, 1962).

Although there is apparently some divergence, it is suggested that the Greenside mineralisation is basically Hercynian in age.

For comparison the galena associated with the Caledonian Shap Granite has a mean model age of 370 ±50 million years. (This topic and the age of other veins in the Lake District is discussed further in Chapter 8). Although there can be no direct evidence, it is suggested that the Greenside Fault and other Group 2 fractures were formed not long before mineralisation.

On this basis, Group 1 fractures and the associated mineralisation are best referred to the Caledonian orogeny. A few Group 3 faults perhaps represent the late Hercynian structures, but hematisation along some faults provides a clue to their age. In west Cumberland post-Triassic faults are frequently heavily hematised while older faults show only sporadic hematisation (Eastwood, Hollingworth, Smith and Dixon, 1931). It is suggested ,therefore, that most of the faults of Group 3 have a post-Triassic age. The post-Triassic faults in West Cumberland are predominantly normal faults; it is therefore possible that the Rake Fault (which continued to the south, causes, probably by tear movement, the displacement of the Coniston Limestone) was formed during a more intense period of orogenesis, perhaps the Caledonian.

In most parts of the Lake District a two-fold pattern of faults - NW-SE and NNE-SSW to N-S - can be recognised. It is probable, judging from the complexity of the fault sequence in the Glenridding area, that this pattern does not have a single, simple origin. Therefore analyses which relate the two-fold pattern to conjugate fracture directions, formed during the Caledonian compression (e.g. Moseley, 1960), are very probably an over-simplification. The general fault and vein

pattern of the Lake District is considered further in Chapter 8.

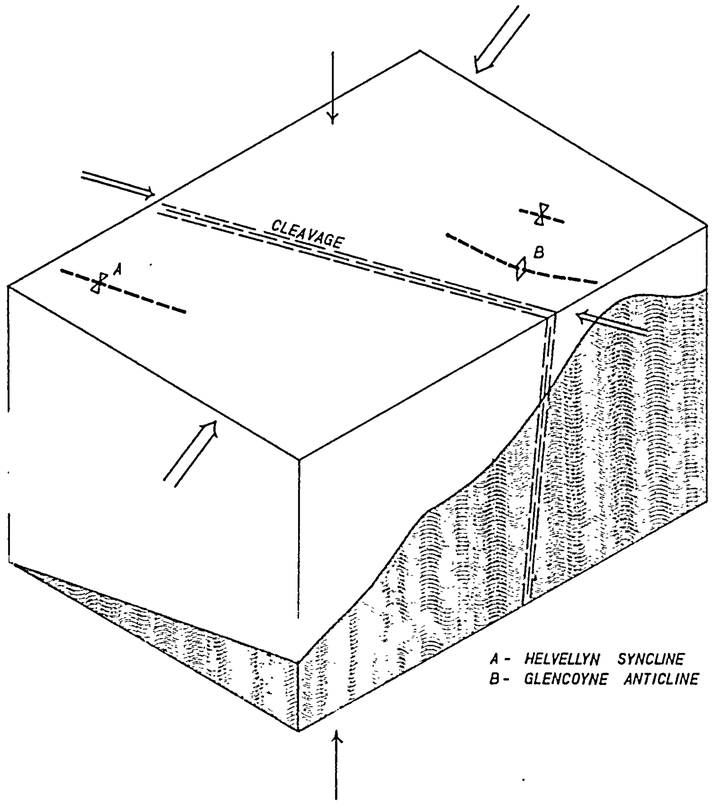
The tectonic sequence in the Glenridding area and the postulated orientations which produced each series of structures is illustrated in Fig. 3.30 . It is felt that the diagrams adequately describe the sequence of events and therefore the following account is brief. (The upper surface of the block shown in Fig. is approximately bounded by N-S grid lines 34 and 39 and E-W grid lines 14 and 21).

The Caledonian orogeny caused folding of the strata, the development of cleavage and the formation of Group 1 faults. (Possible pre-Bala folding is not shown on the diagrams). The Group 1 faults have a similar strike to the fold axes. It is suggested that these normal faults are 'release ' fractures that have developed along conjugate fracture directions, following the release of the NNW-SSE Caledonian compression. The faults make smaller angles with the presumed vertical maximum compression than the ideal 30°. The NNE-SSW Moorhouse Fault was possibly formed as a tear fracture during the main period of compression;normal fault movement then took place on the release of the compression.

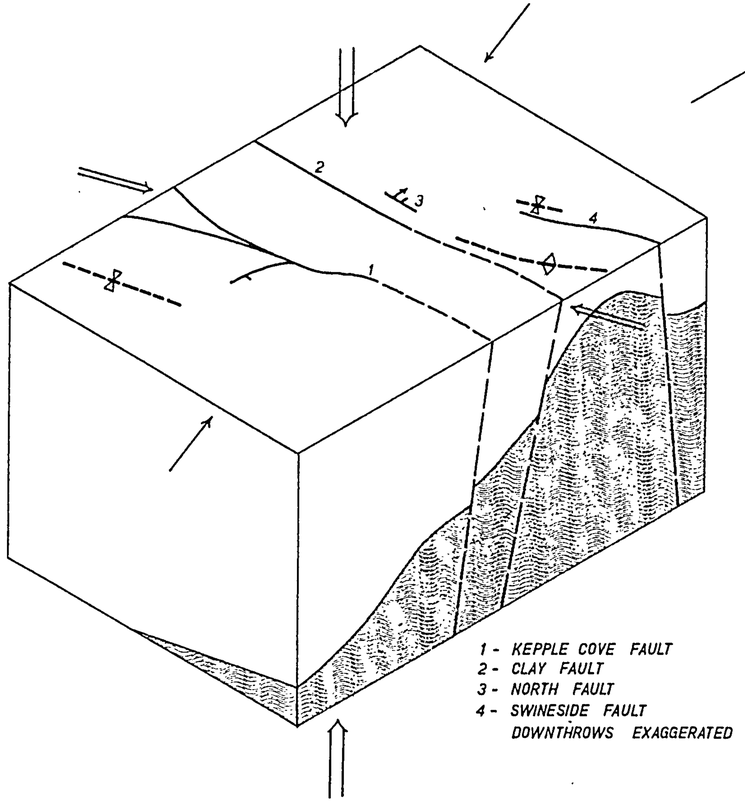
The Hercynian orogeny probably caused gentle doming of the strata which was accompanied or followed, by normal faulting (Group 2). In West Cumberland the Hercynian folds generally have an approximately NE-SW trend, and may be developed along the lines of Caledonian structures, which were therefore accentuated.

The Group 2 fault pattern is not easily interpreted. The number of Hercynian structures in the Glenridding area is few, and therefore it would probably be more meaningful to consider the lead-zinc-barite veins of the Lake District as a whole; this is in fact carried out in

STAGE 1 CALEDONIAN FOLDING, DEVELOPMENT OF CLEAVAGE



STAGE 2 RELEASE OF CALEDONIAN COMPRESSION
FORMATION OF GROUP 1 FAULTS
QTZ-PY-DOL-ANK-CALC MINERALISATION



STAGE 3 RELEASE OF HERCYNIAN COMPRESSION
FORMATION OF GROUP 2 FAULTS
GAL-SPHAL-QTZ-BAR MINERALISATION

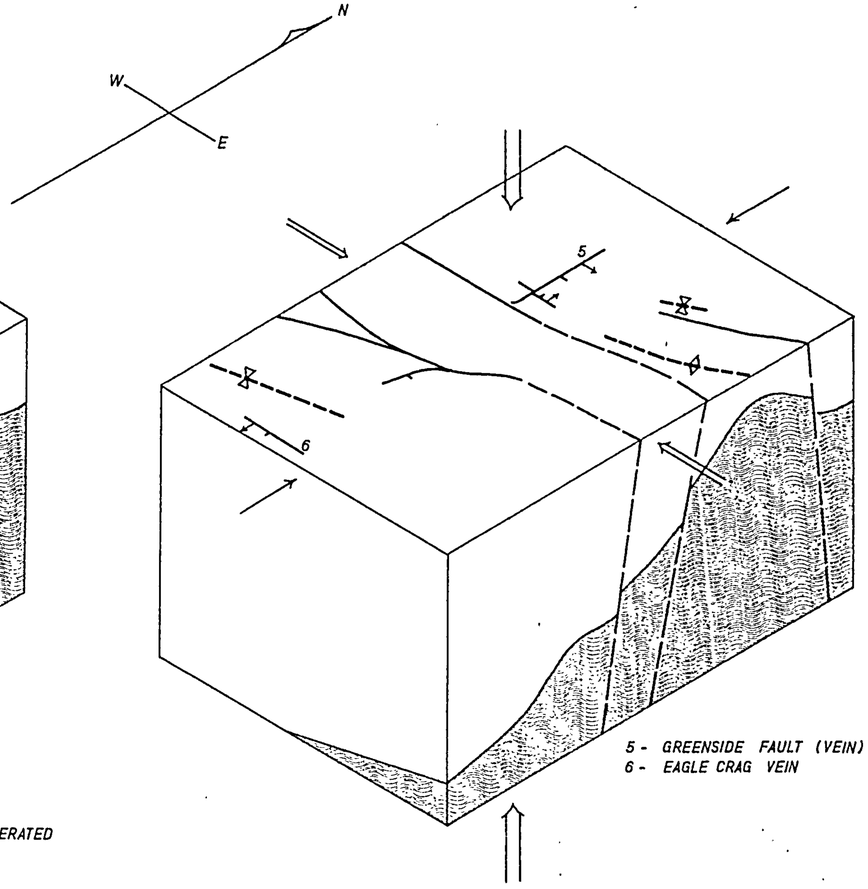
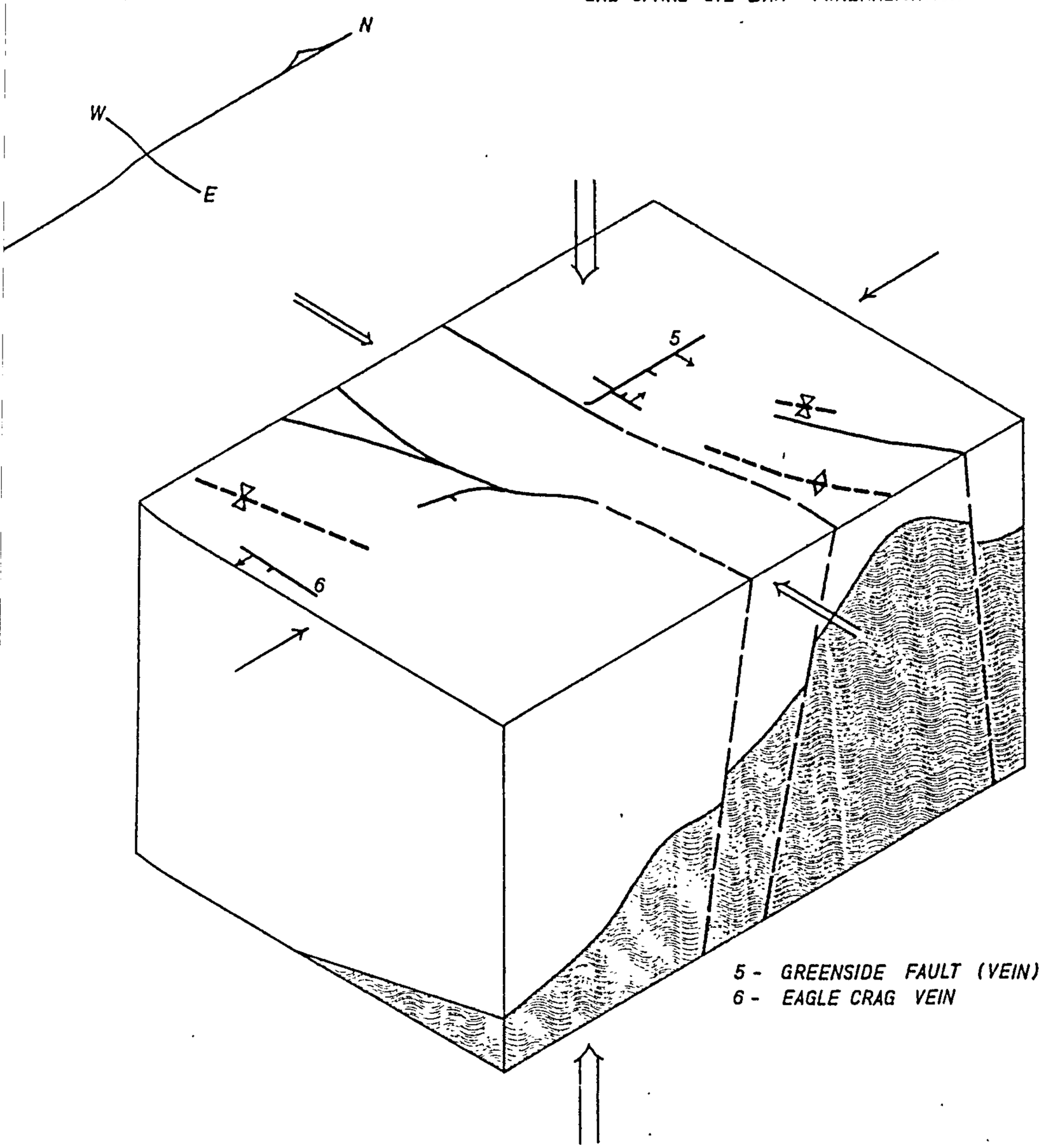


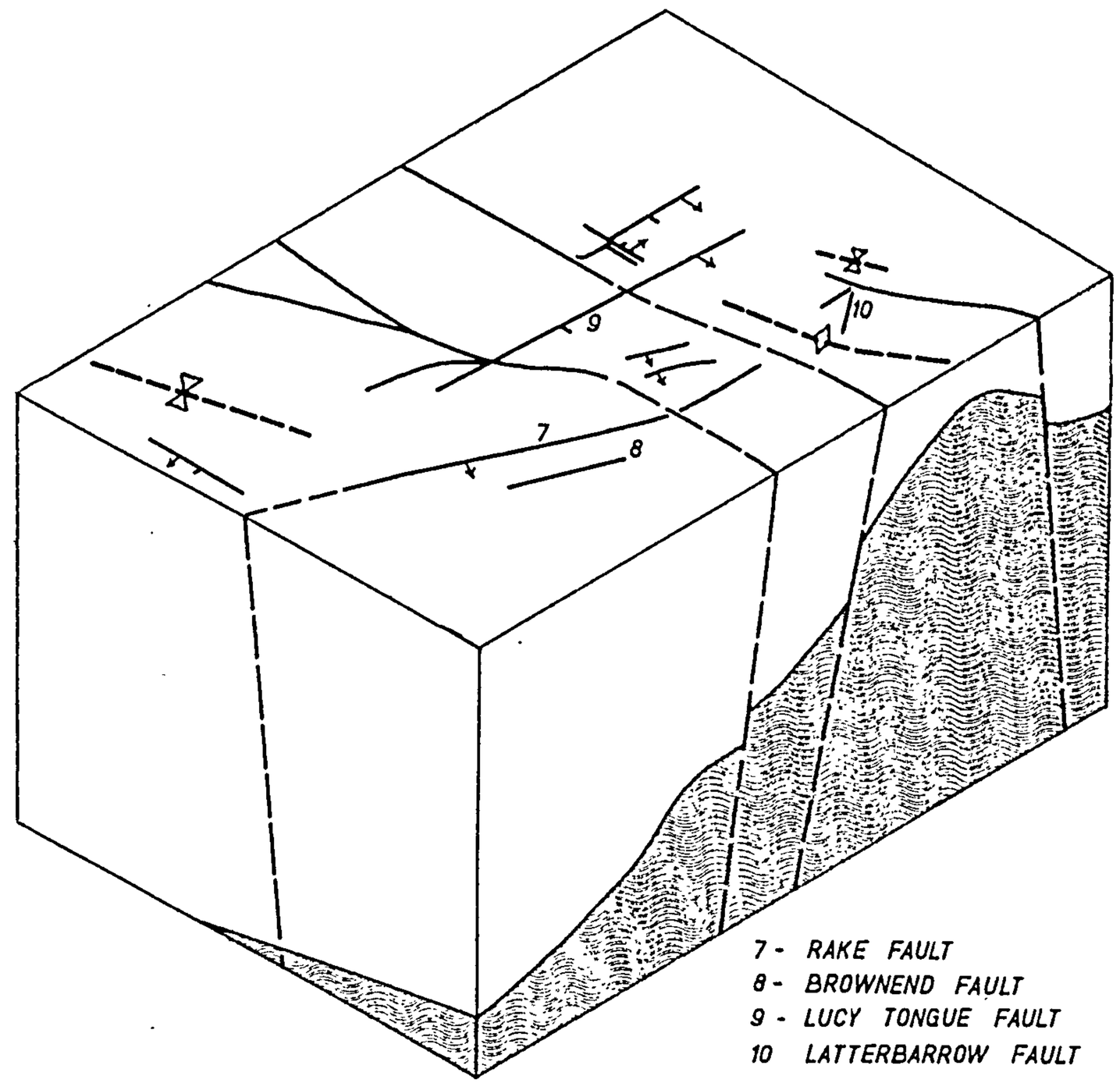
FIG. 3.30 BLOCK DIAGRAMS SHOWING THE TECTONIC SEQUENCE OF THE GLENRIDDING AREA

STAGE 3 RELEASE OF HERCYNIAN COMPRESSION
FORMATION OF GROUP 2 FAULTS
GAL-SPHAL-QTZ-BAR MINERALISATION



5 - GREENSIDE FAULT (VEIN)
6 - EAGLE CRAG VEIN

STAGE 4 POST-TRIASSIC MOVEMENTS
FORMATION OF GROUP 3 FAULTS
DOL-QTZ-CALC-BAR-HEM MINERALISATION



7 - RAKE FAULT
8 - BROWNEND FAULT
9 - LUCY TONGUE FAULT
10 LATTERBARROW FAULT

EXPLANATION

BORROWDALE VOLCANIC SERIES
SKIDDAW SLATES
ANTICLINAL AXIS
SYNCLINAL AXIS
FAULT, DIP & DOWNTHROW

P MAX.
P INTER.
P MIN.

SCALE (APPROX) : 1" = 1.3 MILES

NCE OF THE GLENRIDDING AREA

D.G. 1962

Chapter 8. The Group 2 faults have three trends - N-S, E-W and NE-SW. The faults with the latter trend are probably the latest fractures, but there is no evidence to suggest an age difference between the N-S and E-W faults. Normal faults formed under a single stress system and with a vertical maximum pressure, under ideal conditions, have a single strike direction. Variations of strike could be caused by the equality of the two horizontal forces, in which case the faults could have any trend, or by the non-homogeneous nature of the strata, in which case the faults would occur along the zones of least resistance. It is also conceivable that the E-W and N-S faults represent conjugate tear fractures, along which later normal movement took place. However there is no clear evidence to support this explanation and an original formation as normal fault is preferred.

In conclusion, it is suggested that the normal faults of Group 2 were developed under tension as a result of the collapse of gentle domes and arches, following the release of the Hercynian compression. A similar mechanism has been advocated for the vein systems in the Tertiary lavas of west North America (McKinstry, 1955). In the Northern Pennines Dunham (1959) has suggested that the vein pattern resulted from doming, but he emphasised the effect of the upward push during the formation of the dome, rather than the collapse of the latter.

The post-Triassic movements proabably represent a series of minor movements rather than a single orogeny. The strata were again gently arched, probably along approximatley E-W lines, since this is the trend of the folds in West Cumberland. The system of NNE-SSW and NW-SE trending faults were perhaps formed as conjugate tear fractures. However,

clear evidence of the movement along these faults is lacking and thus their origin must remain uncertain.

CHAPTER 4

STRUCTURAL CONTROL OF THE ORE SHOOTS

1. Introduction - Tectonic Environment of the Greenside Vein

The Greenside Vein has yielded approximately 200,000 tons of PbS concentrates, which probably account for at least 60% of the total lead production of the Lake District. Apart from a few small-scale veins the Greenside Vein is isolated, and lies apart from the areas of lead-zinc mineralisation in the neighbourhood of Keswick and the Caldbeck Fells.

The factors controlling the distribution of the ore deposits in the Lake District are indefinite. The veins have a scattered distribution and variable trends; they show no clear relation to stratigraphy, fold axes. major lines of faulting, or igneous intrusions.

The problem which first of all requires an explanation, is the localisation of the Greenside Vein. Although Chapter 3 provides a basis for this topic, the relevant facts will be re-emphasised here. Then proceeding to greater detail, the localisation of the individual ore shoots will be considered.

There is some evidence that the stratigraphy of the Borrowdale Volcanic Series has influenced to a small degree the localisation of the Greenside Vein. The latter traverses the Ullswater Group while the less productive veins in the Patterdale-Glenridding-Helvellyn area traverse strata which are much higher in the succession. This can probably be attributed to a contrast in the competency of the rocks - the 'basic' and 'acid' andesites which compose the Ullswater Group having a greater competency than the tuffs, which are the predominant rocks of the succeeding strata. Fissures would be more likely to stand open in the more competent rocks.

The marked contrast in the competency of the Borrowdale Volcanic Series and the Skiddaw Slates has caused the junction of the two series to be a zone of weakness. The structure of the junction has played an important part in the localisation of the Greenside Fault, which has followed this zone of weakness in places.

There are no known intrusions, either within the Glenridding area or outside it, to which the Greenside Vein can be genetically related. However the contacts of a Caledonian quartz-porphyry dyke afford planes of weakness which have been followed by the Greenside Vein. The strike and dip of the contacts thus control the strike and dip of the fault. The presence of the North Fault and branches of the Greenside Fault are also related to the dyke.

Apart from the relation of the Greenside Fault to the structure of the Skiddaw Slates/Borrowdale Volcanic Series junction, the influence of folds on the localisation of the fault is indefinite. The fault cuts across the projected axis of the Glencoyne at right angles, but the significance of this is uncertain, especially as the two structures are of different ages. However, the Glencoyne Anticline was probably accentuated during the Hercynian and post-Triassic earth movement, and the Greenside Fault is perhaps related to the release of the compression following the Hercynian accentuation, as outlined on page 102 . The Eagle Crag Vein is perhaps related to the Helvellyn Syncline in a similar fashion, but in this case the vein is parallel to the axis of the fold.

The relation of the Greenside Fault to the fault pattern of the Glenridding area has been illustrated previously (Fig. 3.30). Although

the direct formation of the Greenside Fault has apparently not been influenced by earlier faults, the Clay and North faults have undoubtedly affected the limit of the fault, and the variation in dip and strike.

There are four ore shoots along the Greenside Fault. From south to north they are the South, Central, North and 2300 N ore shoots. Above the Lucy Tongue level the Central and North ore shoots coalesce while above the 36 fm. level this ore shoot coalesces with the South ore shoot. The 2300 N ore shoot is only developed below the Lucy Tongue level. On the following pages the localisation of these ore shoots is described under the headings shown below :-

1. Influence of the Skiddaw Slates/Borrowdale Volcanic Series junctions.
2. Influence of the quartz-porphyry dyke.
3. Influence of pre-mineralisation cross faults .
4. Influence of branch faults .
5. Influence of variations in dip and strike of the Greenside Fault.

2. Influence of the Skiddaw Slates/Borrowdale Volcanic Series Junction

Owing to the close connection of the Skiddaw Slates/Borrowdale Volcanic Series juction with the Greenside Fault, and especially with the mineralisation along the latter, this subject has not been considered in detail previously. However in the following pages, many aspects of the problem are considered, not only the economic ones.

Throughout the years the nature of this junction has stimulated much controversy among geologists who have studied the Lake District. The historical background of this subject has been outlined in the

chapter on regional geology (p. 16). The evidence to date strongly suggests that the original contact was conformable; however faulting and thrusting have complicated the picture in places.

For brevity the Skiddaw Slates/Borrowdale Volcanic Series junction in the Glenridding area, will hereafter be referred to as the "shale/volcanics" junction. Before considering the junction at Greenside, the relations on the surface in the Glenridding-S.E Ullswater area will be briefly described.

Although the Borrowdale Volcanic Series and the Skiddaw Slates are found in close proximity at Glencoyne Farm, the actual contact is not exposed. It is possible that an extension of the Clay Fault separates the two series here. The steeply-faulted contact between Troutbeck road and a point north of Glencoynedale, is probably a continuation of the Swineside Fault (see p.84). Moseley (personal communication) believes that the contact, apart from that marked by the Swineside Fault, is a thrust; furthermore he believes that there is also a parallel thrust within the Skiddaw Slates. However there are no exposures of the contact, and the evidence of both thrusts is flimsy.

South-east of Ullswater there are no clear exposures of the contact. Moseley (1960) concludes that a thrust marks the contact, on the evidence that the contact appears to cut across the strike of the rocks, and rests against progressively higher strata. However the highly discontinuous nature of the volcanic rocks could possibly account for this. In the initial phases of the Borrowdale Volcanic episode, it is possible that overlapping lenses of lava and tuff were formed on the Skiddaw Slates surface, rather than continuous bands. Although not dismissing

Moseley's theory, it is felt that the above factor must be taken into account.

The nature of the shale/volcanics junction in the Greenside mine-workings will now be considered. Skiddaw Slates occur in the lowermost workings, and also at the north end of the 120 fm. level. The shale/volcanics junction is not a uniformly and gently dipping plane as envisaged by Moseley (1960) in the Ullswater area, but has a very variable and sometimes steep dip.

The structure of the Skiddaw Slates in the lowermost levels will be considered in three directions in turn, viz. in longitudinal section, plan, and transverse section. The rocks have only been located with certainty on the foot-wall side of the Greenside Fault.* The line of intersection of the shale/volcanics contact with the Greenside Fault is convex upwards in longitudinal section (Section 2). To the south the line plunges in a southerly direction, while to the north the line has a gentle northerly plunge.

In plan, the shale/volcanics junction intersects the Greenside Fault at a small angle, both to the north and south (Plan 5). Because of the plunge of the line of intersection, described above, the Skiddaw Slates are found for a greater strike length on the 217 fm. level than the 208 fm. sub-level. On the former level the Skiddaw Slates are apparently also found in the hanging-wall of the Greenside Fault, but this is considered in a later section.

Section 5 shows the structure of the Skiddaw Slates in transverse section at various intervals along the strike of the Greenside Fault. At 1600 N, the failure of D.D.H. 137 to intersect Skiddaw Slates

*' The discussion in Moseley, 1960 was written before certain data was available.

indicates that the contact in the foot-wall of the Greenside Fault dips westwards. At 1800 N, D.D.H.140 indicates that between the foot-wall of the fault and the North Shaft, the contact dips to the east; west of the shaft the contact must dip westwards, or at least flatten out, since Skiddaw Slates were not intersected in D.D.H. 136 .

The basic structure of the Skiddaw Slates in these lowermost levels is thus dome-like; however, the westerly limb of the dome can only be recognised to the north. The long axis of the dome trends approximately N-S.

It can be seen from Section 1 that the line of intersection of the Skiddaw Slates, in the foot-wall of the Greenside Fault, coincides with the limit of stoping. The vein, on reaching the contact, pinches out abruptly. The effect of the Skiddaw Slates is two-fold: firstly, the dip of Greenside Fault rapidly decreases when the foot-wall is composed of these rocks, and, as will be shown in a later section , low dips are not favourable to the formation of ore shoots; secondly any openings formed would tend to collapse because of the incompetent nature of the shales. However, immediately above the intersection, the vein was exceptionally rich; this can probably be related to a rapid precipitation of minerals , caused by a release in pressure as the mineralising solutions reached the open spaces above the tight contact.

The structure of the Skiddaw Slates at the north end of the 120 fm. level will now be considered. The rocks were intersected in D.D.H. R.C.E. 5 (Plan 5). It is uncertain whether the rocks are on the foot-wall or the hanging-wall side of the Greenside Fault, since the relations are complicated by a cross-fault at the end of the level. The diamond

drill hole indicated a rapid alternation of andesite and Skiddaw Slate bands. The breccia of andesite scoriae along the contacts of the bands has been described previously (p. 40). The dip and strike of the bands could not be determined.

In the mine workings, the shale/volcanics junction, outside the influence of the Greenside Fault, has only been encountered.in two places. At the bottom of the North Shaft, the contact dips at 65° to the east (Plan 5). There is some uncertainty as to whether the contact is faulted, but judging from reports (Rose , 1944) the junction is clean-cut and is not marked by a zone of gouge or fault breccia, suggesting that if the contact is faulted, then the amount of movement has been very small. The other contact is at the north end of the 120 fm. level. Here the junction of the andesite with the first band of shale (and also the junctions of the other shale and andesite bands) is unfaulted. It is concluded that the junction outside the influence of the Greenside Fault is unfaulted, or else has suffered only minor movement. As noted in the preceding chapter, the junction is conformable.

A problem never resolved at Greenside is the apparent absence of the Skiddaw Slates in the hanging-wall of the Greenside Fault. Assuming, for the present, that the fault does not follow the original shale/volcanics contact, then the Skiddaw Slates must, with dip-slip movement, lie at some depth in the hanging-wall. However R.C.E. failed to locate the Skiddaw Slates in this wall, indicating that the downthrow of the fault, on this basis, is at least 80 feet. Similarly the failure of a diamond drill hole at 2050 N to intersect Skiddaw Slates indicates that the downthrow is at least 100 feet. These estimates

are difficult to reconcile with the downthrow calculated previously (p. 90). The possibility is therefore raised that the Greenside Fault follows the original shale/volcanics contact, which would, on this basis, be the easterly limb of the dome. The transverse section at 1800 N does in fact indicate that the contact dips eastwards, and also at a high angle - 65°, so that the high dip of the Greenside Fault would not be an argument against this theory. On this basis, tha apparent presence of Skiddaw Slates in the hanging-wall on the 217 fm. level indicates that the Greenside Fault has locally entered the Skiddaw Slates, rather than following the contact.

The lithological evidence also favours the theory that the Greenside Fault follows the original shale/volcanics contact. Skiddaw Slates bands in the andesites and bands of andesite in the Skiddaw Slates are found in close proximity to the Greenside Fault, and are not found in the Skiddaw Slates or Borrowdale Volcanic Series further away from the fault (Section 5). If it could be proved that the andesite bands in the Skiddaw Slates, and the bedding of the latter were parallel to the Greenside Fault, then it would be certain that the latter does follow the original shale/volcanics contact. An attempt was made to do this by measuring the inclination of the bedding and the andesite bands in the cores of R.C.E. 1, 2, 3, and 4, relative to the axis of the drill hole. If the strata dips uniformly, then the strike and dip can be found by stereographic projection. However, in this case the values are erratic, and no conclusions as to the dip and strike could be made.

Although this last line of evidence is inconclusive, it is felt that the weight of evidence favours the theory that the Greenside Fault

follows the original shale/volcanics junction, i.e. the easterly limb of the dome composed of Skiddaw Slates. Thus, although the latter rocks apparently have an unfavourable effect on mineralisation, the actual formation of the Greenside Faults is probably closely connected with the plane of weakness afforded by the shale/volcanics junction.

The relation of the shale/volcanics junction to the folding in the Glenridding area will now be discussed. On the basis of the conformable junction of the Skiddaw Slates and the Borrowdale Volcanic Series, it would be expected that the latter rocks would also show this structure. However dip measurements above the 175 fm. level do not corroborate this (Section 2), and the structure must therefore die out rapidly towards the surface. The relation of the dome of Skiddaw Slates in the lower levels to the Skiddaw Slates on the 120 fm. level is uncertain. If the contacts in both areas represent parts of a continuous contact which is uncomplicated by faulting (which seems to be the case), then the absence of Skiddaw Slates at the north end of the 175 fm. level indicates that, north of this point, the contact rises steeply to the 120 fm. level (Section 2). In contrast to the steep dips in the mine workings, the overall dip of the shale/volcanics contact between Greenside and the Vale of Threlkeld is gentle -9°.

The dome of Skiddaw Slates is not easy to correlate with the folding in the Glenridding area. The structure is on strike with the projected axis of the Glencoyne Anticline, but the N-S axis of the dome is difficult to explain. It is tempting to regard the latter as a pre-Bala structure, and the E-W axis as a Caledonian structure, but there is no definite evidence to support this theory. Another

possibility is that the original Skiddaw Slates surface (probably the sea floor), on which the volcanic rocks were formed, was uneven. Although the conduits of the lava in the Skiddaw Slates have not been definitely recognised in the Lake District, the upward push of lava rising in a conduit would cause the surface to be disrupted. Another factor could be the uneven loading of the sea floor, supposing that the lavas were formed in lenses rather than continuous bands.

3. Influence of the Quartz-porphyry Dyke

The petrography of this pale-coloured quartz-porphyry has been described previously (p. 72). The dyke can be conveniently divided into two sections - an E-W trending section, and a N-S trending section. Although nowhere are these seen to be continuous, because of the absence of exposures or workings in the critical areas, the sections are believed to be one and the same dyke. The E-W trending section is followed by the North Fault, while the N-S trending section is followed by the Main Fault, and branches of the latter. Although the E-W trending portion of the dyke and the North Fault are intimately related, this subject is more conveniently considered in the following section on "The Influence of Pre-mineralisation Cross Faults".

The dyke has been traced 1700 feet along the strike of the Greenside Fault, and 2400 feet vertically. The maximum width is 120 feet; in depth the width diminishes, as does the strike length. The E-W section of the dyke dips to the north, while the N-S section dips to the east.

Although the Main Fault does not faithfully follow the foot-wall contact of the N-S section of the dyke, the strike and dip of the fault

are certainly influenced by the latter. The section of the Main Fault which is on the foot-wall side of the dyke is invariably mineralised, and has been stoped. The dyke in fact controls the North ore shoot.

Besides the physical effects of the dyke on the localisation of the North ore shoot, there appears to be a secondary lithological effect. The Main Vein of the North ore shoot is generally fairly narrow (less than 10 feet) in comparison with the vein of the South, Central and 2300 N ore shoots. The galena in the wider veins of the latter ore shoots is diluted with a greater quantity of quartz than the galena in the vein of the North ore shoot. The quantity of sphalerite in the wall rocks is also greater in the North ore shoot, especially where the walls are composed of quartz-porphyry.

The N-S section of the dyke controls three branch faults - the East Branch, the Hanging-wall Branch and the Foot-wall Branch. In addition the contacts of the dyke, which are not followed by these branches, are often faulted to a small extent. The East Branch is developed between the 90 fm. level and the 175 fm. level (Sections 1 and 3, and Plan 5). The branch is controlled by the foot-wall contact of the dyke - the Main Fault where the branch is developed, then lying in the volcanics on the foot-wall side of the dyke. Above the 90 fm. level, the East Branch dies out. The greatest distance between the Main Vein and the East Branch is on the 90 fm. level; below this level the veins converge, and below the 150 fm. level, where the veins were mined in a single stope, the veins intersect. On each level, the East Branch is mineralised near the intersection with the Main Fault, but further away the mineralisation is patchy.

Although the East Branch is controlled by the dyke, it is to some extent independent of the latter, and does not faithfully follow the foot-wall contact, e.g. on the 120 fm. level the branch cuts into the quartz-porphyry. However the intersection of the branch with the Main Fault on each level, is marked by the incoming of quartz-porphyry on the hanging-wall side of the latter, thus establishing a relation between the two.

The Hanging-wall Branch follows the hanging-wall contact of the dyke more closely than the East Branch follows the foot-wall contact. On the Lucy Tongue and the 40 fm. level this fault is clearly a Branch of the Main Fault, but below this level the Hanging-wall "Branch" does not apparently intersect the Main Fault. The fault shows patchy mineralisation and the vein, where developed, has not been stoped. However, on the 40 fm. level, the quartz-porphyry near the contact contains much disseminated galena and sphalerite, so that this area has been stoped.

Comparing the Main Fault, East Branch and the Hanging-wall Branch, the width of the vein, and the width of the gouge-breccia zones along barren sections ,decreases from the first to the last mentioned fault. This probably reflects the amount of displacement along each. Although the displacement of the Main Fault has been calculated, that of the branch faults was immpossible to determine.

On the 40 fm. level 'fliers' have been stoped. These are narrow discontinuous veins actually in the quartz-porphyry dyke, and have a westerly dip (Plan 5). It is probable that the veins represent steeply dipping tension gashes, which are common features of normal

faults (McKinstry, 1955).

The Main Fault at the north end of the mine, above the 40 fm. level, cuts completely through the quartz-porphyry dyke and emerges on the hanging-wall side of the latter. The point where the Main Fault cuts into the quartz-porphyry is marked A, B, C, and D on each level on Plan 5, and the point where the fault emerges on each level is marked A',B',C', and D'. Between these points on each level quartz-porphyry forms both walls of the fault (Section 3). On all levels, except the Low Horse, the cutting through is caused by a change in course of the dyke, rather than a change in course of the Main Fault.

North of the intersection of the Main Fault and the dyke, i.e. at positions A ,B etc., a fault continues northwards along or near the foot-wall contact of the quartz-porphyry dyke. This fault has been termed the Foot-wall Branch. On the High Horse and Low Horse levels the Foot-wall Branch is on strike with, and appears to be a continuation of the Main Fault. On account of this& the erroneous belief that the Main Fault was invariably on the foot-wall side of the quartz-porphyry dyke, Schnellman (1940) believes that the Foot-wall Branch is the Main Fault. On the Low Horse level the Foot-wall Branch has been stoped as a continuation of the Main Fault; however at 1250N,the fault dies out and is overlapped by a fault along the contact of quartz-porphyry (Plan 6).

Below the Low Horse level the Foot-wall Branch closely follows the foot-wall contact of the dyke, but is poorly defined.

The section of the mine immediately above the Alma level has puzzled several geologists.Here the foot-wall contact locally dips to the west, and the Main Fault, which is on the contact, thus has the same dip. Above this point the so-called ' flier ' which switches

from the foot-wall to the hanging-wall contact, is in fact the Main Fault.

The Hanging-wall Branch immediately below the intersection of the Main Fault and the hanging-wall contact has been locally productive.

Below the 90 fm. level the dyke is not cut through by the Main Fault. However on the 150 fm. level the dyke appears to swing into the foot-wall side of the fault and then back into the hanging-wall side. The structure of the quartz-porphyry towards the north on other levels is also rather indefinite, but apart from the unexplained patch of quartz-porphyry at 1600 N on the foot-wall side of the Main Fault on the 90 fm. level, there is no evidence to show that the Main Fault has cut through the dyke.

The cutting through of the dyke has an important effect on ore-shoot localisation. The line joining all points where the Main Fault cuts into the quartz-porphyry, in fact the intersection of the Foot-wall Branch with the Main Fault, approximately marks the limit of stoping (Sections 1 & 3).

However, while the relation with the cutting through of the dykes and the limit of stoping is clear, the geological reasons why this should be so are obscure. The sections of the Main Fault, where both walls are composed of quartz-porphyry (section 3), are barren, but in other areas of the mine the East Branch is productive under similar conditions.

Another factor is that the Main Fault north of the intersection with the dyke tends to have a rather variable dip and strike, while along the productive sections of the fault such variations are not

so common. This topic is considered further in a later section.

4. Influence of Pre-mineralisation Cross-faults

There are three important pre-mineralisation cross-faults in the Greenside workings - the Clay Fault, the North Fault, and the Wynn Fault (Section 1 and Plan 2). All three faults were probably formed during the Caledonian orogeny, but have suffered further movements during the Hercynian and post-Triassic earth movements. A description of the faults appears in Chapter 3 (p. 84).

The Clay Fault has an important effect on the Greenside Fault. The latter, on approaching the Clay Fault, first of all becomes barren, then becomes weaker, and finally swings westwards and splits to form a horse-tail structure, before dying out (Plan 7). The horsetail structure is some distance north of the Clay Fault, but the distance decreases towards the surface. The line which joins the position of dying-out on each level, approximately parallels the Clay Fault, as also does the southern limit of the ore shoot (Section 1).

The horsetail structure is best seen on the 175 fm. level and the the 90 fm. level. Elsewhere the critical areas are inaccessible, but the westerly swing of the fault is indicated by the course of the of the levels, e.g.the 40 fm. level. On the 175 fm. and 90 fm. levels, minor faults continue south of this horsetail structure; on the latter level, the minor fault, after continuing a short distance, again swings abruptly westwards. On the 175 fm. level, the most important vein south of the horsetail structure, is the Dawes Vein. The vein (which has been stoped) extends to the Clay Fault, the foot-wall of which marks the southern

limit of the stope (Section 1). Approximately 3-5 feet from the Clay Fault, the vein swings abruptly westwards into the foot-wall contact of the latter, where it dies out.

The Dawes Vein, and the minor fault south of the horsetail structure on the 90 fm. level , both lie to the east of the Main Fault, i.e. on the side opposite to the swing of the horsetail structure,. This relation is in accordance with the conclusions of Lovering and Goddard (1950), who studied similar structures in the ore deposits of the Front Range area, Colorado.

The geological reasons for the dying out of the Greenside Fault north of the Clay Fault will now be considered. The stress which formed the Greenside Fault was more easily relieved, in the vicinity of the Clay Fault, by movement along this pre-existing zone of weakness, than by the formation of a new fracture to form a southerly continuation of the Greenside Fault. It is perhaps significant that the downthrow of the Greenside Fault is to the east, and therefore to the south along the E-W fractures of the horsetail structure, while the Clay Fault also downthrows to the south.

The relation of the faults south of the Clay Fault (the 348 W and S-W faults) to the Greenside Fault is uncertain, but as noted previously, they are probably later in formation than the latter.

The North Fault has three main effects on the Greenside Fault. These are :-

(1) A change in dip and strike of the Main Fault.
(2) Formation of overlapping faults.
(3) Splitting of the Main Fault.

It is difficult to separate the effects which are due to the E-W trending section of the quartz-porphyry dyke, from those which are due to the faults along the dyke; in this account no such differentiation has been attempted.

On approaching the North Fault from the south, the Main Fault tends to swing from a northerly trend towards the north-east (Plans 5 & 6); the dip of the fault also increases.

Overlapping faults are seen on the 120 fm. and 135 fm. levels,(Plan 5 , and are probably present on the 105 fm.,Low Horse and High Horse levels, although these beds are inaccessible (Plan 6). This overlapping structure has been confused by previous geologists with post-mineralisation displacement of the Greenside Fault by the North Fault. In the workings uncomplicated by overlapping fractures, e.g. on the 175 fm. level, or where the overlapping faults lie to the south of the North Fault, e.g. on the 120 fm. level, this post-mineralisation displacement is a few feet to the west on the north side - probably indicating normal movement.

The dying out of a fault, and its continuation as an overlapping fault, is a common feature of vein deposits. Lovering and Goddard (1950) conclude that "in those fissures along which the right-hand wall moved forward, the overlapping fissure will be found to the left and vice versa". At Greenside the overlapping fault to the north lies on the east side. The relation of the strike slip of the Greenside Fault (dextral) and the overlapping direction is in accord with the above conclusion.

The splitting of the fault is exhibited on the 150 fm. level and to a lesser extent on the 120 fm. level.

Below the latter level the North Fault approximately marks the

southern limit of the North ore shoot (Section 1, Plan 5). Above the 90 fm. level the fault becomes barren not far north of the North Fault. This is connected with the cutting through of the quartz-porphyry dyke, as explained on p. 117. The old Companies therefore believed that the North Fault had an unfavourable effect on mineralisation , and thus below the 90 fm. level the fault was not followed far north of the North Fault. Then Basinghall Mining Syndicate explored this area and developed the lower part of the North ore shoot.

The limitation of ore shoots by pre-mineralisation cross faults is a common feature of vein deposits. However it has seldom been satisfactorily explained why on one side of the cross fault, an ore shoot is developed, while the other side is barren. At Greenside there are two contributary factors. Firstly, the dip of the Greenside Fault increases north of the North Fault, and as will be described in a later section, the dip of the fault has an important bearing on the localisation of ore shoots. Secondly , the northerly downthrow of the North Fault suggests that the downthrow of the Greenside Fault may have a slightly greater downthrow north of the North Fault, than to the south. The amount of downthrow controls the development of openings, and to a certain extent, the larger the downthrow the greater the extent of the openings.

The Wynn Fault will now be considered. This fault could only be examined by the author on the Lucy Tongue level since the critical sections of the levels below were inaccessible (Plan 4 and Section 1. No trace of the fault was found on the High Horse level and on the surface, indicating that the fault has died out in this direction. This displacement of the Greenside Fault by the Wynn Fault clearly indicates

intersection, the development of openings along the Main Fault is not controlled merely by the changes in dip and strike of the Main Fault, but also by changes in dip and strike of the branch fault. Therefore,favourable variations in the course of the latter control openings in both the branch and Main fault,and vice versa. This mutual control will become less important further away from the intersection, and thus the branch fault often becomes barren in this direction.

6. Influence of Variation in Dip and Strike of the Greenside Fault.

A. Introduction

It is a well known principle that the steeper sections of normal faults and the flatter sections of reverse faults are favourable areas of ore deposition. Although this fundamental principle was recognised a century ago (e.g. von Cotta,1859) and has been expanded and utilised by several geologists, notably Emmons (1948), Knopf (1929), Spurr (1925), Hulin (1929) and Lovering and Goddard (1950), few workers have examined the principle thoroughly from a geometrical ppint of view.

One of the chief difficulties of the geometrical approach is to obtain a suitable graphical representation of the fault on which the most favourable areas of ore shoot localisation can easily be plotted. Newhouse,(1942) in the Introduction of "Ore Deposits as Related to Structural Features" used a normal mine plan on which the vein has been plotted on each level - a "contour map" of the vein. By a consideration of the formation of openings formed along hypothetical faults which have simple variations of strike and dip, and with various directions of displacement, the theoretical positions of ore shoots along actual faults can be gauged. However, the precise limits of the

ore shoots are difficultto determine by this method. Newhouse concludes that his qualitative treatment "could be made quantitative by graphical or mathematical means . In this Thesis a quantitative graphical method has been developed.

A qualitative graphical method has been developed by Connolly (1936). In this method the fault is contoured with reference to a datum plane which is chosen so as to have the average strike and dip of the fault plane. The method is undoubtedly useful, but the limits of the ore shoots are still not easily defined. Furthermore the choice of the datum plane adds a subjective element.

The basis of the method developed here lies in a graphical representation of a series of profiles of the fault plane, each profile being orientated with respect to the net slip direction of the fault.

The actual direction of movement along any fault plane is controlled by the tectonic forces operating, and the shape and disposition of the fault plane. Case A of Fig. 4.1 shows a sectional view of a uniformly dipping fault plane (dip is 70°). If this fault suffers normal movement then the direction of the dip slip is inclined 70° to the horizontal. In case B the fault is similar except that there is a short step which has a dip of 40°. If this fault suffers normal movement then the step will be a "bearing surface", and the surfaces which dip at 70° wil be pulled apart to form openings; the direction of dip slip in this case is inclined at 40°.

Consider now a fault which has a variable dip and strike. If the fault suffers normal movement then the bearing surfaces must be those surfaces which have the least dip (the dip being measured in a plane

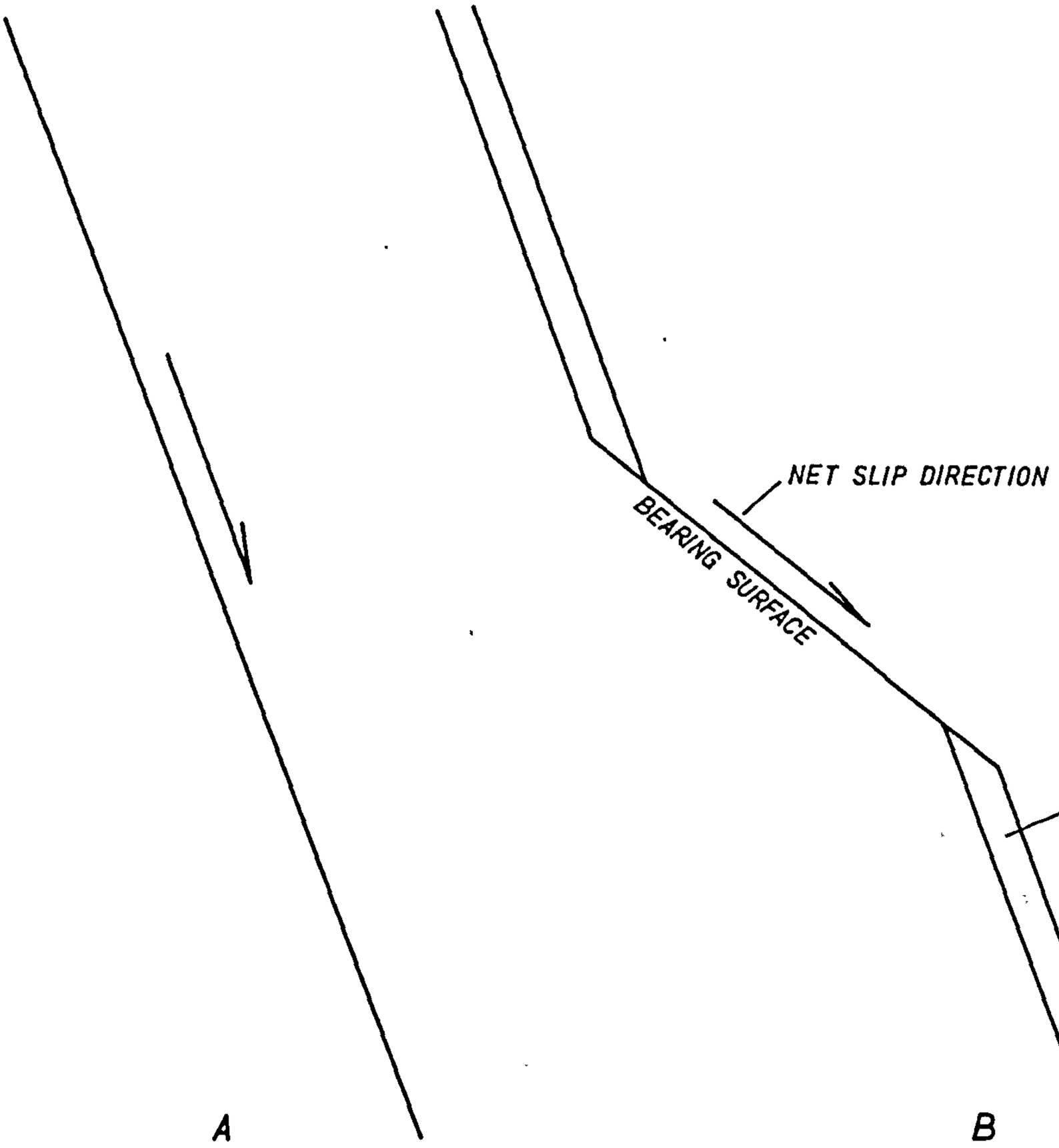


FIG. 4.1 SECTIONAL VIEW OF TWO NORMAL FAULTS

containing the dip slip direction, and not necessarily at right angles to the strike of the fault plane). Theoretically all the remaining surfaces of the fault plane (which have a dip greater than this minimum) will be pulled apart to form openings. If the fault is contoured with respect to the dip, then the theoretical positions of openings can be outlined.

The openings formed along a strike slip fault are in the same way controlled by those fault surfaces which make the greatest angle with the average strike slip direction.

It can be seen that the variation in the attitude of the fault in the plane containing the direction of the net slip determines the localisation of the openings, whatever the variations of dip and strike of the fault plane, and whatever the direction of the net slip. For example, if the movement is oblique then the dip measured in a plane containing the net slip is the critical factor.

So far the geometrical aspects of the formation of openings have been considered. Geological factors play an important part and modify the picture outlined by the geometrical approach. It was previously stated that under theoretical conditions, all the surfaces of a normal fault which have a dip exceeding the minimum dip, will be pulled apart to form openings. In practise the walls of the fault settle and collapse because of forces operating normal to the fault plane, and the openings become bridged, or partially or completely closed. The yielding of the walls of the fault occurs by plastic deformation or by fracturing, according to the competency of the rocks.

The extent of the openings (and also their width) depends basically on three factors :-

(1) Variation of dip or attitude of the fault plane (measured in a plane containing the net slip). A large variation of the dip would increase the likelihood of the formation of open spaces.

(2) Displacement along the fault plane. Up to a certain extent an increased displacement will cause an increased development of openings. However beyond a certain value (depending on the variations in dip and strike of the fault plane) the 'ill-fitting' portions of the fault will be brought together. Increased displacement will also cause a greater amount of gouge and breccia to be produced which will tend to be transported to the openings, thus clogging them. For these reasons, hydrothermal fissure infillings are generally found along faults which have small displacements.

(3) The destruction of open spaces by the collapse of the walls of the fault. Openings in competent rocks are more likely to remain open.

The method of producing a contoured dip diagram of a normal or reverse fault is as follows:-

(1) Plot the best defined wall of the fault or vein (generally the foot-wall in normal faults) on each level, and represent on a plan.

(2) Project the net slip direction on to the plan (the direction in true normal or reverse movement will be at right angle to the average strike of the fault).

(3) Measure the horizontal distance between the foot-wall of the fault on successive levels, in a direction parallel to the projected

net slip, (Fig. 4.2). Take the measurements at 100 feet or 50 feet intervals along the strike. (With rapid changes of dip a small strike interval should be used).

(4) Using the vertical distance between the successive levels, calculate the angle of dip of the fault between the levels. (If the angle of dip is θ , d is the horizontal distance, and v the vertical distance between two levels, then $\tan \theta = v/d$).

(5) Plot the angle of dip on a longitudinal vertical section. Locate each dip value mid-way between the two levels measured.

(6) Contour the dip values.

Since the purpose of this method is to represent the fault in a plane containing the net slip, the plotting of a contour diagram of a strike slip fault would serve no useful purpose, since a simple plan of the vein represents the fault in the correct plane.

An oblique slip fault can be contoured by calculating the dip from a plan in the same way as for a normal fault, except that the dip is measured in a different direction, which is of course parallel to the projected net slip direction.

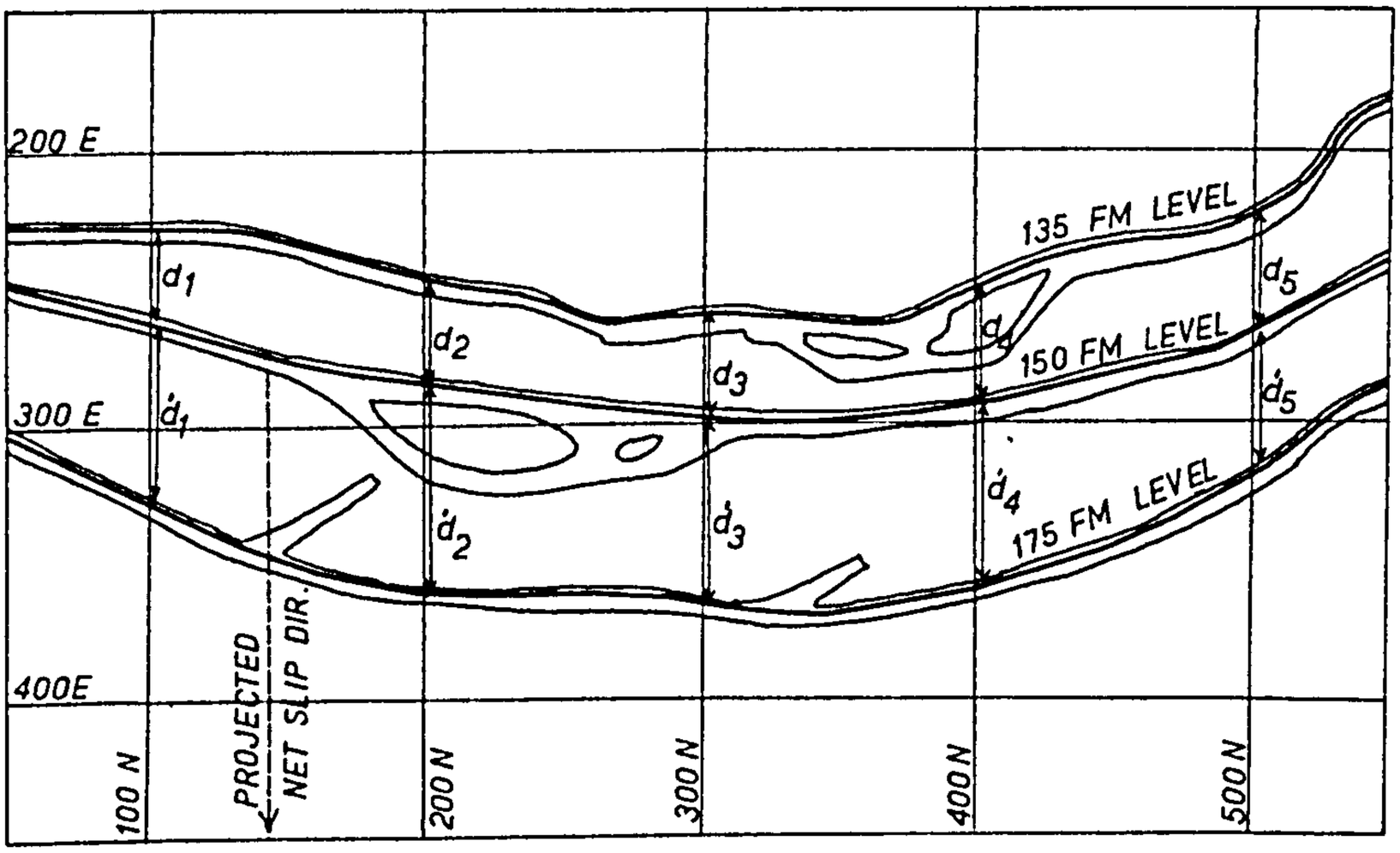
The interpretation of a contoured dip diagram of a normal fault and the theoretical position of ore shoots is illustrated by reference to the Greenside Fault.

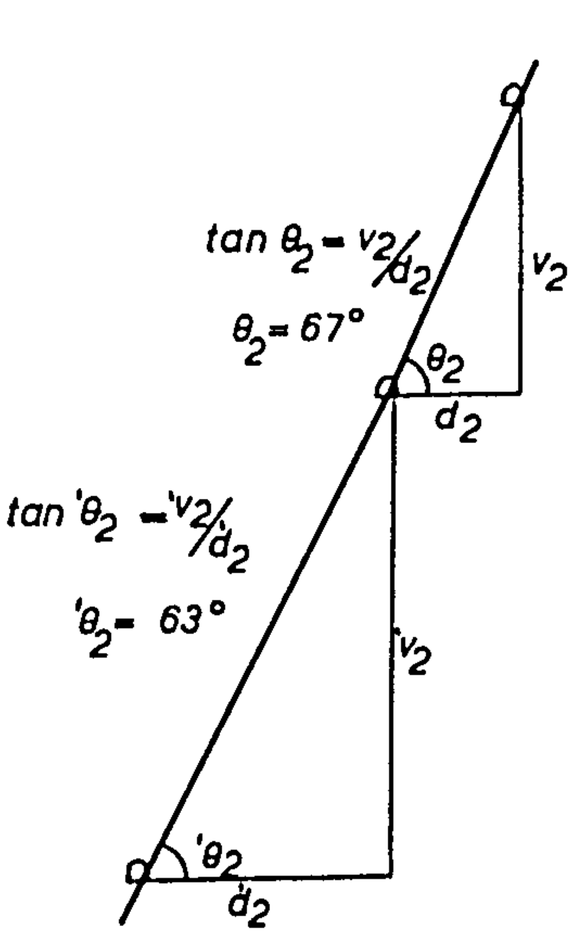
B. Analysis of the Greenside Fault

The downthrow of the Greenside Fault is 50 feet and the strike slip (dextral) is 7 feet (see p. 90). For convenience of the dip calculations, the strike slip, which is small compared with the downthrow, has been neglected.

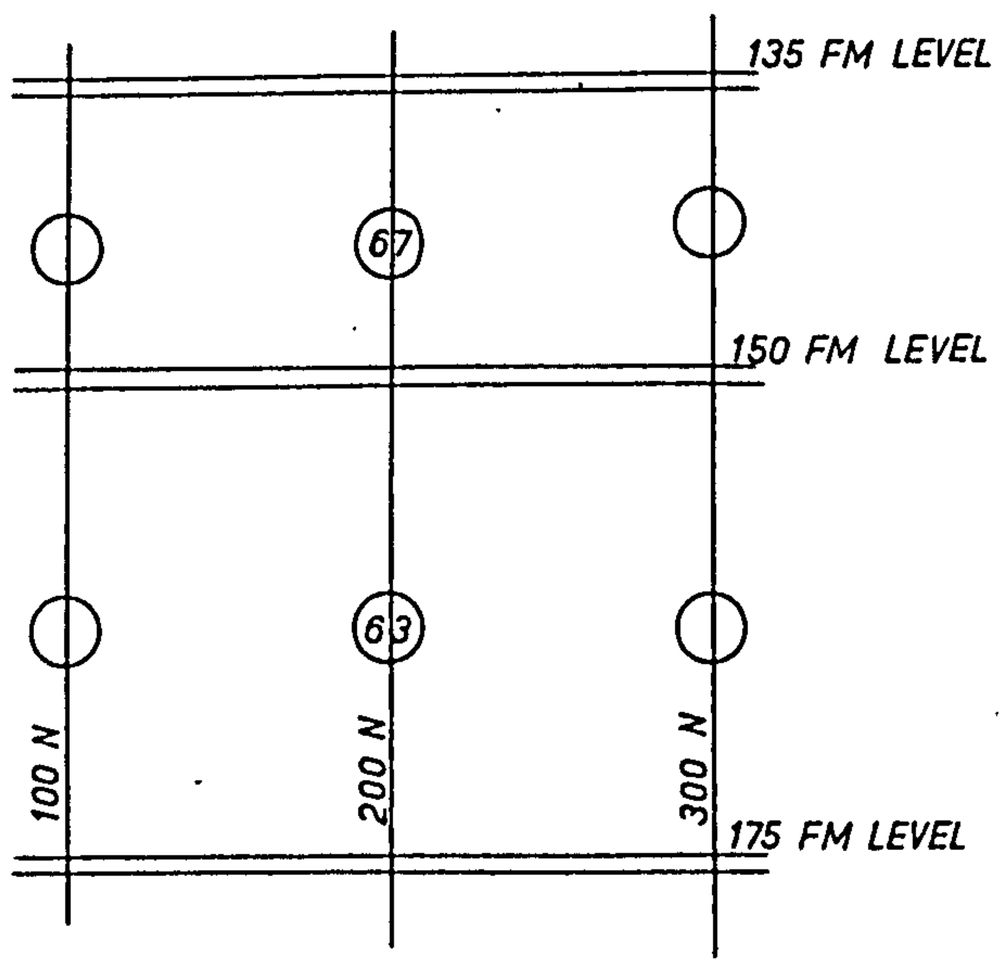
FIG. 4.2 DIAGRAMS TO SHOW THE CALCULATION OF DIP VALUES

A PLAN SHOWING FOOT WALL OF FAULT ON SUCCESSIVE LEVELS





B TRANSVERSE VERTICAL SECTION AT 200 N



C LONGITUDINAL VERTICAL SECTION

SCALE THROUGHOUT 1" = 100 FEET

Plan 3 shows the foot-wall of the fault on each level, and the areas that have been stoped. Before outlining the theoretical positions of ore shoots with respect to variations in the dip and strike of the Greenside Fault, the causes of these variations will be considered.

The variations in dip and strike are believed to be due mainly to the following factors :-

(1) Variations in dip and strike of the contacts of the N-S trending portion of the quartz-porphyry dyke.

(2) Variations in dip and strike of the Skiddaw Slates/Borrowdale Volcanic Series contact.

(3) Pre-mineralisation cross-faults.

(4) Lithology of the wall rocks.

(5) Cleavage and joints.

The effects of (1), (2), and (3) have been described previously and therefore it only remains to consider (4) and (5). Apart from intrusive rocks (see Section 3) and the Skiddaw Slates, the walls of the Greenside Fault are composed of 'acid' and 'basic' andesites, with tuff and breccia intercalations; these rocks comprise the lower half of the Ullswater Group (Fig. 3.2 and Section 2).

Section 3 shows that large areas of the walls of the Greenside Fault are composed of quartz-porphyry. However the fault follows mainly the contacts of the dyke and therefore the competency of the quartz-porphyry compared to that of the volcanics is relatively unimportant. Where the Main Fault cuts through the N-S trending portion of the dyke, there is no apparent change in dip and strike of the fault. However, the E-W trending portion of the dyke (which controls the North Fault) causes the Main Fault to form an overlapping structure, while the dip increases

and the strike swings to a more north-easterly direction. Other dykes in the walls of the fault do not have any apparent effect on the course of the Greenside Fault.

Although the structure of the Skiddaw Slates/Borrowdale Volcanic Series has been emphasised in connection with the variations in dip and strike of the Greenside Fault, this zone of weakness owes its origin to the contrasting competency of the two series of rocks. Furthermore, although the dip and strike of the contact, which is followed by the Greenside Fault, may locally be unfavourable to the formation of open spaces, the incompetent nature of the shale in one wall would probably cause the opening to collapse.

Section 2 shows the lithology of the walls of the Greenside Fault which are composed of the Borrowdale Volcanic Series. It can be seen that above the 90 fm. level the walls are composed predominantly of 'acid' andesites, while below this level the walls are composed mainly of 'basic' andesites. This junction of the two groups of lavas could not be plotted accurately, but it apparently dips at a small angle. In contrast, the recorded dips are rather higher; the reason for this is uncertain, but variation in the initial dips is perhaps an important factor; if it had been possible to obtain more dip and strike readings this divergence would probably become less apparent.

It can be seen that the tuffs and breccias form lenses and thin intercalations, but never continuous bands, The tuffs do not occur at any particular horizon, but the breccias tend to be developed in the lower part of the succession. The distribution of the ore shoots cannot be related to the lithology of the volanics, and furthermore

the plunge of the former is independent of the dip of the volcanics.

The strike and dip of the cleavage and joint planes probably have some influence on the course of the Greenside Fault. The effect of the cleavage is perhaps illustrated by the similarity in the plunge of the South and 2300 N ore shoots, and the dip of the cleavage planes. On the other hand, cleavage in the andesites is feebly developed, suggesting that this similarity is merely superficial; furthermore the plunge of the South ore shoot is more directly related to the dip of the Clay Fault. In the Glenridding area there are two important joint maxima which have trends similar to those of some sections of the Greenside Fault (Fig. 3. 29). It is probable that the swinging of the fault from a northerly trend to a north-easterly or north-westerly trend is partially controlled by these joint directions.

In conclusion, the major factors controlling the variations in dip and strike of the Greenside Fault are the presence of pre-mineralisation cross-faults and the planes of weakness afforded by the contacts of the quartz-porphyry dyke. The lithology if the wall rocks, except for the contrasted competency of the volcanics and the Skiddaw Slates, apparently plays a minor role. The effect of cleavage and joint planes is probably more important. Another possible cause of fault deviation is a variation in the stress distribution during the formation of the fault (Newhouse, 1942). There is no clear evidence to suggest that the Greenside Fault was formed under such conditions.

The effect of variations in dip and strike of the Greenside Fault on ore shoot localisation will now be considered. Plan 3 shows clearly that the ore shoots are localised where the Greenside Fault has the

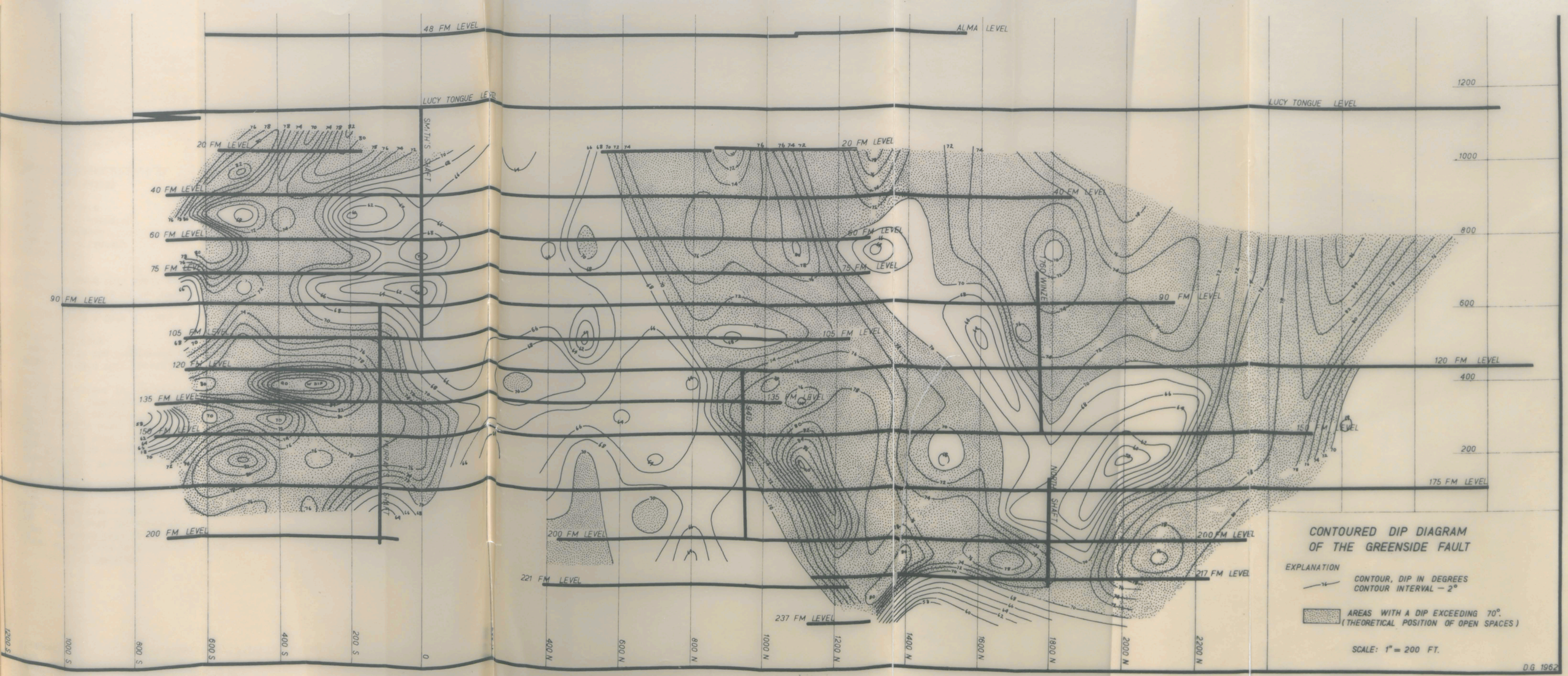
greatest dip. The South, North and 2300 N ore shoots are each marked by a convergence of the contours. The patchy Central ore shoot does not show this convergence to the same extent. The strike of the fault does not show any definite relation to the ore shoots.

A contoured dip diagram (Section 4) was produced as explained on page 126. The horizontal distance between the foot-wall of the fault on successive levels were measured from Plan 3 ; the measurements were taken at 100 feet intervals, along the strike, and in a direction parallel to the E-W co-ordinates. The vertical distances between successive levels were measured from Section 1.

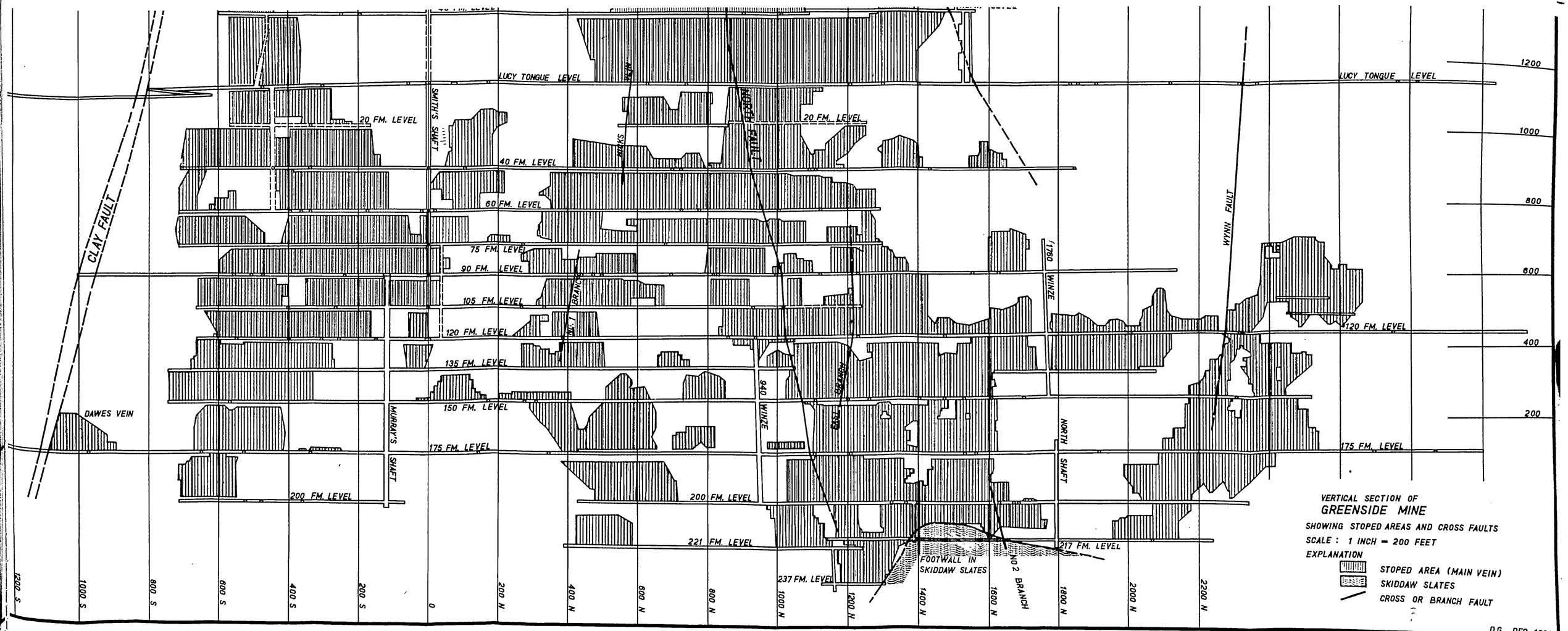
The dip of the fault above the Lucy Tongue level, between the 105 fm. and 120 fm. levels, and between the 75 fm. and 60 fm. levels north of Smith's shaft, were not measured. Almost all these old workings are inaccessible and have not been accurately surveyed.

The dip of that section of the Greenside Fault considered (measured in an E-W direction) varies from 58° east to vertical; in one place, at 300 S between the 135 fm. and 120 fm. levels, the dip is 83° west.

In the preceding section it was noted that with dip-slip movement the areas of the fault surfaces with the lowest dip should be bearing surfaces, while surfaces with greater dips should be pulled apart to form openings. However, some of these openings will be closed as a result of the walls collapsing. The openings most easily closed will be those which have a dip near to that of the minimum dip. The bearing surfaces will certainly have a range of dips, and it is probable that the range varies from one part of the fault to another, accordings to the contrast of the dip values. Areas of the fault surface which have dips significantly


48 FM LEVEL
LUCY TONGUE LEVEL
20 FM LEVEL
40 FM LEVEL
60 FM LEVEL
75 FM LEVEL
90 FM LEVEL
105 FM LEVEL
120 FM LEVEL
135 FM LEVEL
150 FM LEVEL
200 FM LEVEL
SMITH'S SHAFT
ALMA LEVEL
221 FM LEVEL
237 FM LEVEL
GOD WINZE
NORTH SHAFT
175 FM LEVEL
217 FM LEVEL
1200
1000
800
600
400
200
1200 S
1000 S
800 S
600 S
400 S
200 S
0
400 N
600 N
800 N
1000 N
1200 N
1400 N
1600 N
1800 N
2000 N
2200 N
CONTOURED DIP DIAGRAM
OF THE GREENSIDE FAULT
EXPLANATION
CONTOUR, DIP IN DEGREES
CONTOUR INTERVAL — 2°
AREAS WITH A DIP EXCEEDING 70°.
(THEORETICAL POSITION OF OPEN SPACES)
SCALE: 1" = 200 FT.
D.G. 1962

SECTION 4


LUCY TONGUE LEVEL
20 FM. LEVEL
40 FM. LEVEL
60 FM. LEVEL
75 FM. LEVEL
90 FM. LEVEL
105 FM. LEVEL
120 FM. LEVEL
135 FM. LEVEL
150 FM. LEVEL
175 FM. LEVEL
200 FM. LEVEL
221 FM. LEVEL
237 FM. LEVEL
217 FM. LEVEL
CLAY FAULT
DAWES VEIN
SMITH'S SHAFT
MURRAY'S SHAFT
SIXTEEN
BRANCH
940 WINZE
1760 WINZE
NORTH SHAFT
WYNN FAULT
FOOTWALL IN SKIDDAW SLATES
NO 2 BRANCH
1200
1000
800
600
400
200
1200 S
1000 S
800 S
600 S
400 S
200 S
0
200 N
400 N
600 N
800 N
1000 N
1200 N
1400 N
1600 N
1800 N
2000 N
2200 N
VERTICAL SECTION OF
GREENSIDE MINE
SHOWING STOPED AREAS AND CROSS FAULTS
SCALE : 1 INCH = 200 FEET
EXPLANATION
STOPED AREA (MAIN VEIN)
SKIDDAW SLATES
CROSS OR BRANCH FAULT
D.G. DEC. 1961.

SECTION 1

reflected in the dip values. These are remarkably uniform compared with the remainder of the fault; such uniformity is not conducive to the formation of openings. The areas of theoretical openings are smaller than the actual stoped areas, which are better defined by the 68° or 66° contour .

The North ore shoot is exellently defined by the 70° contour. Both the north and south limits, especially the latter, are marked by a steep dip gradient. On the stope section this limit is only clear below the 90 fm. level; above this level the North ore shoot coalesces with the Central ore shoot. However, on the contoured dip diagram the steep dip gradient associated with the stope limit below the 90 fm. level can be traced up to the Lucy Tongue level. The base of the North ore shoot (marked by the intersection of Skiddaw Slates in the foot-wall of the fault) shows ar excellent correlation with the 70° contour.

The 2300 N ore shoot is again well defined by the 70° contour, and both the north and south limits are marked by a steep dip gradient.

The contoured dip diagram also shows a position of theoretical openings between 1800 N and 2300 N, above the 90 fm. level, where in fact the fault is barren. The reasons for this are uncertain, but as noted previously, the Main Fault north of the position where it cuts through the quartz-porphyry dyke is unfavourable to mineralisation.

The dip of the fault between the 120 fm. and Lucy Tongue levels at 2600 N is 86°. It would therefore be expected that the 2300 N ore shoot would continue up to the Lucy Tongue level. The dying out of the ore shoot well below this level is probably mainly due to the splitting up of the fault into diamond drill holes from the Lucy Tongue

level revealed a series of fractures rather than a single fault. The unfavourable nature of the Main Fault after it has cut through the dyke is probably a contributory factor.

7. Path of the Mineralising Solutions

As at many mines, the ore shoots at Greenside pinch out in depth and the specific path of the mineralising solutions is obscure. It is possible that the section of the Greenside Fault, at or near the intersection with the North Fault, was the most important channelway, and perhaps the other ore shoots to the south and to the north were formed by the lateral and upward movement of the ore solutions from this central source. The Greenside Fault dies out before reaching the Clay Fault, however it is probable that the latter acted as an impermeable barrier, which inhibited, to a large extent , the mineralisation of possible potential openings to the south. Although the Greenside Fault 'follows the shale/volcanics contact in the lower levels of the mine, at greater depth the contact probably flattens out, the fault then entering the Skiddaw Slates; therefore the horizontal movement of mineralising solutions along the shale/volcanics junction is not envisaged.

8. Future Prospects of Greenside Mine

For completeness, and for the purposes of Greenside Mines Ltd., a brief account of the prospects of the Greenside Mine is appended here. From an economic point of view the likelihood of the mine ever being reopened is remote. However the geological reasons for the

closure of the mine, and the possibility of some ore remaining are considered.

The possible continuation of the Greenside Fault to the south, to the north, and in depth will first be discussed. The Greenside Fault dies out before reaching the Clay Fault and does not continue south of the latter. The faults located south of the Clay Fault - the 348 W and S-W faults - although probably formed during the same period as the Greenside Fault, show only patchy, uneconomic mineralisation.

To the north, the strike and dip of the Greenside Fault from level to level is very variable, a factor not conducive to the localisation of ore shoots. On surface, the fault cannot be traced north of the head of Glencoynedale, and although a resistivity survey indicated the possible continuation of the fault on Hart Side (Bruckshaw, 1943), trenching operations drew negative results. It is therefore probable that the fault dies out to the north, and the variable dip and strike is perhaps suggestive of this. The presence of Skiddaw Slates at the end of the 120 fm. level, prohibited further investigation on and below this level.

In depth, the North and probably the 2300 N ore shoots bottom at the intersection of Skiddaw Slates. The Central and South ore shoots probably extend some distance in depth before reaching the Skiddaw Slates. However, the main block of the Central ore shoot has a diminished strike length in depth, and the low grade on the 221 fm. amd 200 fm. levels did not warrant the southerly continuation of the 237 fm. level. The strike-length of the South ore shoot also rapidly diminishes in depth. However, it is conceivable that the strike-length increases with greater

depth. Another faint possibility is that the Greenside Fault, where it follows the Skiddaw Slates/Borrowdale Volcanic Series junction, is mineralised at greater depth, although it is barren on the 208 fm., 217 fm. and 237 fm. levels.

A glance at Plan 1 is sufficient to see that very little cross-cutting has been carried out at Greenside. The possibility therefore exists that parallel or branch veins have been missed. A long diamond drill hole into the hanging-wall of the Greenside Fault at 481 N did not intersect a fault or vein, but a cross-cut into the hanging-wall of the fault from central positions of the South, North and 2300 N ore shoots might have proved more useful. A cross-cut from the latter ore shoot might possibly have intersected the northerly continuation of the East and Hanging-wall branches.

On the 90 fm. and 120 fm. levels an exploration of the intersection of the Hanging-wall Branch and the North Fault might have proved interesting from an economic as well as geological point of view.

All these suggestions are in the nature of 'wild cat' prospects, and the exploration programmes of Greenside Mines Ltd. have tested almost every practical possibility.

CHAPTER 5

HYDROTHERMAL ALTERATION OF THE WALL ROCKS

1. Introduction

The hydrothermal alteration of the wall rocks of the Greenside Vein is extensive and has produced the following minerals :- quartz (including chalcedony), sericite, carbonates, chlorite, Fe oxides and sulphides. All these minerals except chalcedony, galena and sphalerite, are also the normal products of alteration which is widespread in the volanic and intrusive rocks of the Glennridding area. The alteration of the wall rocks of the Greenside Vein (here termed 'hydrothermal alteration') has thus been superimposed on this earlier regional alteration (here termed 'pre-ore alteration'). Although the latter alteration of the volcanic and intrusive rocks has been described in Chapter 3, the subject is considered here as a whole so that the later changes associated with mineralisation can be readily understood.

2. Pre-ore Alteration.

The widespread pre-ore alteration of the Borrowdale Volcanic Series is the total effect of :-

(1) autometamorphism (in lavas and ignimbrites) and solfataric activity (Ordovician)

(2) alteration caused by the burial of the rocks at the base of the geosyncline (Caledonian)

(3) alteration caused by igneous intrusions (probably late Caledonian)

Alteration of the intrusive rocks is probably caused mainly by autometamorphism. Except for local contact metamorphic minerals, the alteration products in the volcanic rocks, which were formed by these three phases of regional alteration, are very similar. In the following

account no attempt is made to differentiate between the effects of these phases.

In general the volcaniclastic rocks, because of their greater porosity, are more altered than the more massive lavas(and also the intrusive rocks). The components of the volcanic and intrusive rocks are considered in turn and the alteration of each is described below.

A. Groundmass and Matrix.

The original groundmass of the lavas varies in texture from glassy (in rhyolites) to intersertal (in basalts). The glassy type of groundmass is usually devitrified, and is now composed of cryptocrystalline or microcrystalline material which may show mosaic extinction. Where determinable, the microcrystalline minerals include quartz, sericite, calcite, chlorite and iron oxides (mainly 'leucoxene'). The glassy base of the hyalopilitic type of groundmass is altered to similar minerals, while the interstitial material of the intersertal types contains a greater amount of chlorite and iron oxides. The alteration of plagioclase microlites is similar to that of the plagioclase phenocrysts, described below. The groundmass of the intrusive rocks and the matrix of tuffs and breccias are altered to the same minerals as those found in the lavas, although their proportions are variable. Scattered patches of quartz, calcite, and cubes of pyrite are found in both the volcanic and intrusive rocks.

B. Felspars.

Many of the plagioclase phenocrysts in the rhyolites and some of those in the andesites, are composed of cloudy, unzoned albite which is probably of secondary origin. Irregular patches of secondary albite are also found in the tuffs. The albite is slightly altered to sericite,

but the more calcic plagioclase may be extensively altered to both sericite and calcite. Generally incipient alteration produces sericite, while calcite is only found when alteration is more extensive. Calcite may be the sole alteration product of plagioclase, or may form an aggregate with sericite. A granular, colourless epidote (probably clinozoisite) is sometimes found in the cores of plagioclase phenocrysts, while quartz and chlorite are rare alteration products. Potash felspar may be partially altered to sericite and calcite.

C. Ferromagnesian Minerals.

Except in the basalts and some dolerites, both clinopyroxene and orthopyroxene are completely altered to chlorite, and smaller quantities of calcite, 'leucoxene', hematite, epidote, and occasionally quartz. The chlorite may be fibrous, flaky or occur as single plates, often with the (001) cleavage parallel to the c axis of the original pyroxene. The chlorite determined in the andesites has the following optical properties:-

(a) Colour: nearly colourless to fairly dark green (usually pale green)

(b) Pleochroism: greatest absorption parallel to slow ray.

(c) R.I. : Y = 1.632 to 1.640

(d) Birefringence: .003 to .007 (approx.), (usually ultra-blue colours)

(e) 2 V: approx. uniaxial.

(f) Sign : negative

(g) Orientation: slow ray parallel to (001) cleavage.

On the basis of the recent review of the chlorites by Hey (1954) the species is brunsvigite.

The 'leucoxene' is of two types : firstly a cloudy, opaque, whitish, powdery mineral (after ilmemite or titaniferous magnetite), and secondly,

a fine-grained, granular mineral, yellow-brown in colour, and having a high R.I. and birefringence (rutile or anatase ?). The latter type of 'leucoxene' often occurs between the cleavages of the chlorite. Epidote is mainly confined to basic rocks, while hematite is found in flow-breccias.

Biotite is invariably completely altered to chlorite, 'leucoxene' (usually after ilmemite), and occasionally epidote.

D. Accessory and Other Minerals.

Garnet may be partially altered to chlorite and iron oxides, and occasionally to quartz (see p. 53). Quartz, apatite, zircon, rutile, sphene and rutile are unaltered.

3. Hydrothermal Alteration of the Volcanics.

For uniformity with the preceding section, the hydrothermal alteration of the volcanic wall rocks is described in a similar fashion.

A. Groundmass and Matrix.

The groundmass of lavas, and the matrix of tuffs and breccias is altered to an aggregate of quartz and sericite, with minor amounts of carbonates (mainly calcite) and fine-grained iron oxides (mainly 'leucoxene'). The sericite flakes may be scattered throughout or may be grouped together to form lenticles or a lace pattern. Microlites are generally completely altered, and can rarely be distinguished from the groundmass. Patches of coarse mosaic quartz, and occasionally chalcedony, may be scattered throughout.

B. Felspars.

Plagioclase is further altered to sericite and especially calcite (Fig.5.3). Where alteration is intense, quartz may also be developed

and the phenocrysts cannot then be distinguished from the groundmass. Epidote and chlorite (rare pre-ore alteration products of plagioclase) are not found in the highly altered zones near the vein, where they are presumably unstable.

C. Ferromagnesian Minerals.

Chlorite, the main pre-ore alteration product of pyroxenes and biotite, is generally the first mineral in the volcanics to undergo change. Sericite, quartz and fine-grained iron oxides are the alteration products (Fig. 5.1). In slightly altered rocks the chlorite is sometimes almost colourless, suggesting a decrease in the iron content in the first stages of hydrothermal alteration before the complete breakdown to sericite and other minerals.

D. Accessory Minerals.

Garnet was not observed in the hydrothermally altered wall rocks of the Greenside Vein. Apatite, zircon, and rutile remain unaltered.

4. Hydrothermal Alteration of the Quartz-porphyry.

Although dykes of dolerite, granite-porphyry, porphyrite and dark-coloured quartz-porphyry are encountered in the mine workings, they generally occur in cross-cuts, or along barren sections of the Greenside Vein, so that they have suffered little hydrothermal alteration. Therefore only the alteration of the pale-coloured quartz-porphyry is considered here.

In this the groundmass is altered to a mosaic of quartz with scattered sericite flakes, and minor carbonates (Fig. 5.2); the grain size of the groundmass increases as the alteration becomes more advanced.

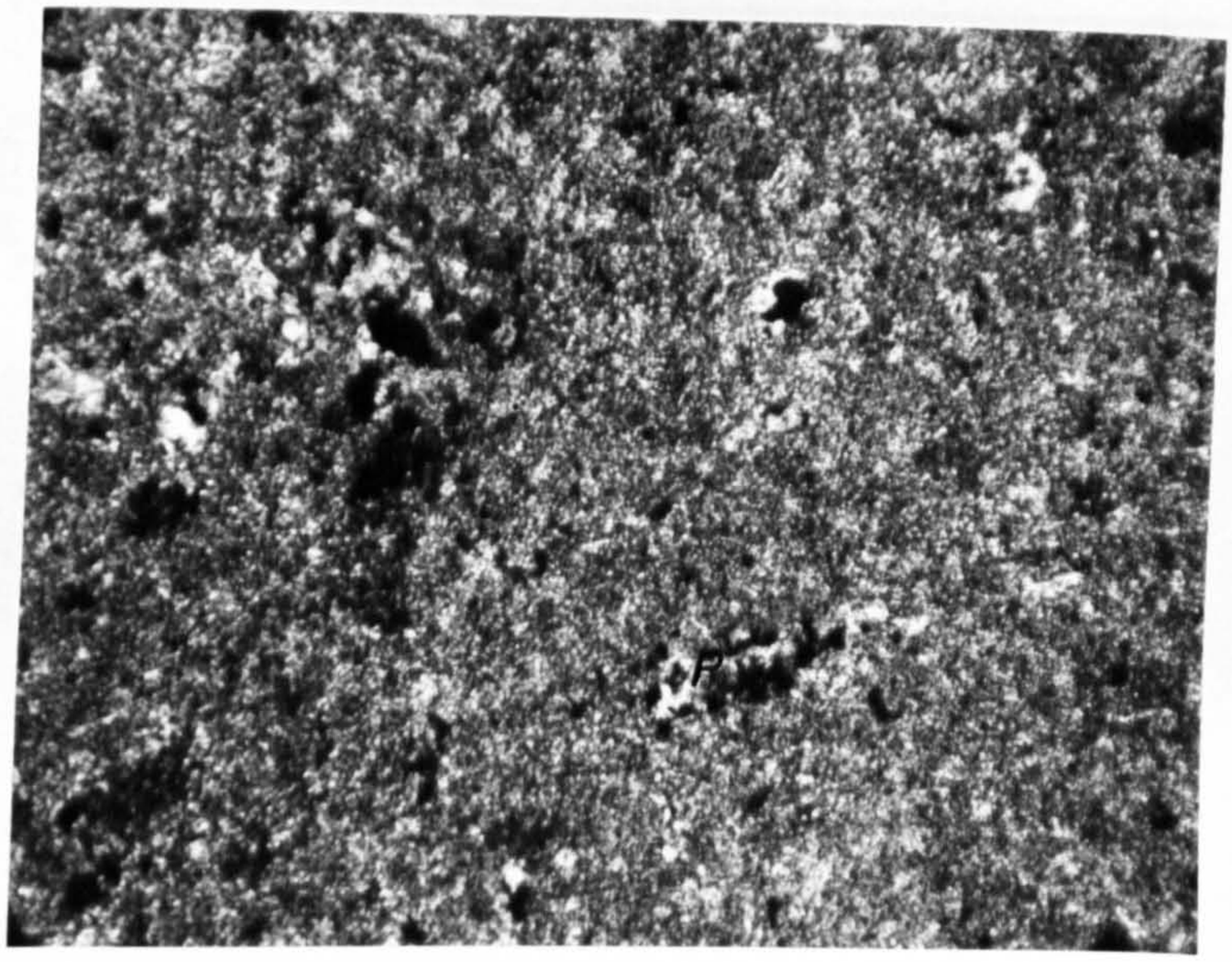


Fig. 5.1 Altered andesite: diffuse areas of 'leucoxene' and quartz represent an original pyroxene (P). Plagioclase is completely altered to diffuse areas of calcite which merge imperceptibly into a quartz-sericite groundmass. 1522 N, 120 fm. level. X 20. Crossed nicols

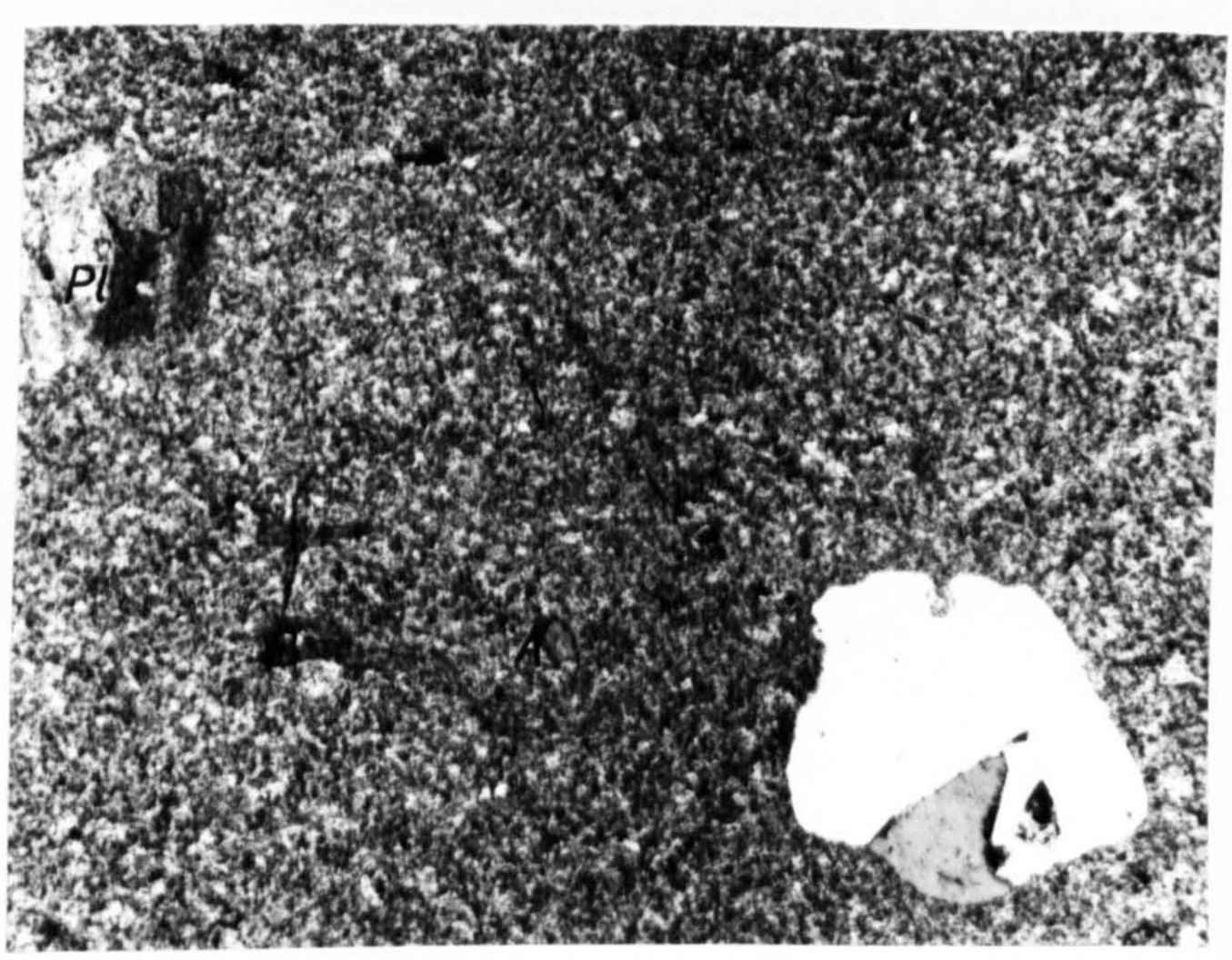


Fig. 5.2 Altered quartz-porphyry: diffuse calcitised, sericitised plagioclase (Pl), and sericitised biotite (B). Unaltered subhedral quartz, and apatite (A). Coarse-grained quartz-sericite-carbonate groundmass. 1522 N, 120 fm. level. X20. Crossed nicols.

Chlorite, the pre-ore alteration product of biotite, is the mineral which is most readily altered in the quartz-porphyry; sericite and iron oxides are the alteration products.

Plagioclase is further altered to sericite and calcite. Quartz remains unaltered (Fig. 5.2) and, in extreme degrees of hydrothermal alteration, is the only diagnostic feature by which the rock can be distinguished fron altered volcanics. Apatite, zircon, and rutile also remain unaltered.

Sulphides (pyrite, sphalerite and galena) are found both in the quartz-porphyry and the volcanics. The minerals are disseminated, or are associated with quartz, dolomite-ankerite, and calcite in veinlets. Both pyrite and sphalerite tend th be restricted to the wall rocks adjacent to the vein, rather than the vein itself. Quartz-porphyry is the most favourable host rock for sphalerite. These sulphides are considered in greater detail in the following chapter.

5. Zones of Hydrothermal Alteration.

The mineralogical changes involved in hydrothermal alteration of the wall rocks (described in sections 3 and 4, above) are shown in diagrammatic form in Table 5.1. Minerals which were developed during hydrothermal alteration, not by the direct breakdown of pre-existing minerals, but by the 'introduction' of new material are also shown in Table 5.1. Some of the 'introduced' material has probably resulted from the reconstitution and redistribution of pre-existing minerals; this factor is considered later. It can be seen that, except for sulphides, the products of pre-ore alteration and hydrothermal alteration are similar. Distribution and

Table 5.1 Pre-ore and hydrothermal alteration of the minerals composing the volcanics and quartz-porphyry.

Original Mineral	Pre-ore Alteration	Hydrothermal Alteration
1. Plagioclase	sericite	sericite
	calcite	calcite
	epidote	?
	chlorite	sericite + Fe oxides
	quartz	quartz
2. Pyroxene	chlorite	Fe-poor chlorite---sericite + Fe oxides
	calcite	calcite
	Fe oxides	Fe oxides
	quartz	quartz
3. Biotite	chlorite	sericite + Fe oxides
	Fe oxides	Fe oxides
	epidote	?
4. Garnet	chlorite	?
	Fe oxides	?
5. Quartz	unaltered	unaltered
6. Apatite	unaltered	unaltered
7. Zircon	unaltered	unaltered
8. Rutile	unaltered	unaltered
		Minerals 'introduced' during hydrothermal alteration: galena, sphalerite, pyrite, quartz, sericite, calcite, dolomite-ankerite, chlorite.

Explanation.

X-------Y-------Z Pre-ore alteration of X to Y, and then hydrothermal alteration of Y to Z.

X-------Y.....Y Pre-ore alteration of X to Y, and then continued alteration of X to Y by hydrothermal processes.

relative proportions of the various minerals are, however, very different.

The processes involved in the hydrothermal alteration of the volcanic and quartz-porphyry wall rocks are :-

(a) silicification
(b) sericitisation
(c) carbonatisation
(d) chloritisation
(e) sulphide introduction

Silicification, sericitisation and carbonatisation are the most important hydrothermal alteration processes at Greenside. The combined effect of these three processes is to produce a bleaching of the wall rocks. The degree of alteration, especially silicification, increases towards the vein; the wall rock adjacent to a wide vein may be composed almost entirely of quartz.

Chloritisation generally affects the wall rocks which are some distance from the vein. The chlorite forms scattered flakes in the groundmass, and is often localised next to fractures and veinlets (Figs. 5.3 and 5.4). Andesite fragments in andesitic breccias are often chloritised along their edges, thus gaining a 'corona' structure (Fig. 3.15,p.58).

The minerals developed as a result of these hydrothermal processes thus vary with the distance from the vein, and the following zones can be recognised:

VEIN

ZONE 1 Strong silicification, sericitisation and carbonatisation. Disseminations and veinlets of sulphides.

ZONE 2 Moderate silicification, sericitisation, and carbonatisation.

ZONE 3 Weak and patchy silicification, sericitisation and carbonatisation. Patchy chloritisation.

ZONE 4 Pre-ore alteration only.

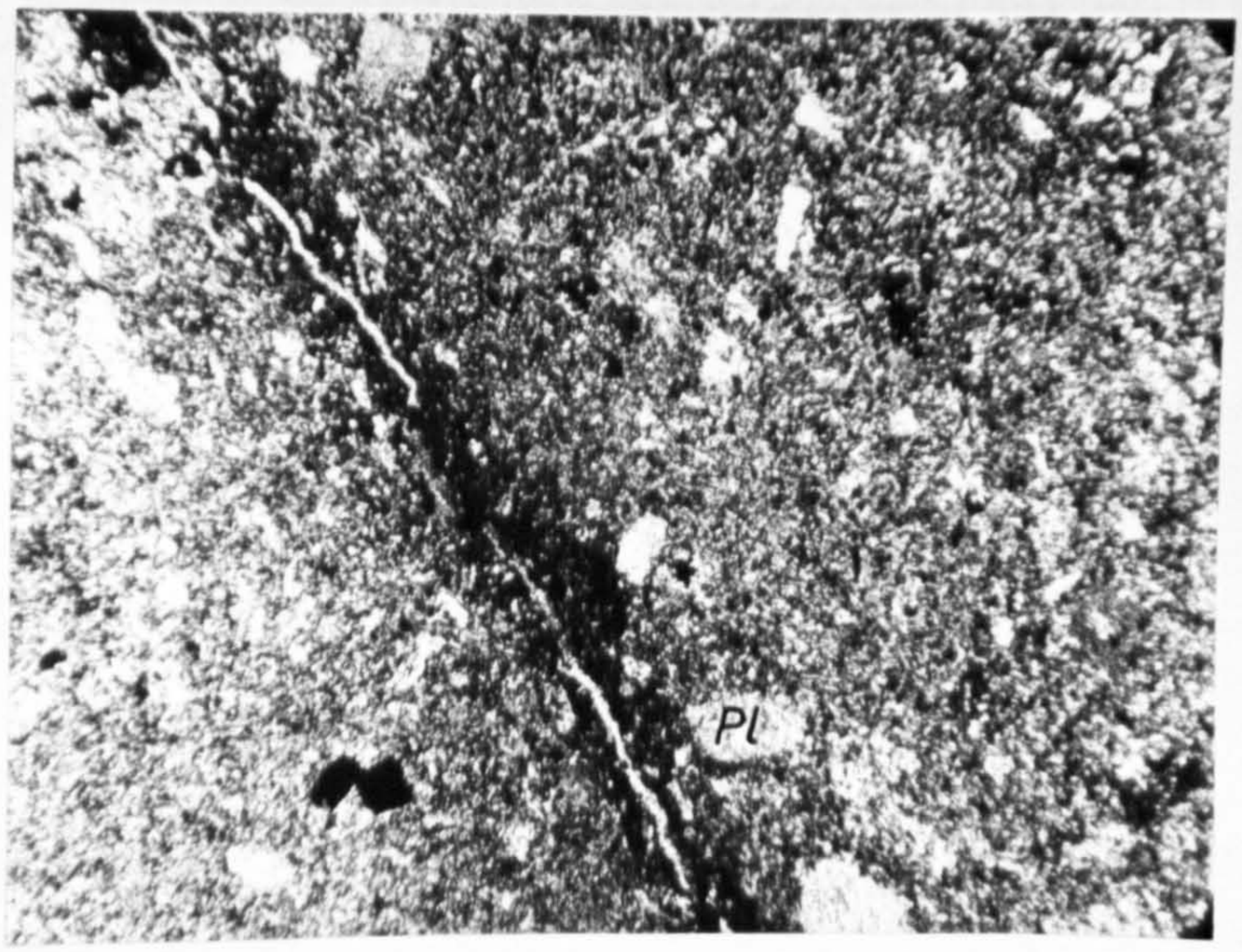


Fig.5.3 Altered andesite: carbonate veinlet associated with fine grained chlorite. The plagioclase phenocrysts (Pl) are completely altered to calcite. Original ferromagnesian minerals probably represented by diffuse areas of iron oxides. Microcrystalline groundmass. 1111 N, 40 fm. level. X 30. Crossed nicols.

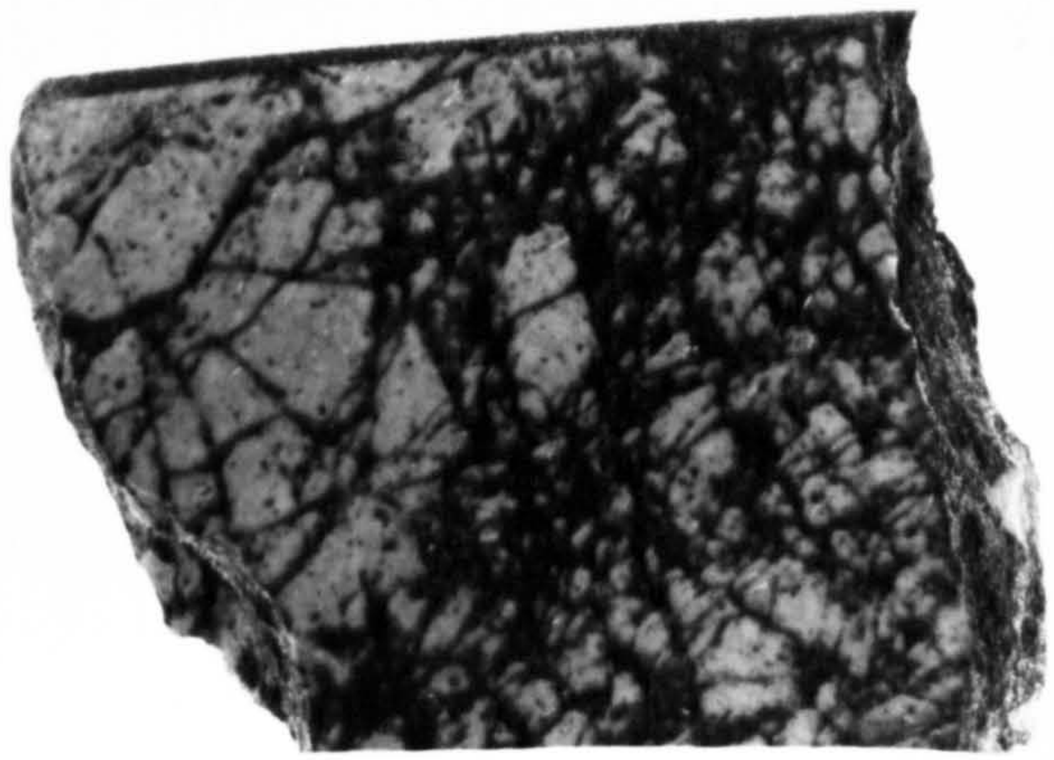


Fig. 5.4 D.D.H. core composed of'acid'(biotite) andesite showing extensive chloritisation along fractures. At 195', D.D.H.No. 1., 2760 N cross-cut, Lucy Tongue level. X 1.

The development of chlorite at some distance from the vein is typical of many ore deposits (Schwartz, 1959). Veinlets associated with chloritisation frequently cut silicified wall rock; the absence of chlorite adjacent to the vein suggests that the sequence of alteration was as follows:-

(1) Widespread silicification
(2) Chloritisation
(3) Silicification, restricted to a narrow zone near the vein (?)

6. Extent of Hydrothermal Alteration.

The intensity and extent of the wall rock alteration associated with the Greenside Vein varies according to :-

(a) depth
(b) rock-type
(c) degree of brecciation
(d) distance from the vein
(e) width of vein

The most noticable change in all rock-types is a pronounced bleaching caused mainly by silicification. The bleached zone envelops the vein and often extends, parallel to the strike of the vein, approximately 20 feet beyond the point where the vein dies out. The width of the bleached zone is generally greater on the hanging-wall side than the foot-wall side; this is because the former is more brecciated and cut by more branch faults than the foot-wall, and therefore affords greater penetration by the hydrothermal solutions. In the upper levels, the bleached zone may be only a few feet wide on each side of the vein, but the degree of alteration and the width of the bleached zone becomes progressively

greater as the depth increases, so that in the lower levels the bleached zone may be up to 50 feet wide. Alteration, excepting chloritisation, is always greatest immediately next to the vein and decreases in intensity as the distance from the vein increases. The extent and intensity of alteration is also roughly proportional to the width of the vein . In the upper levels of the mine the wall rocks of narrow branch veins may show no detectable alteration in hand specimen (Fig. 5.5).

Generally, the quartz-porphyry wall rocks are more altered than those composed of volcanics. Strong silicification has caused induration of the volcanics and the quartz-porphyry especially, the latter being converted to a pale-green, very hard rock, known at the mine as 'greenstone'.

Hydrothermal alteration of the wall rocks at Greenside has undoubtedly been a guide to ore. The discovery of the 2300 N ore-shoot was largely due to the recognition of a zone of altered rocks. There are doubtless other examples: the miners invariably knew the proximity of a vein by the fault zone becoming 'tight' and the wall rocks becoming harder and bleached.

7. Discussion and Conclusions.

The close association of the ore and the altered wall rock at Greenside suggests that mineralisation and alteration occurred approximately contemporaneously, and were the result of ascending hydrothermal solutions. Wall rock alteration was not a simple continuous process but occurred in stages.

Although the composition and texture of the fresh rocks have influenced the degree of alteration, the ultimate products resulting



Fig. 5.5 Narrow vein of quartz, galena and barite cutting quartz-porphyry which is comparatively unaltered and still preserves a fresh, porphyritic texture. (Scale has $\frac{1}{2}$ inch divisions). 1444 N, 40 fm. level.

from hydrothermal alteration of basic andesite, acid andesite, volcaniclastic rocks and quartz-porphyry have a similar composition. The convergence to a uniform composition is a common feature of wall rock alteration (Schwartz, 1959).

Without complete chemical analysis it is very difficult to judge the quantity of elements introduced during hydrothermal alteration. In fact the material which has seemingly been introduced may be the result of reconstitution and redistribution of the elements of the primary minerals. The lack of minerals containing appreciable amounts of potassium in the Greenside wall rocks shows that the presence of sericite is partially due to the introduction of this element. The wall rock adjacent to the vein may be composed almost entirely of quartz, which therefore has been clearly introduced. The presence of carbonates shows that carbon dioxide has been introduced. However calcium and magnesium which are components of the carbonates, were probably derived from the breakdown of plagioclase and ferromagnesian minerals.

In extreme degrees of alteration, ferromagnesian minerals are altered almost entirely to sericite and quartz, thus apparently pointing to the removal of iron. However the iron was probably taken into solution during the initial stages of alteration and was precipitated later as pyrite, ankerite and sphalerite. Sodium and titanium both appear to have been removed during hydrothermal alteration.

The chemical changes may be summarised as follows:-

Introduced : SiO_2, CO_2, K, Pb, Zn, OH.
Removed : Na, Ti.
Reconstituted and redistributed : Fe, Ca, Mg.

CHAPTER 6

DISTRIBUTION AND PARAGENESIS OF THE VEIN MINERALS.

1. General Structure of the Vein.

The most important minerals composing the Greenside Vein are quartz, galena, barite and sphalerite; chalcopyrite, pyrite, marcasite, calcite, dolomite and ankerite are present in smaller quantities, while chlorite, witherite, tetrahedrite, and bournonite are minor minerals.

The vein shows many characteristic features of ore deposits formed by infilling of fault fissures. The margin of the vein shows a sharp contact with the wall rocks, except in the lower levels of the mine where the vein may locally merge imperceptibly into silicified wall rock. The volume of replaced rock is, however, relatively small and therefore replacement has played a relatively insignificant role in the formation of the ore.

Except in the upper levels of the mine, where barite is important, the vein is composed largely of quartz. The galena occurs as discontinuous bands, lines of crystals and disseminations within the quartz (Figs. 6.1 and 6.2). Large blocks of wall rock are very seldom found enclosed in the vein. Blocks and fragments, when present, are generally restricted to the margins of the vein and grade into brecciated wall rock (Fig. 6.3). Smaller fragments are often aligned to form bands parallel to the margins of the vein. A well developed crustified structure around a rock fragment enclosed in the vein is occasionally found.

The vein is generally approximately symetrical in cross-section; clear evidence of intra-mineralisation fracturing is uncommon. Such

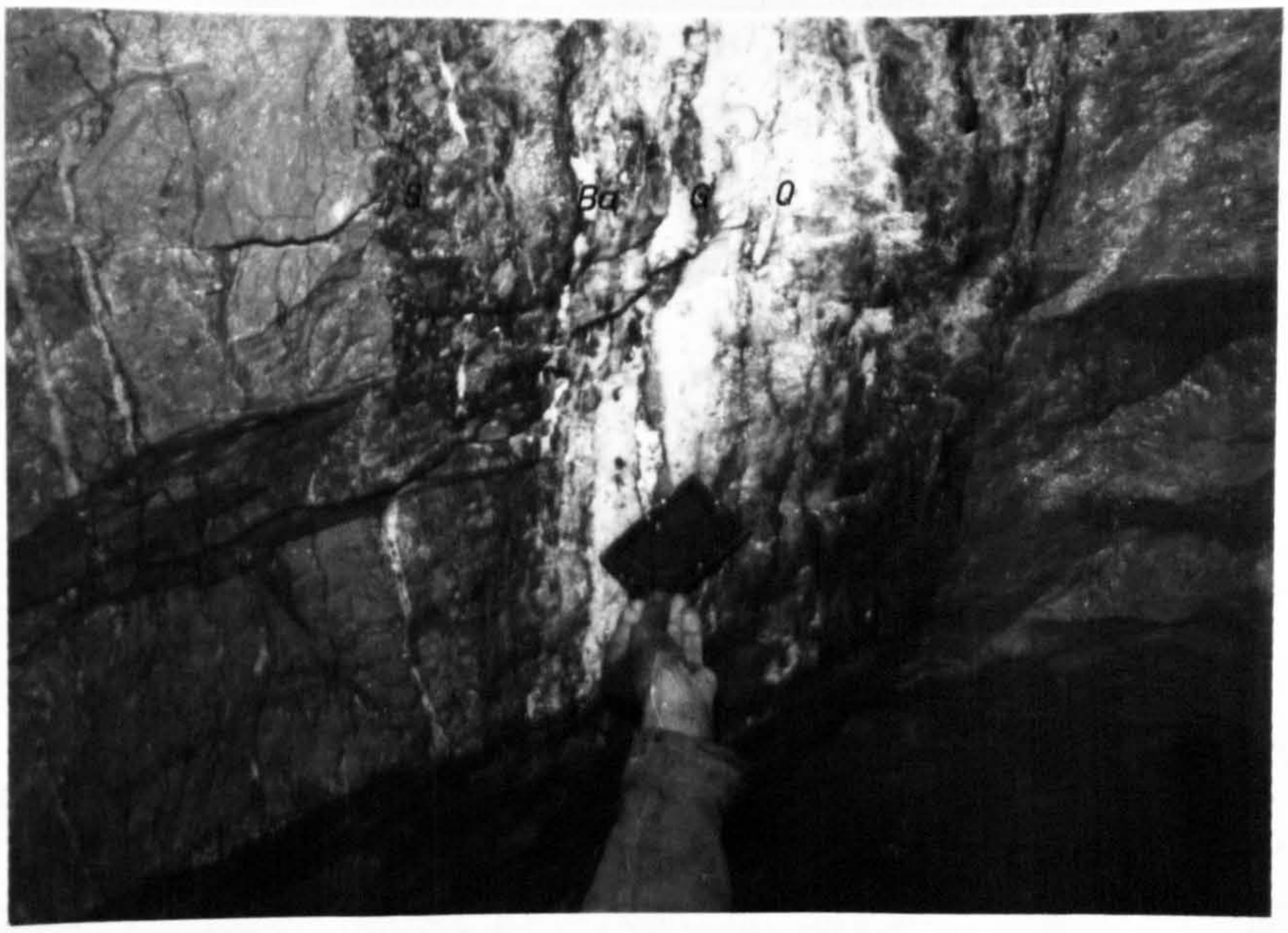


Fig. 6.1 Main Vein at 585 N, 20 fm. level. Sphalerite (S) cements fragments of silicified volcanics on the hanging-wall margin of the vein, and also forms narrow veinlets in the wall rock. Galena (G) occurs as narrow bands in quartz (Q), while the later barite (Ba) forms narrow stringers.



Fig. 6.2 Main Vein at 605 N, 20 fm. level. Disseminated sphalerite (S) in quartz (Q) forms the margins of the vein. Galena (G) occurs as discontinuous bands in quartz, while late barite (Ba) forms narrow stringers, some cross-cutting.

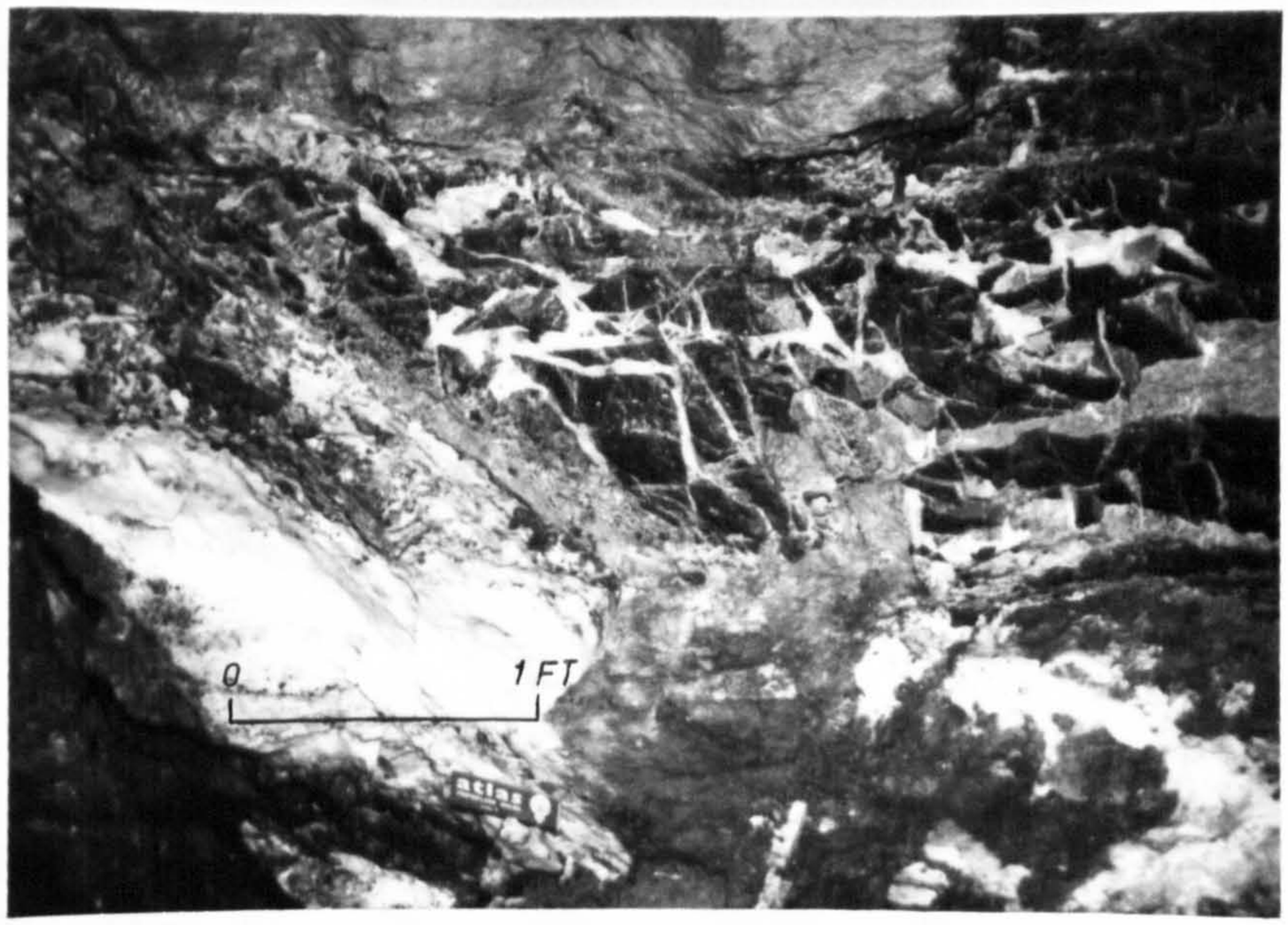


Fig. 6.3 Main Vein at 484 S, 175 fm. level. Area of breccia in the vein: fragments of amygdaloidal 'basic' andesite enclosed by quartz.

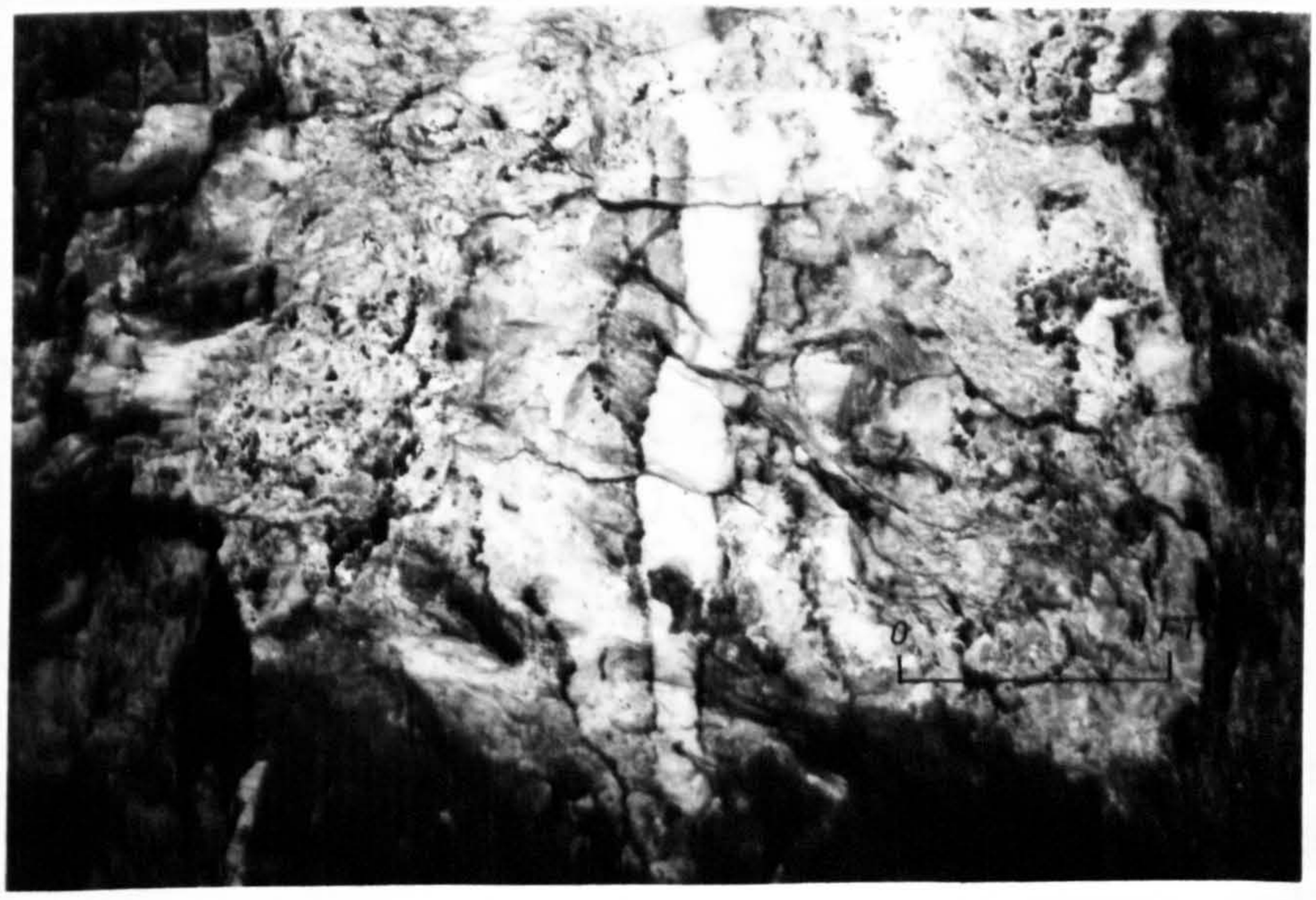


Fig. 6.4 Main Vein at 545 S, 175 fm. level. Late band of quartz cuts earlier vein-material which is largely composed of sugary quartz with bands of galena, and disseminations of both galena and sphalerite.

fracturing has generally produced little brecciation and is marked only by the 'cross-cutting' nature of later bands of minerals (Fig. 6.4). The dimensions of the vein have been described previously (p.90).

Vugs are very common and may reach large proportions. The vugs are lined with crystals of calcite (or barite in the upper levels).

2. Gangue Minerals.

A. Barite.

This mineral is considered first because much of the quartz, the most important gangue mineral, is believed to have been formed at the expense of barite.

Barite is found in three main environments:-

(a) In central infillings or vugs

(b) In narrow veins containing no other mineral

(c) Throughout the vein, but often partially or completely replaced by quartz.

The barite of environment (a) (Fig. 6.5) is found mainly above the 40 fm. level. Vugs containing a small amount of barite are found in places on the 90 fm. level, while below the 120 fm. level barite is completely absent. (The mineral is however found in the 348 W Vein and associated veins , on the 175 fm. level.) The barite is slightly pinkish in colour in contrast to barite of environments (b) and (c) which are whiter in colour. Well developed cock's comb aggregates are common.

Above the 40 fm. level barite may form narrow veins either along Greenside Fault or else cutting across the fault e.g. the Hicks Vein.



Fig. 6.5 Main Vein at 1345 N, 40 fm. level. Sphalerite (S) forms veinlets in the silicified wall rock. Galena (G) occurs as irregular areas in quartz, while barite (Ba)fills central pockets.

These veins (environment b) are believed to have been formed during the last stages of mineralisation following a minor period of local fracturing.

The barite of environment (c) is found above the Lucy Tongue level and is locally the major gangue mineral in the vein. Partial alteration to quartz is common. Much of the quartz below the Lucy Tongue level has a structure which indicates that barite was the original mineral. This type of quartz is described below.

B. Quartz.

Excepting the quartz found in vugs, this mineral is always fine-grained, and the usual type of 'comb quartz', typical of many veins, is absent. Because of the fine grain size, fragments of vein quartz are seldom transparent and are always semi-opaque or translucent. Small cavities between the grains may give the quartz a sugary appearance. In thin section the quartz shows a mosaic texture.

The quartz may also show an unusual lamellar structure. The lamellae are composed largely of chalcedony while fine grained quartz usually forms the interstitial areas between the lamellae. The lamellae are grouped together to form radiating sheaf-like aggregates and these in turn make up discontinuous bands. Such bands may be present in the vein throughout the mine and show no special development in any specific sections.

The margins of the bands of lamellar quartz are always gradational. Bands of lamellar quartz are often separated by areas of sugary quartz.

Generally the 'central point' of a radiating sheaf of lamellae is on the side nearest the margin of the vein, so that the lamellae radiate

outwards towards the centre of the vein. The lamellae are approximately perpendicular to the band and thus to the margins of the vein.

This radiating sheaf-like structure thus simulates the structure of cock's comb aggregates of barite, and has in fact resulted from the replacement of the latter. However the replacement is usually complete, and partial alteration was only observed in the upper levels of the mine. The barite found in vugs (environment (a)) is seldom replaced but occasionally the base, i.e. central point, of a radiating cock's comb aggregate is silicified: narrow lamellae, largely composed of chalcedony and quartz, extend between the plates of barite and along the basal cleavages, but become narrower and finally die out some distance from the central point (Figs. 6.6 and 6.7). Lamellae of sphalerite are also associated with the chalcedony and quartz.

The barite of environment (c), as described above, may be partially replaced by quartz and chalcedony. Often residual islands of barite are enclosed by quartz which preserves the structure of barite and is therefore lamellar. Some barite is also replaced by sugary quartz which shows no lamellar structure.

It should be noted that the lamellae of chalcedony do not represent a single plate of barite, but have resulted from the replacement of barite on each side of the junction between two plates, or else on either side of a basal cleavage plane. However the length of the lamellae will be some indication of the original size of the barite plates.

The interstitial areas between the lamellae, if not infilled by quartz, either remain as cavities or are filled with galena, sphalerite, chalcopyrite or pyrite (Figs. 6.8,6.9 and 6.10). The quartz in the

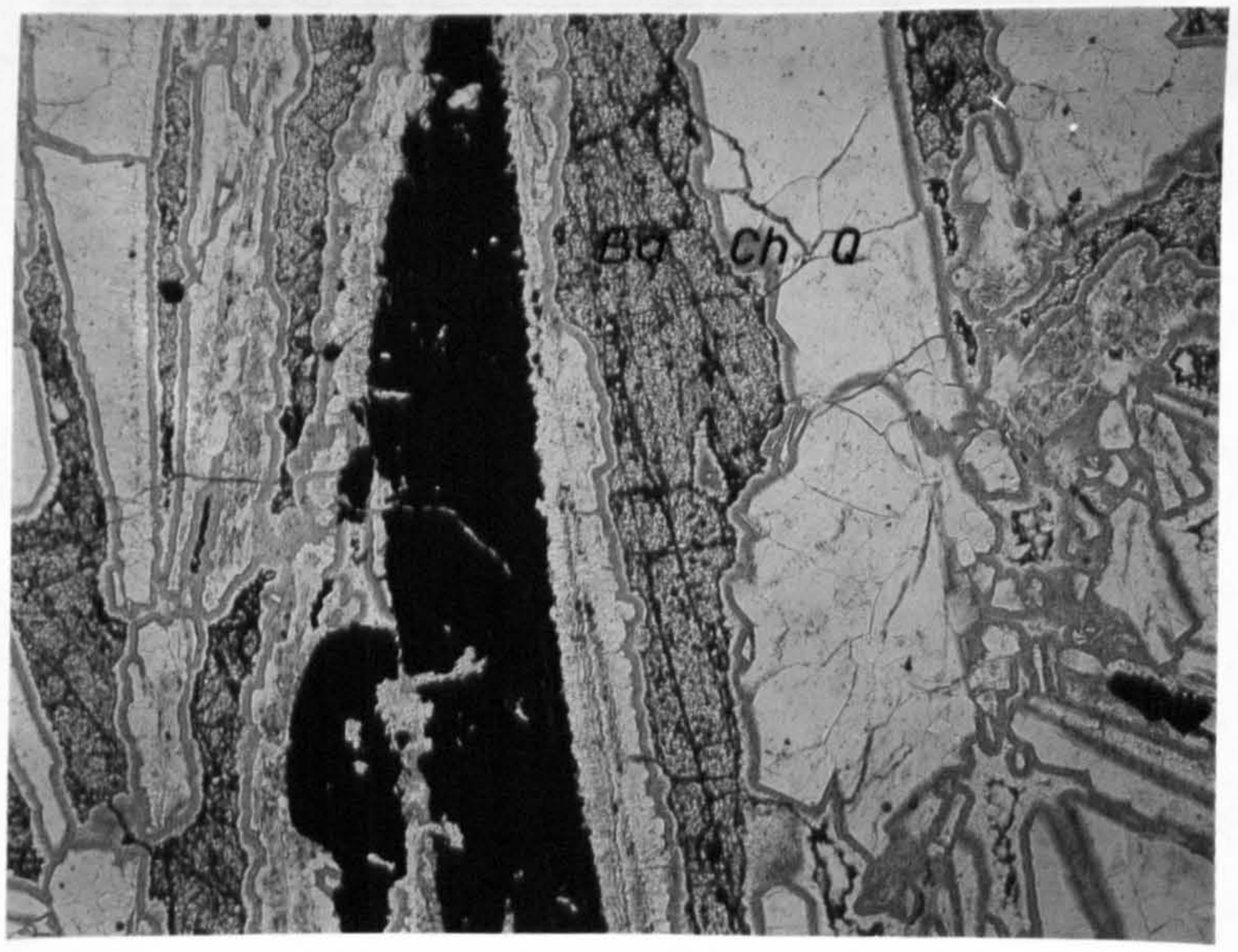


Fig. 6.6 Barite replaced by quartz: irregular blades of barite (Ba), mosaic quartz (Q) rimmed by chalcedony (Ch). Sphalerite is black. 1300 N, Lucy Tongue level. X 20. Ordinary light.

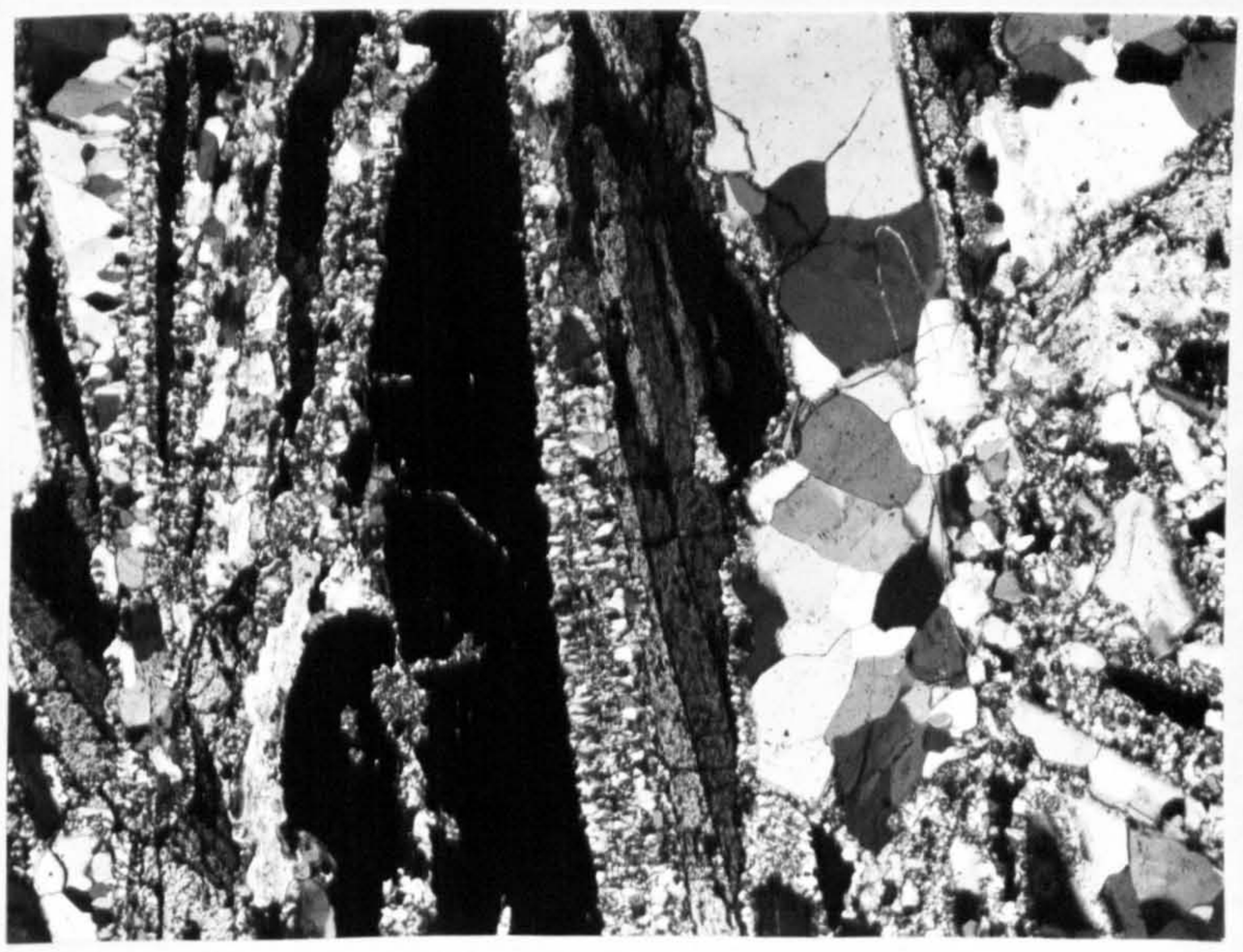


Fig. 6.7 As Fig. 6.6 . X 20. Crossed nicols.

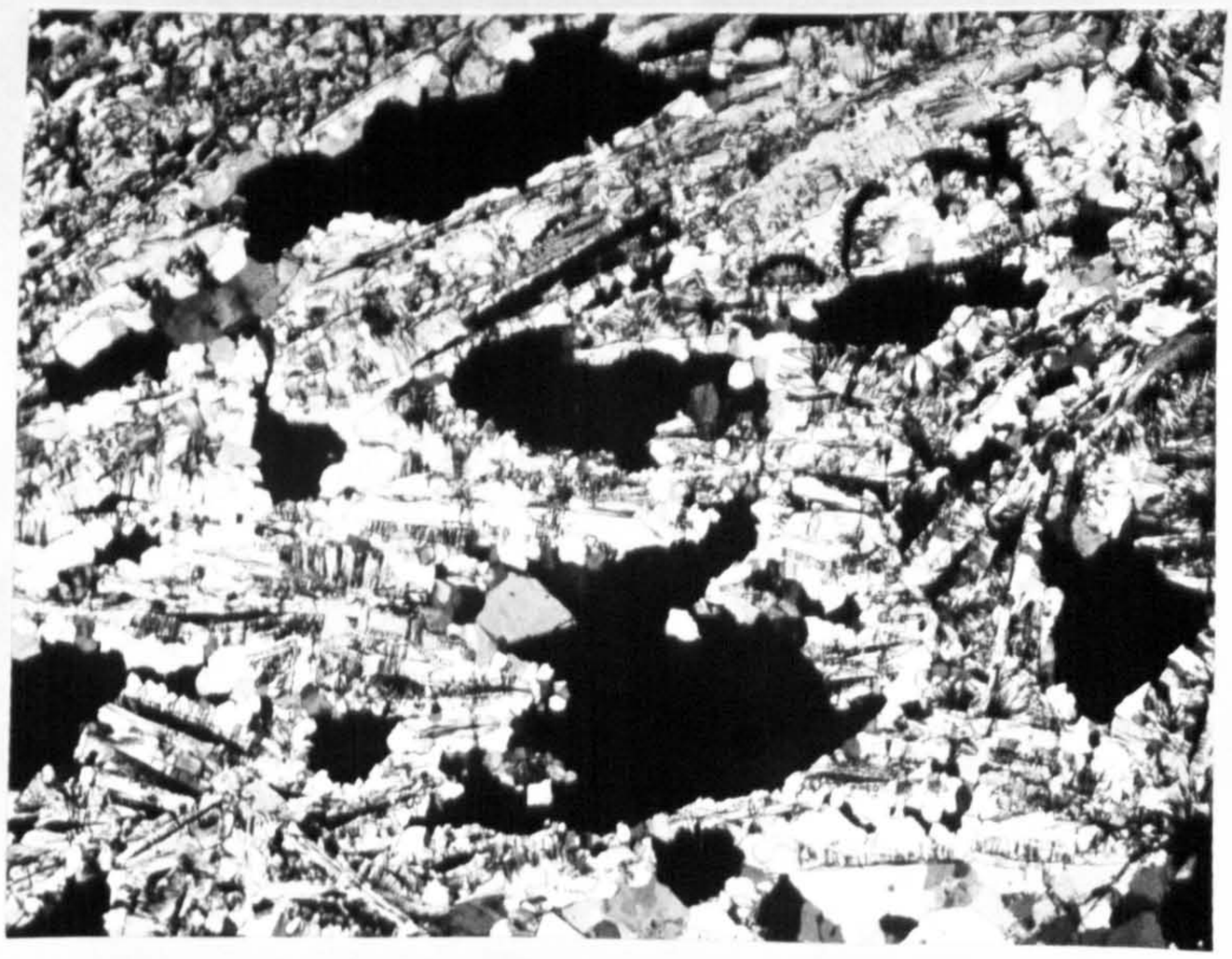


Fig. 6.8 Lamellar quartz (after barite): chalcedony lamellae with interstitial mosaic quartz. Black areas are cavities, some of which are natural, while others were produced by the removal of interstitial galena as a result of sectioning.

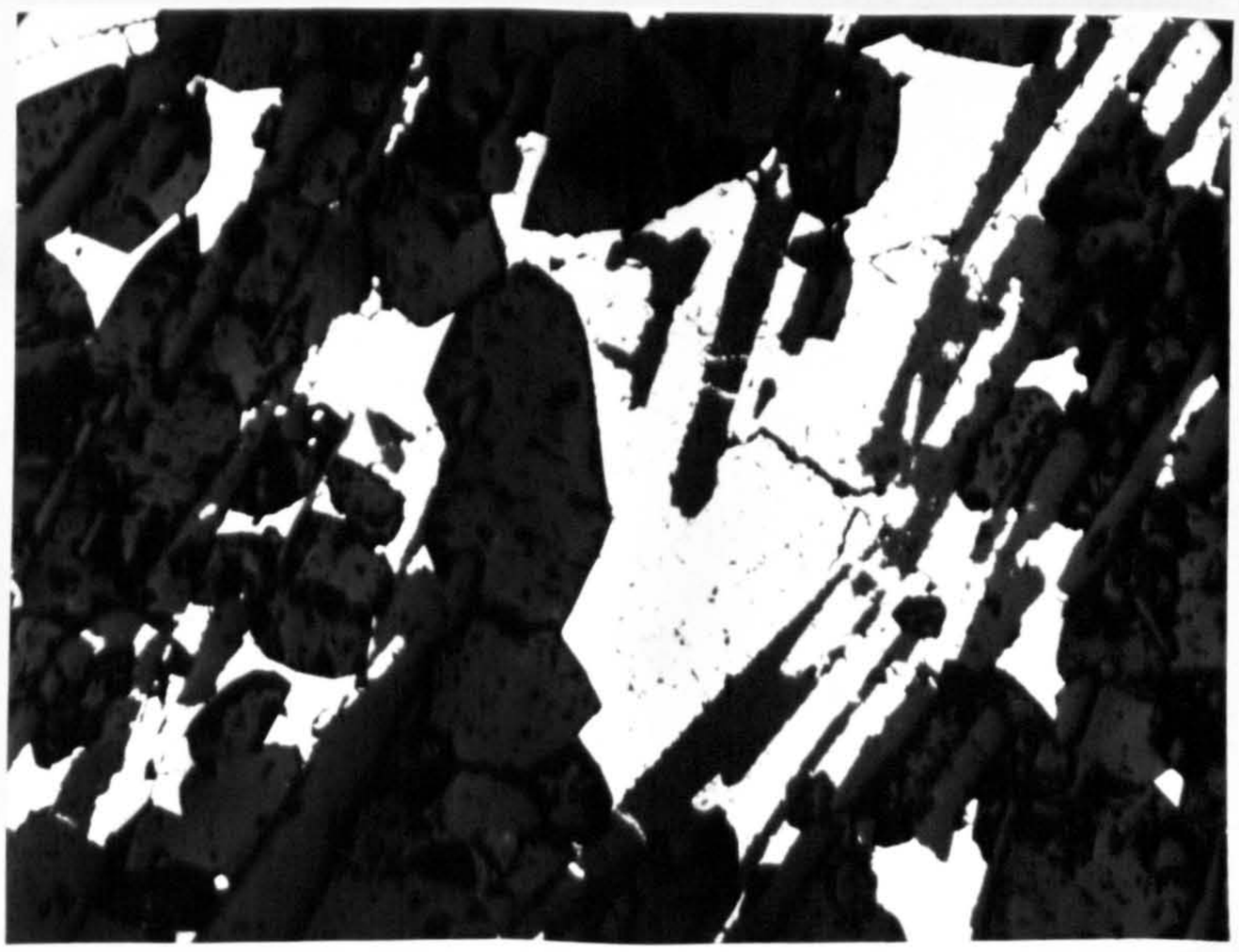


Fig. 6.9 Lamellar quartz (dark) with interstitial pyrite. 614 S, 90 fm. level. X 50. Ordinary light.

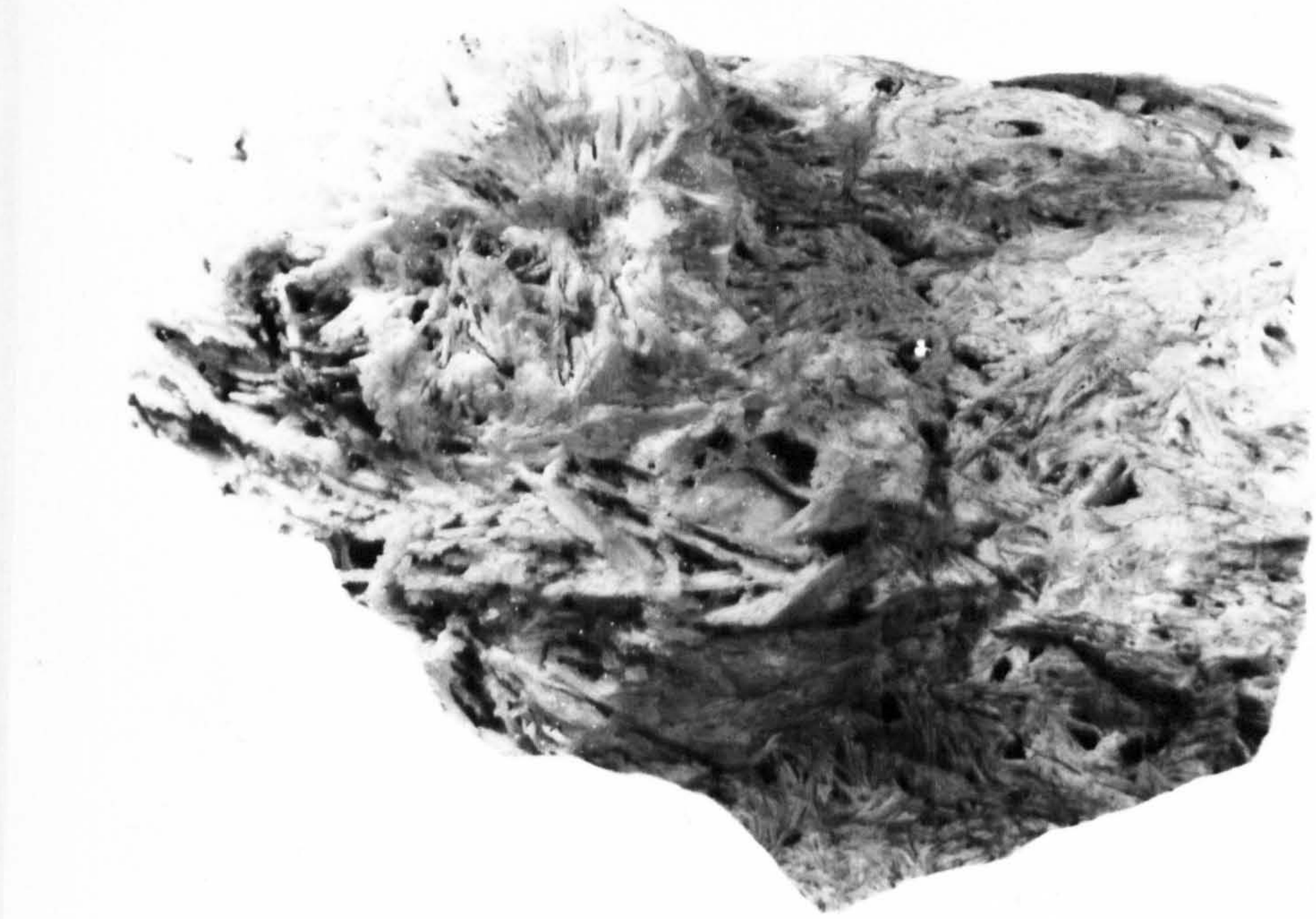


Fig. 6.10 Lamellar quartz (after barite): chalcedony lamellae with interstitial cavities which are lined by quartz crystals, or filled by galena and minor chalcopyrite. 632 S, 175 fm. level. X 1.

interstitial areas has been formed initially against the lamellae and has grown inwards towards the centre of the interstitial areas, the grain size of the quartz increasing towards the centre. This texture and the presence of cavities between lamellae indicates that the replacement has taken place in three stages :-

(1) formation of chalcedony lamellae and to a lesser extent quartz along crystal boundaries and basal cleavages of barite.

(2) solution of barite in interstitial areas

(3) infilling by various minerals of most, but not all, of of the interstitial areas.

The interstitial areas in the lamellar quartz have in fact been important in localising the galena; often the galena in the vein is concentrated in bands of lamellar quartz. Etching with nitric acid has revealed how the galena has grown inwards towards the centre of the interstitial areas.

It is uncertain how much of the vein was originally barite: as noted previously sugary quartz as well as lamellar has resulted from the replacement of barite. Replacement of barite by quartz is a fairly well-known phenomenon, but the formation of lamellar quartz with interstitial sulphides has apparently not been recorded elsewhere. However this type of quartz seems typical of Lake District lead veins and was recorded by the author at the following mines :-

(a) Threlkeld
(b) Hartsop Hall
(c) Myers Head
(d) Eagle Crag
(e) Helvellyn (Wythburn)

Specimens in the Royal School of Mines collection show that lamellar quartz is also present at Thornthwaite, Driggith and Roughtongill mines.

C. Witherite.

This mineral was not observed by the author and neither is it recorded in any of the reports of the mine. However a specimen of massive radiating witherite was apparently collected at the mine and now resides at the Natural History Museum, South Kensington.

D. Calcite.

The most common occurence of calcite is in vugs. Well formed crystals are common and several beautiful specimens have been acquired by museums. Calcite is invariably later than any barite present.

The mineral shows a variety of crystal habits: in addition to the 'nail-head' and the 'dog-tooth' habit, flat crystals, tabular on (001), are sometimes found, and also rhombohedral crystals. There is no apparent variation in crystal habit throughout the mine. In ultra-violet light the calcite shows a pink fluorescence and strong zoning, indicative of variations in the manganese content.

Veinlets of calcite (sometimes associated with galena and sphalerite) are found in the wall rock of the vein and were perhaps formed during the earliest stages of mineralisation. Other calcite veinlets occur along with veinlets of dolomite and ankerite in the barren sections of the Greenside Fault. Veins of slightly pinkish calcite, sometimes associated with chalcopyrite, which cut across the vein, were formed during the last phases of mineralisation (Fig. 6.12).

E. Dolomite and Ankerite.

Except in the upper levels of the mine, these minerals are never found in the vein but are restricted to the wall rock and to the barren sections of the Greenside Fault, where they form narrow veinlets or enclose fragments



Fig. 6.12 Main Vein (composed of quartz with bands of galena) cut and displaced by a later calcite vein. 370 N, 175 fm. level.

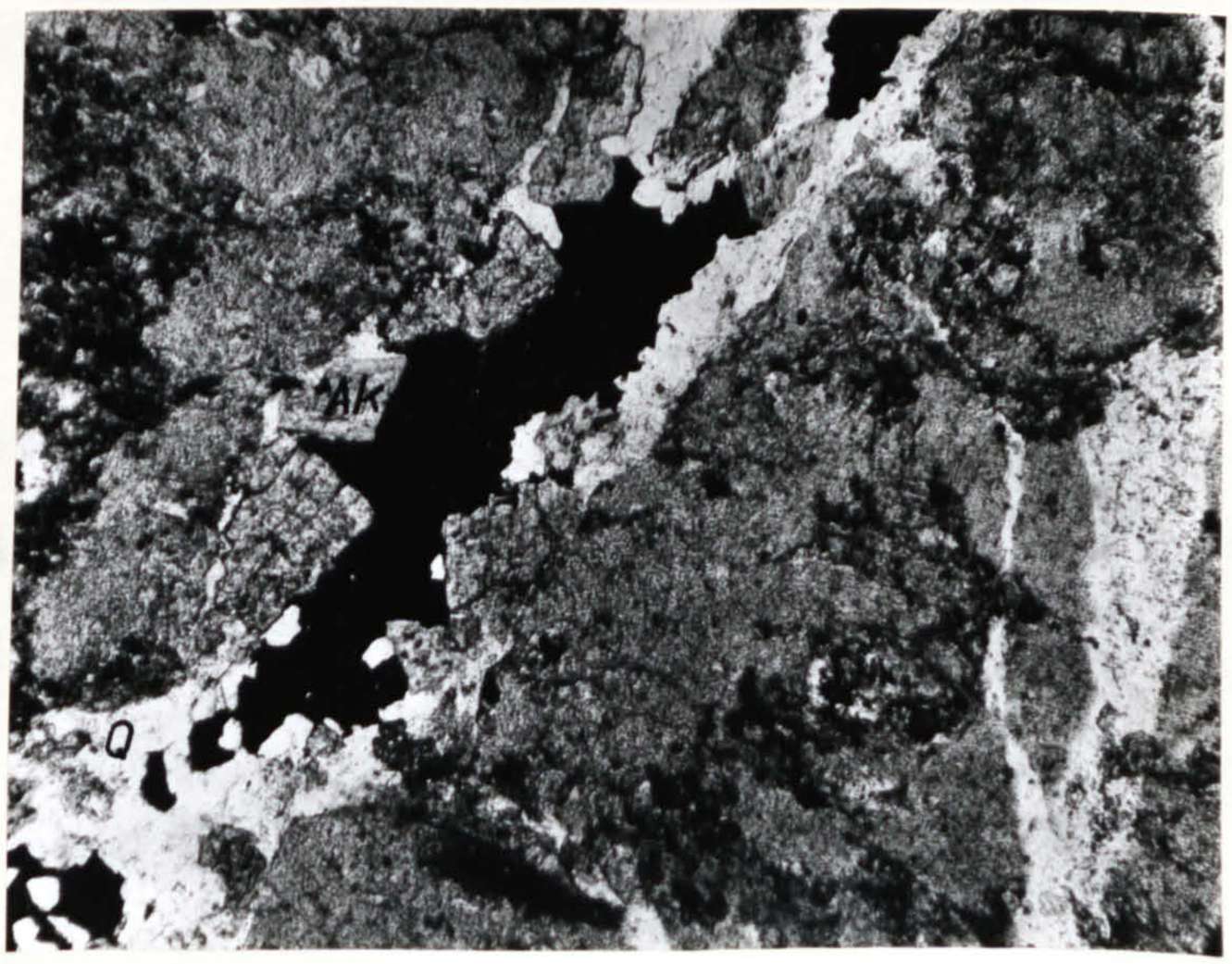


Fig. 6.13 Quartz-ankerite-sphalerite veinlet in altered andesite: quartz (Q), ankerite rhombohedra (Ak), and sphalerite (black). Not shown - grains of pyrite enclosed in sphalerite. 876 N, 120 fm. level. X 50. Ordinary light.

of brecciated wall rock (Fig. 6.13). The ankerite in this environment was formed during the initial stages of mineralisation and is relatively poor in Fe (O = 1.690 - 1.697).

The ankerite from the vein in the upper levels of the mine could not be observed in situ, but judging from the quantity found in the mine dumps near the adit of the High Horse level the mineral is plentiful. The usual vein components quartz, galena and barite are enclosed, or sometimes brecciated and enclosed, by ankerite which therefore must have been formed during the last stages of mineralisation. This ankerite is richer in Fe than the early formed ankerite and has an R.I. (O) of 1.712.

F. Chlorite.

Chloritisation of the wall rocks has been described previously. On the 90 fm. level at 430 N small amounts of chlorite were found in the vein itself, and often infilling interstitial areas in lamellar quartz. The time relations with other minerals could not be observed.

3. Sulphides.

A. Galena.

As described previously, galena may occur as bands, lines of crystals, disseminations, and infillings of lamellar quartz (Figs. 6.1, 6.2, 6.5, 6.9 and 6.14). Veinlets and disseminations of galena with quartz and sphalerite are also found in the wall rocks.

Usually galena forms a small percentage of the total volume of the vein. Where the vein pinches and swells, it is found that the wider sections of the vein are composed of a larger percentage of quartz compared to galena, than the narrow sections. However wide veins are never

of such low grade as to be sub-economic. Occasionally veins up to three feet wide may be composed entirely of galena.

The galena crystals found in vugs show a combination of the cubic and octahedral habit; curved faces are common. No variation in the relative dominance of these two habits was observed vertically or laterally throughout the mine.

Etching with nitric acid revealed no inclusions that were not already visible in unetched specimens, but a well developed zoning was observed (Fig. 6.15). This zoning perhaps reflects variations in the trace element content during growth or non-stoichiometry.

B. Sphalerite.

The greatest concentration of sphalerite is found in the wall rocks of the vein, especially the quartz-porphyry. Immediately next to the vein the sphalerite may cement fragments of silicified wall rock, while further away irregular veinlets and disseminations of sphalerite are found (Figs. 6.1, 6.5 and 6.13). Small quantities of quartz and galena may be associated with the sphalerite.

Sphalerite is found disseminated in quartz near the margins of the vein (Fig. 6.2) and may infill interstitial areas in lamellar quartz. Small amounts of sphalerite may be associated with barite in vugs. The ankerite found in the dumps near the High Horse adit is also associated with sphalerite, while in the lower levels of the mine veinlets of sphalerite which cut across the vein perhaps represent a similar late stage of mineralisation.

The amount of sphalerite in the wall rocks and the margins of the vein increases with depth. During the working of the lower levels the conc-



Fig. 6.14 Main Vein at 516 S, 175 fm. level. Galena forms sinuate bands and scattered crystals, some of which are large and blade-like.



Fig. 6.15 Galena (etched with 1:1 HNO_3) showing zoning (at point X). 398 S, 135 fm. level. X50. Ordinary light.

entration of sphalerite almost merited its separation in the milling.

Well formed crystals of sphalerite show a combination of several crystal faces. The colour of the sphalerite ranges from yellow-brown to dark brown, correlating with an iron content of approximately 1 -4%. Crystals often show an alternation of light and dark coloured zones, but no regular pattern of zoning could be observed.

C. Chalcopyrite.

Scattered crystals and narrow bands of chalcopyrite are found throughout the vein and show no special development either near the margins nor towards the centre. The bands are up to 1 cm. in width but are discontinuous. The distribution of chalcopyrite in general is erratic although there is an increase with depth.

Since both galena and chalcopyrite are found throughout the vein, sometimes in alternate bands, galena may overgrow chalcopyrite or vice versa. Evidence of replacement of chalcopyrite by galena is occasionally found(Fig. 6.16). Small blebs of chalcopyrite are often enclosed in sphalerite. Chalcopyrite sometimes fills interstitial areas in lamellar quartz, and is also associated with calcite and barite in vugs.

D. Pyrite.

Pyrite is mainly concentrated in the wall rocks and margins of the vein. The distribution is erratic and shows no apparent variation either vertically or laterally. The wall rocks in the barren sections as well as those in the productive sections may contain pyrite, which appears to be the first mineral formed in the mineralisation sequence. The mineral forms scattered cubes and disseminations in the wall rocks, but seldom veinlets. Interstitial areas in lamellar quartz are occasionally infilled

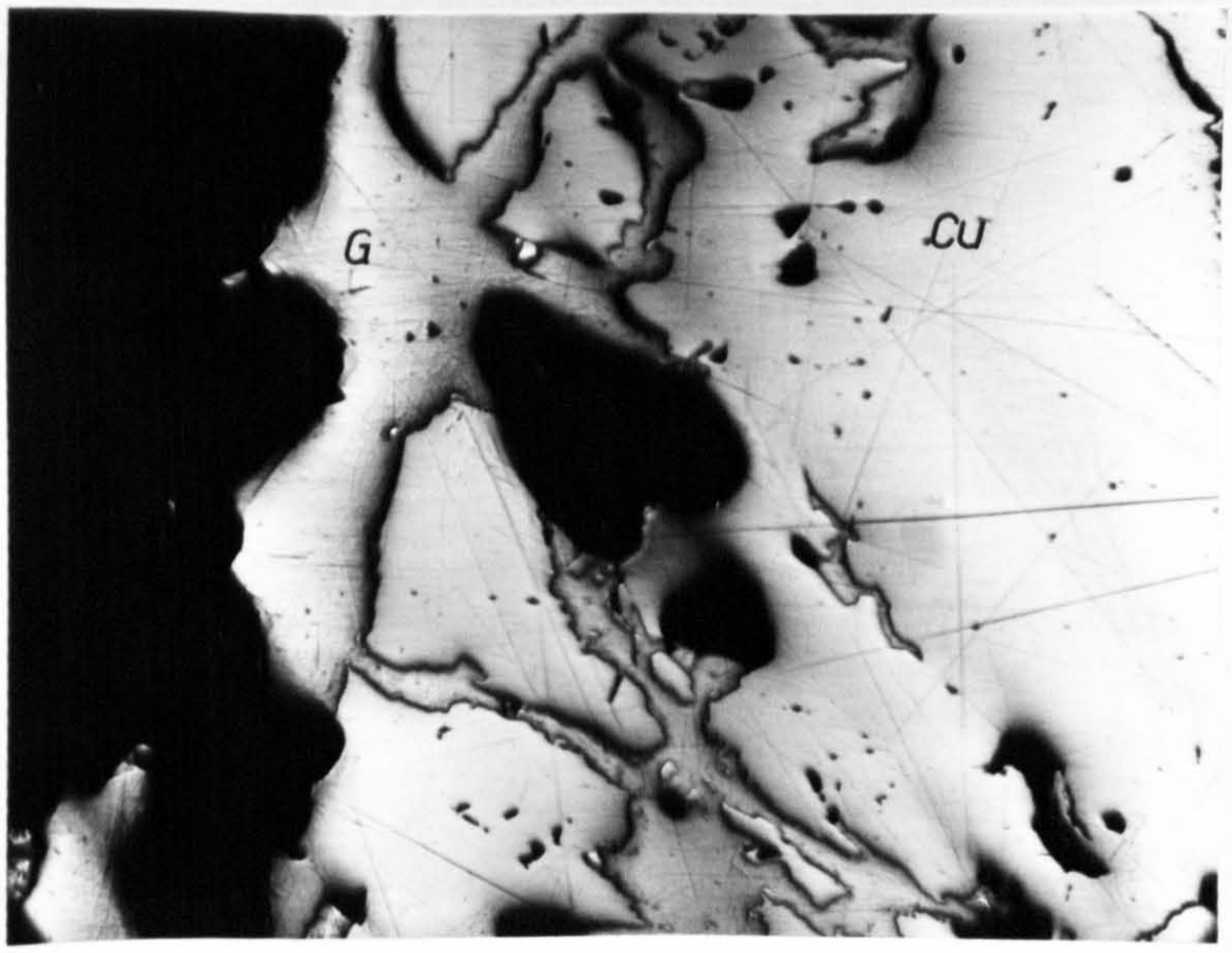


Fig. 6.16 Chalcopyrite (Cu) veined and replaced by galena (G). 400-600 N stope, 175 fm. level. X 50. Ordinary light.

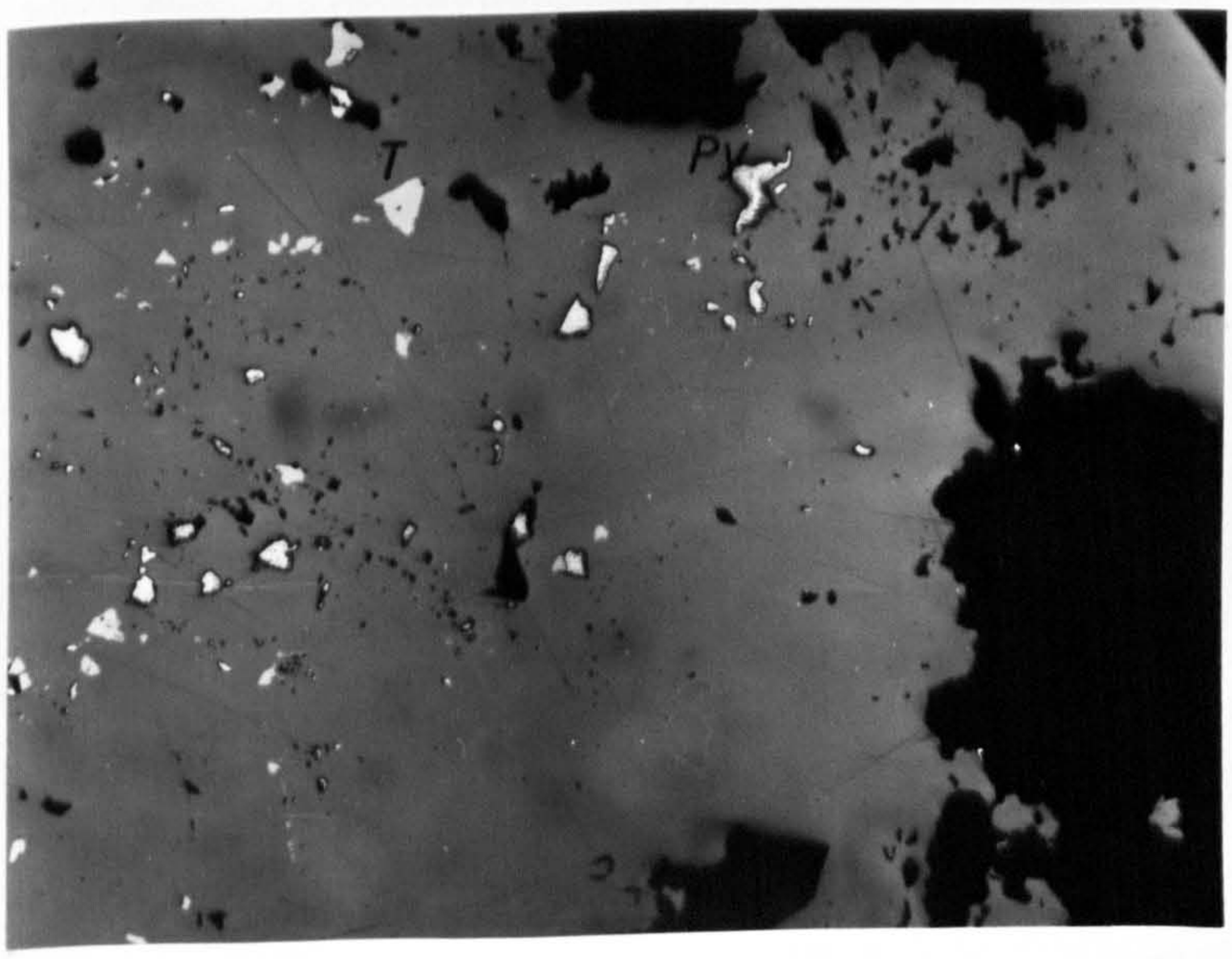


Fig. 6.17 Sphalerite with irregular inclusions of pyrite (Py) and tetrahedrite (T). Black areas are quartz. 1277 N, 40 fm.level. X 150. Ordinary light.

by pyrite (Fig. 6.9), while blebs, minute cubes and pyritohedra are sometimes enclosed in sphalerite (Fig. 6.17). Pyrite is also found in vugs where it is associated with calcite and barite. Curved faces are frequently exhibited by pyrite in the latter environment.

E. Marcasite.

Calcite which occurs in vugs may be associated with small amounts of fine grained marcasite. Marcasite is also found with chalcopyrite along barren sections of the Greenside Fault. Galena may occasionally enclose irregular grains of marcasite (Fig. 6.18).

F. Tetrahedrite.

This mineral is occasionally found as small inclusions in both sphalerite and galena (Fig. 6.17). It is impossible to tell whether or not these inclusions are a result of exsolution.

G. Bournonite.

Chalcopyrite is occasionally overgrown and partially replaced by bournonite (Fig. 6.19). In polished section the mineral is moderately anistropic and shows lamellar twinning. The mineral was confirmed by a micro-hardness determination ($V.M.H._{100}$ = 170-192).

4. Paragenesis of the Vein Minerals.

Fig. 6.20 illustrates the paragenesis of the vein minerals. The main mineralisation episode is represented by Stage 1. Initially carbonates, mainly dolomite and Fe-poor ankerite, were introduced into the wall rocks of both barren gouge zones and open fissure zones. Pyrite was formed concomitantly or perhaps slightly later. Then followed the



Fig. 6.18 Galena with irregular inclusions of marcasite. X 50. Ordinary light. 135 fm. level. 398 S.

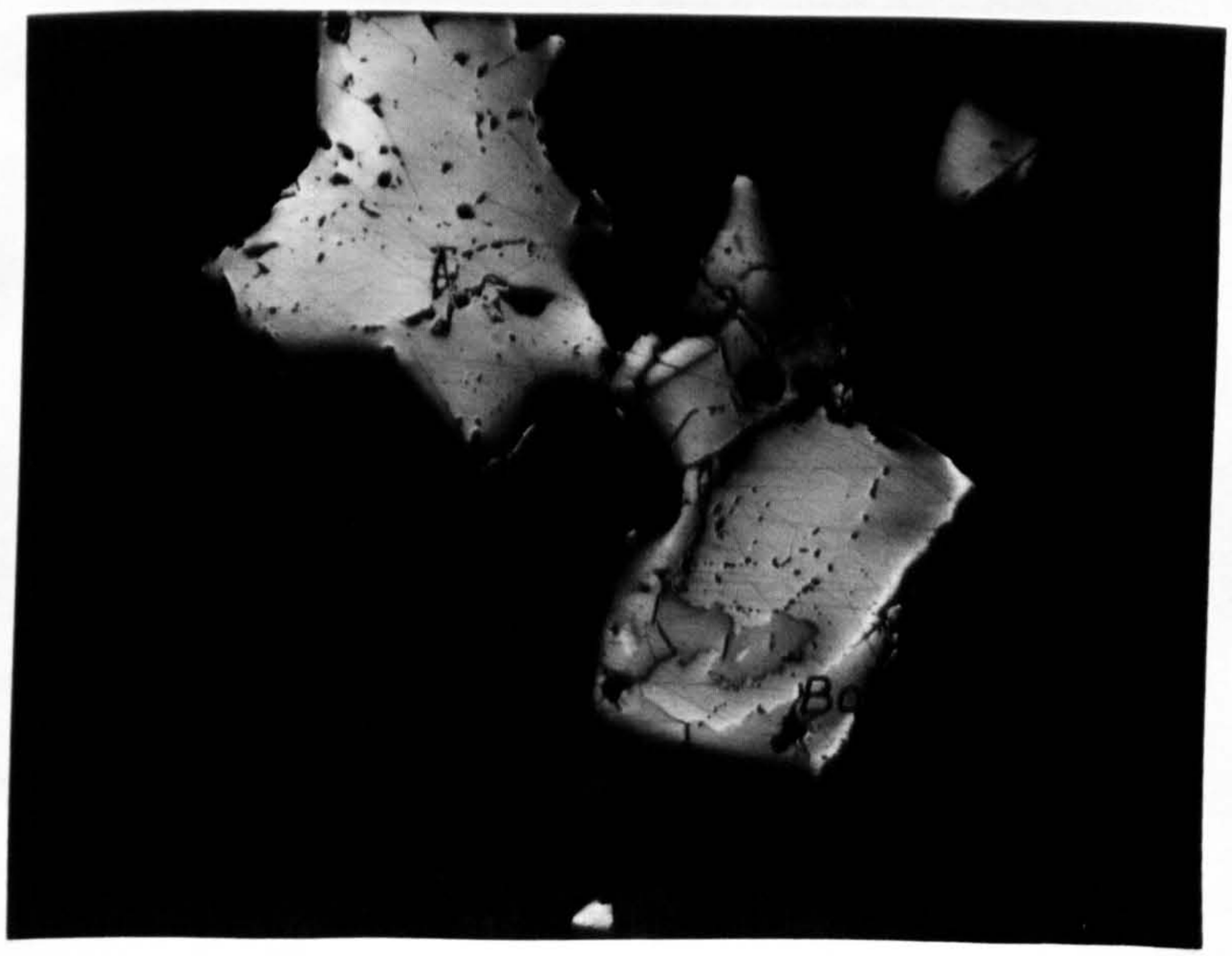


Fig. 6.19 Chalcopyrite overgrown and partially replaced by bournonite (Bo). Black areas are quartz. 992 N, 175 fm. level. X 55. Ordinary light.

main period of sulphide formation - initially sphalerite and subsequently quartz, galena, barite and chalcopyrite in alternating and overlapping sequence. Since it is not known how much of the quartz, apart from the lamellar type, has resulted from the replacement of barite, the exact time relations of the latter are uncertain. Towards the end of Stage 1 calcite, barite, chalcopyrite, pyrite and marcasite were formed in vugs. Minor fracturing occurred throughout the stage.

Stage 2 represents later formed veins which carry galena, sphalerite, chalcopyrite, barite and calcite. Examples of these veins include the 348 W Vein and other veins south of the Clay Fault, and also the No. 1 Branch.

Stages 3 and 4 represent respectively veins of calcite (sometimes with chalcopyrite) and veins of barite, e.g. the Hicks' Vein. The time relations between these stages is uncertain.

The last stage of mineralisation - Stage 5 - represents the ankerite and other minerals formed in the upper levels of the mine.

The general paragenetic sequence is similar to that found in many lead-zinc veins. The sphalerite at Greenside, as in the majority of lead-zinc veins predates galena. The position of pyrite and chalcopyrite in the paragenetic sequence of lead-zinc veins is however variable and therefore no comparisons can be made. An anomalous feature is, however, the relatively early formation of barite followed by its replacement by quartz and the introduction of sulphides.

The zoning of the Greenside Vein and the relation to the paragenesis is considered in the following chapter, after the discussion concerning the geochemistry of the vein minerals. The physico-chemical conditions

during ore-deposition are also discussed.

5. Supergene Minerals.

Alteration of the vein minerals by supergene processes is apparently very restricted. The vein on surface shows neligible alteration, the galena sometimes being slightly replaced along cleavages and fractures by cerussite. Anglesite has also been recorded, while hemimorphite has been obtained from the vein outcrop near the Glencoyne adit.

CHAPTER 7

GEOCHEMISTRY OF THE VEIN MINERALS AND THE RELATION TO ZONING.

1. Introduction.

The purpose of this study is to gain a fuller knowledge of the physico-chemical conditions that prevailed during the successive phases of ore deposition. An important aspect is the elucidation of a relationship, if any, between the minor element content of the minerals and the zoning shown by the Greenside vein.

The minor or trace element content of a mineral, excluding that due to inclusions or intergrowths of foreign minerals, is a result of either isomorphous substitution, adsorption, or the filling of vacancies in the structure of non-stoichiometric minerals. Isomorphous substitution is the most common mechanism, and the factors controlling the presence of an element depend on the ionic or covalent radius, and the valency of that element, compared with the same properties of the elements composing the 'host' mineral.

The concentration of a trace element in a mineral is governed by the availability of that element, and the ability of the 'host' mineral to accomodate it. The latter factor depends on the temperature, pressure, chemical composition, and other properties of the mineralising solutions and the crystal chemistry of the mineral being precipitated.

In most cases there is little evidence to show that the trace element concentration of a mineral being precipitated, is in equilibruim with the trace element concentration of the mineralising solution. Theoretically then, the concentration of any trace element must depend mainly on its availibility. Nevertheless, the bulk of mineral analyses

indicates, in many cases, a relationship between the trace element content and the temperature of formation or other factors.

If, for the present purpose, it is assumed that the minor element content of the minerals from the Greenside Vein is a function of the temperature of formation, then it would be expected, assuming the mineralising solutions flowed upwards and outwards from a source at depth, that there would be a significant variation in the composition of the minerals in three directions, viz, (1) vertically (2) laterally and (3) across the vein. Ideally, to show such a variation vertically and laterally, samples should be selected from the same generation (e.g., band)of mineral over as great an area of vein as possible with a uniform scatter of samples in each ore-shoot. For several reasons this was not a practical proposition. Firstly, many of the workings, especially the older levels, were inaccessible, and furthermore, in the accessible levels where the vein had been stoped above, the backs were often partially or completely timbered. It was thus impossible to obtain samples from these areas and there are necessarily some gaps in the overall picture. Secondly, the vein minerals, especially galena, tend to have an irregular and discontinuous distribution so that it was impossible for instance, to trace one band of galena from one level to another. This latter difficulty was not encountered to such a great extent with sphalerite and barite which were restricted mainly to the walls or margins of the vein, and vug linings, respectively.

2. Galena.

Spectrographic analyses were made of 57 galena samples from the Main Vein, 9 samples from other veins in the mine area, and 3 samples

from veins in the Brotherswater and Helvellyn areas.

A. Sample Preparation and Analysis.

The majority of the samples were composed of fairly coarse grained galena embedded in quartz or less commonly, silicified wall rock; it was therefore easy to prise out crystals or parts of crystals which were subsequently crushed to a fragment size of .5 mm. or less. The finer grained samples were crushed to a grain size required to release the mineral from the gangue. Using a fine paint brush, cleavage fragments of galena were picked out from the crushed material. This fraction was examined under a binocular microscope and untarnished gangue-free fragments were selected and transferred to a glass sample tube; about 200 mg. were needed. The samples were then crushed in an agate pestle and mortar to about 200 mesh.

As far as could be seen from under the binocular microscope most of the samples were free from impurities. Polished sections, however, revealed that in a few cases small quantities of quartz were present, and occasionally small inclusions of marcasite and tetrahedrite (samples H19 and K78 respectively).

The arced samples were composed of 50 mg. of galena sample, 50 mg. of 'Spec-pure' zinc oxide, and 100 mg. of pure carbon powder. The components were thoroughly mixed under ether, in an agate pestle and mortar.

In the spectrographic analysis carried out the Cathode-Layer Arc Method was employed. The method gives high sensitivity and good reproducibility of results. The instrument used was a Hilger Large Quartz Spectrograph (E742), with a 6 step sector. The spectrograms were

recorded on Ilford N 30 plates over the range 2450 - 3500 A.

The standard mixtures for use with the sphalerite samples were made up in a zinc sulphide base. The galena standards have a zinc sulphide-lead oxide base and were made by diluting the sphalerite standards with an equal weight of lead oxide. It was assumed that in the spectrographic arc the galena-zinc oxide mixture would behave in a similar as was the standard mixture of zinc sulphide-lead oxide. The carbon powder, zinc sulphide, zinc oxide and lead oxide were checked for purity and found to be satisfactory. The elements in the standards are Ag, Sb, Bi, Mn, Fe,Cd, in dilution steps of 10,000, 3000, 1000, 300, 100 and 30 p.p.m., and Ga, Ge, In, Sn and Co in dilution steps of 1000,300, 100, 30, 10 and 3 p.p.m. the sample spectrograms were directly compared with the standard spectrograms by means of a Hilger Projection Spectrum Comparator.

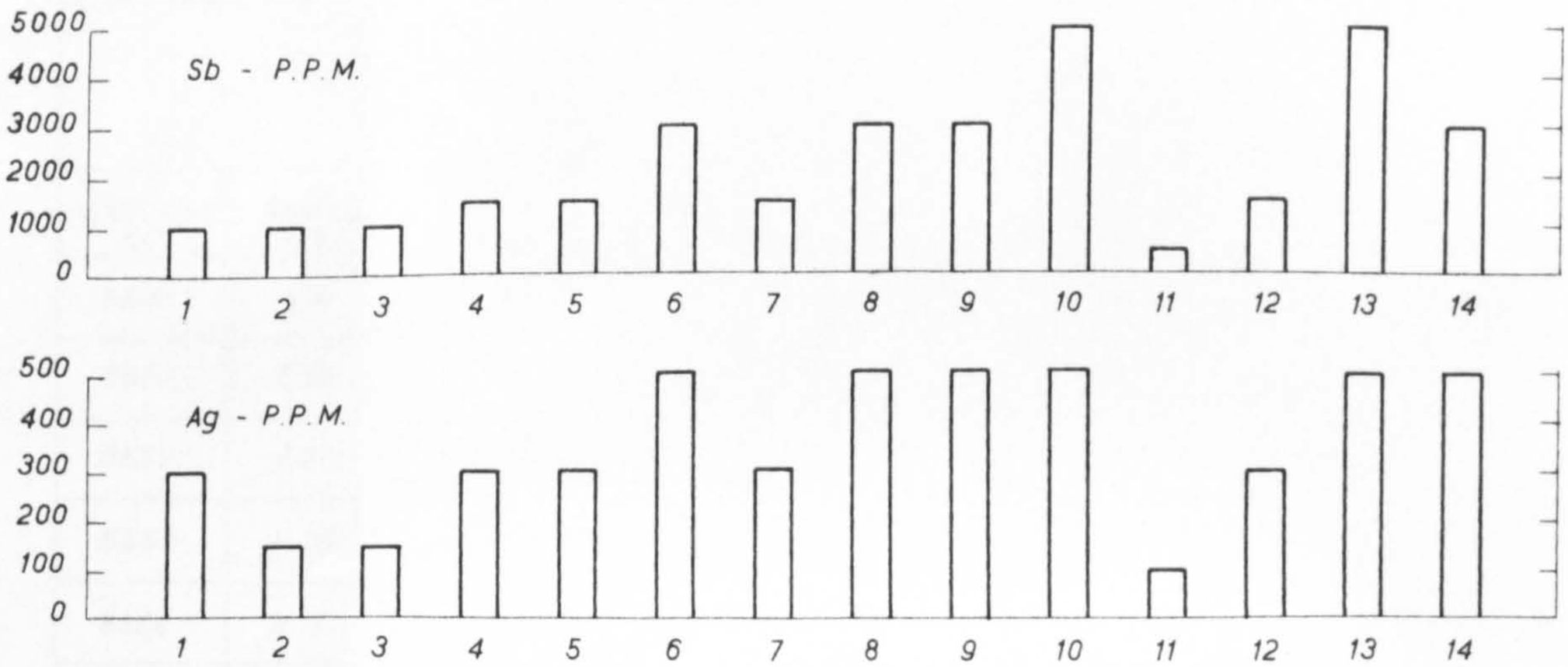
On each sample plate one standard was burnt and the intensity of the lines produced by the latter was compared with the lines of corresponding value on the standard plate. By this method any variation of the sensitivity of the emulsion could be allowed for. A few samples were arced several times as a check and the reproducibility was found to be very good. The results are semi-quantitative and have a standard deviation of $\pm$30%, provided the lines are neither too intense nor to close to the limits of detection. Table 7.1 shows the wavelength of the lines used for each element sought, together with the limits of detection.

(Table 7.1 overleaf)

FIG. 7.1 Ag AND Sb VALUES OF THE GALENA ACROSS THE MAIN VEIN AT 645 S, 175 FM LEVEL



SCALE
0 1 FOOT



D.G. 1962

TABLE 7-2 Ag AND Sb CONTENT OF GALENA SAMPLES FROM MAIN VEIN AT 645 S, 175 FM. LEVEL

SPEC. LAB. NO.	SAMPLE NO.	POSITION	AV. CRYSTAL SIZE MM. ACROSS	Ag P.P.M.	Sb P.P.M.	Sb/Ag RATIO	REMARKS
6360	K 195	1	2	300	1000	3	DISSD. ASSOCD. WITH SUGARY QTZ.
6361	K 196	2	5	150	1000	7	
6362	K 197	3	5	150	1000	7	
6363	K 198	4	5	300	1500	5	
6364	K 199	5	10	300	1500	5	ASSOCD. WITH LAMELLAR QTZ.
6365	K 200	6	3	500	3000	6	ASSOCD. WITH LAMELLAR QTZ.
6366	K 201	7	10	300	1500	5	ASSOCD. WITH SUGARY QTZ.
6367	K 202	8	15	500	3000	6	
6368	K 203	9	10	500	3000	6	
6369	K 204	10	10	500	5000	10	
6370	K 205	11	5	100	500	5	ASSOCD. WITH SUGARY QTZ.
6371	K 207	12	3	300	1500	5	DISSD.
6372	K 208	13	3	500	5000	10	DISSD. ASSOCD. WITH SUGARY QTZ.
6372	K 209	14	5	500	3000	6	

TABLE 7-6 TRACE ELEMENT CONTENT OF GALENA SAMPLES FROM BRANCH, CROSS, AND OTHER VEINS

SPEC. LAB. NO.	SAMPLE NO.	LEVEL	LATITUDE	AV. CRYSTAL SIZE MM. ACROSS	Bi P.P.M.	Mn P.P.M.	Sn P.P.M.	Ag P.P.M.	Sb P.P.M.	Sb/Ag RATIO	REMARKS
6334	A 5	HIGH HORSE	1050 N	2	100	5	10	150	3000	20	VEIN NEAR H.W. CONTACT OF DYKE, ASSOCD. WITH BARITE AND CPY.
6551	E 12	40 FM.	1277 N	5	30	5	10	300	1500	5	'FLIER' IN QTZ. PORPHYRY DYKE
6552	E 20	40 FM.	1425 N	5	30	5	10	500	3000	6	'FLIER' IN QTZ. PORPHYRY DYKE
6553	F 36	90 FM.	410 N	10	15	5	10	500	5000	10	LATE, CROSS CUTTING VEIN ON F.W. SIDE,(NO. 1 BRANCH)
6554	K 7	175 FM.	910 S	7	15	5	10	300	1500	5	DAWES VEIN, STRINGER IN SILICD. VOLCANICS
6559	K 189	175 FM.	1000 S	5	100	3	10	500	5000	10	DAWES VEIN, CENTRE OF VEIN
6557	K 143	175 FM.	1666 S	10	15	3	10	50	1000	20	348 W VEIN, STRINGER IN SILICD. VOLCANICS, ASSOCD. WITH BARITE
6558	K 150	175 FM.	1781 S	5	15	3	10	500	5000	10	348 W VEIN, CENTRE OF VEIN

banded structure, but is not symmetrical. However the thick bands of coarse grained galena are the last formed, as evidenced by the localised symmetry about a central vug. The great thickness of sugary quartz with finely disseminated galena and sphalerite, and of lamellar quartz with scattered clots of galena, found on the footwall side of the vein, is not apparently represented on the hanging-wall side.

Bismuth, manganese and tin show no measurable variation across the vein. All the values for these elements are near the limits of detection and thus have a rather larger standard deviation than $\pm$30%. The silver content varies from 100 to 500 p.p.m. and that of antimonyfrom 500 to 5000 p.p.m. The Sb/Ag ratio was worked out for each sample and is given in Table 7.2. The two elements were found to vary directly with each other, the greatest Sb/Ag values occuring at highest concentrations.

The pattern of variation is shown graphically in Fig.7.1. Antimony has a well defined maximum at position 10,near the centre of the vein, and another at position 13. Minor variations are superimposed on these maxima. The silver values correlate reasonably well with the antimony values. The values of the Sb/Ag ratio also reach maxima at positions 9 and 13. Samples 1 to 5, from the sugary and lamellar quartz on the hanging-wall side of the vein, show fairly low values of both elements. Similar low values are not found on the foot-wall side but this is probably accounted for by the absence of this early phase of mineralisation on this side. Samples 6 and7 on the hanging-wall side represented by samples 13, 14 and 11, 12 respectively on the foot-wall side show a fair degree of correlation in their silver and antimony contents. The last formed galena, represented by samples 8, 9, and 10 have similar, high

silver and antimony values.

(b) Variation Vertically and Laterally.

Table 7.3 shows the composition of 43 galena samples selected from the Main Vein throughout the mine. Section 6 shows the positions of the samples and their silver and antimony values.

The tin content is near the limit of detection, 10 p.p.m., and thus has a rather larger standard deviation than ±30%. No measurable variation was noted. The manganese content varies from 3 to 10 p.p.m. but there is no apparent directional variation. The bismuth content of the majority of the samples is between 10 and 30 p.p.m. Samples H 19, K 83 and K 55 have values of 100, 150 and 50 p.p.m. respectively. All three samples are from the centre of the vein and all have high antimony concentrations and, with the exception of K 55, high silver concentrations. It is notable however that other samples with equal or larger antimony and silver concentrations have only low bismuth values.

The silver content varies from 100 - 900 p.p.m. and the antimony content from 500 - 5,000 p.p.m. The two elements, as noted in the preceding section vary directly with each other, and the greatest Sb/Ag ratios are found at the highest concentrations.

As explained in the introduction it was impossible to select samples from the same generation of galena throughout the mine. The composition variation of the bands of galena across the vein has been shown to be very large - 100 to 500 p.p.m. for silver and 500 to 5000 p.p.m. for antimony. Bearing these considerations in mind, the weight that can be attached to a single value is small and the comparison of values from level to level must be made with extreme caution.

TABLE 7-3 TRACE ELEMENT CONTENT OF GALENA SAMPLES FROM MAIN VEIN

SPEC. LAB. NO.	SAMPLE NO.	LEVEL	LATITUDE	AV. CRYSTAL SIZE MM. ACROSS	Bi P.P.M.	Mn P.P.M.	Sn P.P.M.	Ag P.P.M.	Sb P.P.M.	Sb/Ag RATIO	REMARKS
6574	14	(SURFACE)	560 S	10	15	N.D.	10	100	1500	15	BAND ON H.W. SIDE
6575	15	(SURFACE)	20 S	10	15	N.D.	10	500	5000	10	STRINGER IN SILICD. VOLCANICS
6576	16	(SURFACE)	80 N	15	15	3	10	300	3000	10	STRINGER IN SILICD. VOLCANICS
6577	17	(SURFACE)	140 N	10	15	N.D.	10	500	5000	10	STRINGER IN SILICD. VOLCANICS
6578	18	(SURFACE)	200 N	10	15	N.D.	10	300	3000	10	CENTRE OF VEIN
6579	19	(SURFACE)	2140 N	3	15	10	10	300	1500	5	DISSD. IN SILICD. VOLCANICS
6335	C 4	70 FOOT SUB-LEVEL	1510 N	20	15	5	10	100	1000	10	STRINGERS IN QTZ PORPHYRY, F.W.
6336	C 5	70 FOOT SUB-LEVEL	1510 N	10	15	5	10	100	500	5	
6550	C 11	70 FOOT SUB-LEVEL	1620 N	10	15	5	10	100	500	5	STRINGER IN SILICD. VOLCANICS
6337	C 7	ALMA	1400 N	10	30	10	10	100	1500	15	CENTRE OF VEIN
6338	D 51	LUCY	1350 N	3	15	5	10	150	1500	10	
6339	D 52	LUCY	1300 N	30	15	5	10	300	1500	5	CENTRE OF VEIN
6340	D 12	LUCY	400 S	10	15	5	10	150	1000	7	CENTRE OF VEIN, ASSOCD. WITH BAR.
6341	S 4	20 FM.	590 N	15	15	3	10	300	1500	5	VEIN IN H.W.
6342	S 19	20 FM.	800 N	10	15	3	10	300	1500	5	H.W. SIDE OF VEIN
6343	E 26	40 FM.	1344 N	10	10	5	10	150	1000	7	CENTRE OF VEIN
6344	E 42	40 FM.	1158 N	10	10	5	10	300	1500	5	CENTRE OF VEIN
6345	F 7	90 FM.	226 S	25	10	5	10	150	1500	10	LARGE CUBES EMBEDDED IN SILICD. QTZ. PORPHYRY, F.W.
6346	F 31	90 FM.	323 N	10	10	3	10	100	1500	15	ASSOCD. WITH CPY.
6347	F 39	90 FM.	438 N	5	10	3	10	300	3000	10	LATE, CROSS CUTTING 5 MM. WIDE BAND
6348	F 47	90 FM.	523 N	5	15	10	10	300	3000	10	FROM ZONE OF IRREGULAR VEINLETS IN SILICD. VOLCANICS
6349	F 51	90 FM.	868 N	25	15	3	10	150	3000	20	CENTRE OF VEIN

TABLE 7-3 (CONTD. FROM OVERLEAF)

SPEC. LAB NO.	SAMPLE NO.	LEVEL	LATITUDE	AV. CRYSTAL SIZE MM. ACROSS	Bi P.P.M.	Mn P.P.M.	Sn P.P.M.	Ag P.P.M.	Sb P.P.M.	Sb / Ag RATIO	REMARKS
6350	F 62	90 FM.	1186 N	5	30	5	10	300	1500	5	CENTRE OF VEIN
6351	G 53	120 FM.	175 S	10	10	3	10	150	1000	7	IRREGULAR STRINGERS IN H.W. ASSOCD. WITH PY.
6352	G 74	120 FM.	277 S	25	10	3	10	150	1500	10	IRREGULAR STRINGER IN QTZ. PORPHYRY
6353	G 28	120 FM.	1007 N	10	30	3	10	300	1500	5	CENTRE OF VEIN
6354	G 75	120 FM.	1425 N	10	10	3	10	300	3000	10	1 1/2 FT. WIDE VEIN IN F.W.
6355	G 79	120 FM.	1430 N	20	15	3	10	300	3000	10	CENTRE OF VEIN MASSIVE
6356	H 19	135 FM.	398 S	10	100	3	10	300	5000	17	CENTRE OF VEIN
6357	H 8	135 FM.	14 N	10	15	3	10	300	5000	17	H.W. SIDE OF VEIN ASSOCD. WITH CPY.
6358	J 9	150 FM.	68 N	7	15	3	10	300	3000	10	CENTRE OF VEIN
6359	J 6	150 FM.	102 N	5	15	3	10	300	5000	17	CENTRE OF VEIN
6360	J 2	150 FM.	293 N	20	15	5	10	150	1500	10	H.W. SIDE OF VEIN
6362	K 191	175 FM.	512 S	40	15	5	10	150	1500	10	CENTRE OF VEIN
6556	K 110	175 FM.	246 S	7	15	3	10	150	500	3	STRINGER IN SILICD. VOLCANICS OR DOLERITE
6363	K 97	175 FM.	366 N	5	30	5	10	300	1500	5	CENTRE OF VEIN
6555	K 86	175 FM.	803 N	10	15	3	10	300	3000	10	STRINGERS IN SILICD. VOLCANICS
6364	K 83	175 FM.	992 N	5	150	3	10	300	3000	10	CENTRE OF VEIN
6365	K 78	175 FM.	1085 N	2	30	3	10	500	5000	10	CENTRE OF VEIN, SHEARED AND STEELY
6366	K 55	175 FM.	1523 N	20	50	3	10	150	3000	20	CENTRE OF VEIN
6367	K 53	175 FM.	1608 N	10	15	3	10	100	1000	10	CENTRE OF VEIN
6368	K 50	175 FM	1608 N	5	30	5	10	150	3000	20	CENTRE OF VEIN
6349	K 24	175 FM.	2069 N	5	15	5	10	300	3000	10	SCATTERED CRYSTALS IN SILICD. VOLCANICS

NOTES: N.D. = NOT DETECTED DISSD. = DISSEMINATED SILICD. = SILICIFIED F.W. = FOOT WALL H.W. = HANGING-WALL

The silver and antimony values of the samples were therefore averaged and the results are shown in Table 7.4. However no significant variation from depth to surface is revealed.

The silver content of the galena produced at the mine between the years 1835 and 1960 has been calculated from production and assay records (Table 7.5). From 1835 to 1903 the concentrates were smelted and desilverised at the mine, and the silver values for this period have been calculated from silver production figures. The silver values for the period 1904 to 1960 have been computed from assay data in the Ministry of Power records.

Because of the limitations described previously , a perfect correlation of the silver assay-production values and the spectrographic values would not be expected. In contrast to the large variation of the silver content of the individual samples,revealed by spectrographic analysis, (100 - 500 p.p.m.), the total range of the 'bulk analyses' is smaller (215 - 390 p.p.m. of silver). The patterns of variation of the spectrographic and assay-production values show little correlation. The latter values show a marked decrease as mining proceeded to deeper and deeper levels. However the decrease is not altogether uniform and there was a temporary increase in the silver content during the period 1921 to 1928.

During the period 1935 - 1960 the major tonnage of ore was mined from blocks located between the 237 fm. and 90 fm. levels. Since the ore was drawn from several sources simultaneously, it is difficult to ascertain the specific silver values of the individual blocks. However, Section 6 shows the estimated silver values of various blocks throughout the mine, based on information supplied be H.E.Evans (personal communication).

Table 7.4. Average Antimony and Silver Contents of Samples from each level

No. of Samples	Av. Sb p.p.m.	Av. Ag p.p.m.	Level
6	3200	330	(surface)
4	900	100	Alma and 70 S.L.
3	1300	200	Lucy
2	1500	300	20 fm.
2	1300	230	40 fm.
6	2800	220	90 fm.
5	2000	240	120 fm.
2	5000	300	135 fm.
3	3200	250	150 fm.
24*	2300	300	175 fm.

* - 14 samples at 645 S included.

Table 7.5 Silver content of the galena produced between the years 1835 and 1961

Period	Average silver content of galena	Approx. source of ore
1835 - 1844	380	High Horse - surface
1845 - 1854	390	Low Horse - surface
1855 - 1864	360	36 fm. - surface
1865 - 1874	350	48 fm. - surface
1875 - 1884	325	Lucy - High Horse
1885 - 1894	250	40 fm. - Lucy
1895 - 1904	250	90 fm. - Lucy
1905 - 1913	295	90 fm. - Lucy
1914 - 1920	no data	
1921 - 1928	305	150 fm. - Lucy
1929	no data	
1930 - 1934	275	150 fm. - Lucy
1935 - 1938	no data	
1939 - 1948	255	mainly below 90 fm.
1949 - 1960	215	mainly below 90 fm.

These values are rather erratic and are insufficient in number to delineate the overall pattern observed in the assay production values. The 'anomalous' fluctuations in the overall pattern can probably be related to such erratic silver values of some blecks.

It was found in the majority of cases that, at any single point throughout the mine, galena samples from stringers in the wall rock or from the margins of the vein have lower silver and antimony values than samples from the centre of the vein. This is in agreement with findings noted in the preceding section (P.179). Samples F 39 was collected from a band of galena that cuts through the Main Vein. The silver and antimony content of this late generation galena (Stage 2 of the paragenetic sequence) is higher than that of galena from the Main Vein in this area.

The maximum conentrations of both antimony and silver, as recorded in the summary of previous work by Fleischer (1955), is 3%. Some of the high values are probably due to intergrowths of antimony and silver minerals, but many samples are said to be homogeneous, as far as can be determined under the reflecting microscope. It is uncertain whether the tetrahedrite inclusions, noted in sample K 78, are due to exsolution (see P.170). Etching with nitric acid revealed no other inclusions or intergrowths of foreign minerals. Zoning of the galena crystals (revealed by etching) is perhaps indicative of a variation of the trace element content during growth.

Nesterova (1958) believes that most of the minor elements in galena can be attributed to sub-microscopic intergrowths of separate minerals. Such intergrowths, if present, are probably in most cases, the result of exsolution rather than replacement, so that the usefulness of the study is in no way diminished, since the analyses indicate the primary content at

the time of deposition, before exsolution took place.

Marshall and Joensuu (1961) have recently studied the relation between the trace element content and crystal habit of galena samples collected from the Upper Mississippi Valley district, the Picher field, and southwestern U.S.A.. The workers made a quantitative determination of the relative dominance of the cubic and octahedral crystal habits. They concluded that the octahedral habit tends to develop with low antimony concentrations but that the silver and bismuth contents do not affect the crystal habit; low temperatures were found to favour the formation of the cubic rather than the octahedral form. Most of the Greenside samples were unsuitable for a quantitative estimation of crystal habit, but qualitative observations revealed no relation between crystal habit and the trace element content; there is also no significant variation of crystal habit either across the vein, or laterally and vertically throughout the orebody.

The grainsize of the galena is also independent of the trace element content. This conclusion is in contrast to that of Fischendorf (1953) who found that in the fluorite-barite-lead deposit of Freiberg, E. Germany, the bismuth, silver and antimony contents of the galena dropped significantly as the average grain size of the mineral increased. Fine grained galena from Cardiganshire and Merionethshire also tends to have higher antimony and silver values than coarse grained galena from the same areas (El Shazly, 1951). The latter worker also found that sheared galena has a higher antimony content than undeformed galena from the same area. The sheared galena at Greenside is restricted to a narrow zone adjacent to the North Fault; the single sample (K 78) from this zone shows a high

silver and antimony values, which are, however, similar to the undeformed galena further from the fault.

Apart from quartz, the galena from the Main Vein may be associated with barite, sphalerite and chalcopyrite. The presence or absence of these minerals does not appear to influence the galena composition. Samples from stringers in the wall rock and from the centre of the vein tend to have low and high silver and antimony values respectively, as noted previously. The occurrence of sphalerite in the former environment and barite in the latter is probably an indirect relation.

(c) Trace Element Content of Galena from Other Veins.

Table 7.6 shows the trace element content of galena samples from veins, apart from the Main Vein, within the mine area. The composition of these galenas is basically similar to that of the Main Vein thus indicating that the veins are a result of the same general period of mineralisation. The veins which can be referred to Stage 2 of the paragenetic sequence, generally have fairly high silver and antimony values, for example the No. 1 Branch.

The mineral composition of the 348 W Vein, found on the 175 fm. level, is very different from the Main Vein on the same level. The galena from the centre of the vein which is associated with spalerite and chalcopyrite, has a high antimony content and especially silver content. The sample which is associated with barite was probably formed later than the latter sample. The silver and antimony content are however very low.

Galena samples from the Brotherswater and Helvellyn areas were also analysed (Table 7.7). The trace element contents are essentially similar to the Greenside Vein, thus further substantiating their similar age.

TABLE 7-7 TRACE ELEMENT CONTENT OF GALENA SAMPLES FROM VEINS IN THE BROTHERSWATER AND HELVELLYN AREAS

SPEC. LAB. NO.	SAMPLE NO.	AV. CRYSTAL SIZE MM. ACROSS	Bi P.P.M.	Mn P.P.M.	Sn P.P.M.	Ag P.P.M.	Sb P.P.M.	Sb / Ag RATIO	REMARKS
7091	208	2	10	3	N.D.	300	1500	5	MYERS HEAD VEIN, DUMP MATERIAL, DISSD. IN QTZ. ASSOCD. WITH SPHAL. AND CPY.
7092	209	5	10	N.D.	10	500	10000	20	HARTSOP HALL VEIN, DUMP MATERIAL FROM LR. LEVEL, ASSOCD. WITH BAR. AND FLUOR
7093	210	5	10	N.D.	N.D.	500	5000	10	EAGLE CRAG VEIN, DUMP MATERIAL, ASSOCD. WITH QTZ. AND MINOR CPY.

TABLE 7-9 TRACE ELEMENT CONTENT OF SPHALERITE SAMPLES FROM MAIN VEIN

SPEC. LAB NO.	SAMPLE NO.	LEVEL	LATITUDE	AV. CRYSTAL SIZE MM. ACROSS	Co P.P.M.	Sn P.P.M.	Bi P.P.M.	In P.P.M.	Ga P.P.M.	Ge P.P.M.	Sb P.P.M.	Mn P.P.M.	REMARKS
6451	C 11	70 FOOT SUB LEVEL	1620 N	5	3	50	30	150	100	300	150 (Pb)	5	STRINGER IN SILICD. VOLCANICS
6452	C 12	70 FOOT SUB LEVEL	1600 N	10	3	30	30	100	100	300	100	15	TENSION GASH IN QTZ. PORPHYRY
6453	D 11	LUCY	370 S	3	10	30	30	50	50	150	500	10	STRINGER IN SILICD. VOLCANICS
6454	D 19	LUCY	1300 N	4	30	30	30	150	150	100	500	5	ASSOCD. WITH LAMELLAR QTZ.
6461	S 15	20 FM.	790 N	2	3	30	30	300	300	50	300	3	BRECCD. SILICD. VOLCANICS, INFILLING OF SPHAL.
6455	E 12	40 FM.	1277 N	3	10	50	30	150	150	300	1500 (Pb)	3	STRINGER IN SILICD. QTZ. PORPHYRY
6456	G 34	120 FM.	982 N	3	3	30	30	50	100	300	1000 (Pb)	10	STRINGERS (PROBABLY LATE GENERATION) IN QTZ.
6457	G 51	120 FM.	162 S	1	10	50	30	300	300	100	1000 (Pb)	5	FRAGMENTS OF SILICD. VOLCANICS RIMMED BY SPHAL. AND ENCLOSED BY QTZ.
6458	J 17	150 FM.	66 S	3	15	150	30	150	150	100	300 (Pb)	150	ASSOCD. WITH LAMELLAR QTZ.
6459	K 7	175 FM.	910 S	3	3	30	30	150	50	150	150 (Pb)	15	STRINGER IN SILICD. VOLCANICS (DAWES VEIN)
6460	K 52	175 FM.	1588 N	2	3	30	30	100	150	100	150	30	STRINGER IN SILICD. VOLCANICS OR QTZ. PORPHYRY.

These analyses and others will be treated in greater detail in Chapter 8 which concerns the regional aspects of mineralisation.

(d) General Conclusions.

The large variation in the composition of successive galena bands across the vein suggests that mineralisation was not a continuous process but rather consisted of a succession of phases or pulses. From the earliest to the last phases of Stage 1 of the mineralisation there was an overall increase in the silver and antimony concentrations in the galena precipitated. The increase was not gradual but occurred in a series of steps, corresponding to the pulses, some of which were however associated with a temporary decrease in the silver and antimony content of the galena. In general the antimony concentration increased at a rate greater than that of silver.

The large variation of the minor element content in successive galena generations across the vein is in marked contrast to the small variation of the bulk silver analyses from depth to surface. Throughout the mine, however the range of variation of successive bands of galena across the vein is similar so that it may be deduced that all the pulses of mineralisation caused precipitation of galena, both in open fissures near the source of the solutions and also in fissures much further away. However, the mass of galena precipitated by the earliest pulses of mineralisation tended to be concentrated at depth while the mass of galena precipitated by subsequent pulses t nded to increase upwards.

Following this first stage of mineralisation minor fracturing took place locally, followed soon after by further mineralisation (Stage 2) along the fissures formed, for example the No. 1 Branch. Other veins in the mine area are probably associated with this stage of mineralisation,

characterised by high antimony and silver values.

The positions of the main conduits of the mineralising solutions were described in a preceding chapter. The high silver values at 1000N between the 175 fm. and 150 fm. levels, may perhaps be due to a late generation of galena which was precipitated within the conduit, perhaps as a result of the trapping of the mineralising solution.

3. Sphalerite.

A. Sample Preparation and Analysis.

The procedure in this case was exactly the same as that employed in the preparation and analysis of the galena samples, except that the arced samples were composed of 100 mg. of sphalerite sample and 100 mg. of pure carbon powder. Examination under the ore microscope revealed small quantities of galena, chalcopyrite, tetrahedrite and quartz in a few samples. The table on p.178 shows the wavelengths of the lines used for each element sought, together with the limits of detection.

B. Iron Content.

Table 7.8 shows the iron content of 10 sphalerite samples from the Main Vein. The exact position of the samples is indicated in Table 7.8 and also in Section 6.

The colour of the growth zones of sphalerite crystals has been described previously (p.168). The iron content of individual growth zones was not determined and the values given in Table 7.8 are thus the average of all the growth zones composing the crystals. All the values are greater than 10,000 p.p.m. (the top standard) and thus are only approximate. Insufficient quantity of each sample precluded analysis by X-ray fluorescence but a bulk analysis of equal proportions of samples 6452,-4,-5,-6,-8,-9

and 6461 by this method indicated 2.0% Fe (±40%), showing that the spectrographic values are of the correct order of magnitude.

The iron content of the sphalerite samples from the Main Vein (excluding sample G34 which is of late formation) tends to increase with depth. Whether this trend is a function of the temperature of formation will be discussed later.

Table 7.8 Iron content of sphalerite from the Main Vein.

Spec. Lab. No.	Sample No.	Level	Fe Wt.% (very approximate)
6451	C11	70's-l.	1.5
6452	C12	70's-l	2.0
6453	D11	Lucy	2.0
6454	D19	Lucy	1.5
6461	S15	20fm.	1.5
6455	E12	40fm.	1.5
6456	G34	120fm.	1.5
6457	G51	120fm.	2.5
6458	J17	150fm.	2.0
6469	K52	175fm.	3.0

Barton and Sims (1961) have suggested that sphalerite which is precipitated from a solution which is in contact with earlier formed pyrite, is saturated with respect to iron. The requirements for the application of the Fe-Zn-S system for geothermometry will, however, only be realised provided there is clear evidence of corrosion of the earlier pyrite.

Such evidence is lacking for the Greenside samples and therefore only a minimum temperature of formation can be determined. Assuming the total range of the sphalerite growth zones at Greenside is 0.5 - 4% Fe (approx. 1-7 mole % FeS) then the range of minimum temperature (from Fig. 7.2) is 100°C to 320°C, at a pressure of 1 atmosphere *. If the deposit was formed at a pressure of 1000 atmospheres (approximately equivalent to a depth of 2.5 miles) the above temperatures must be increased by approximately 25°C.

C. Trace Element Content.

The trace elements sought in the sphalerite samples were Co, Sn, Bi, Cd, In, Ga, Ge, Sb, and Mn. The spectrographic technique employed has poor sensitivity for As, Hg, Se and Tl, while the presence of Pb, Ag and sometimes Cu can usually be attributed to impurities. These elements were not therefore sought.

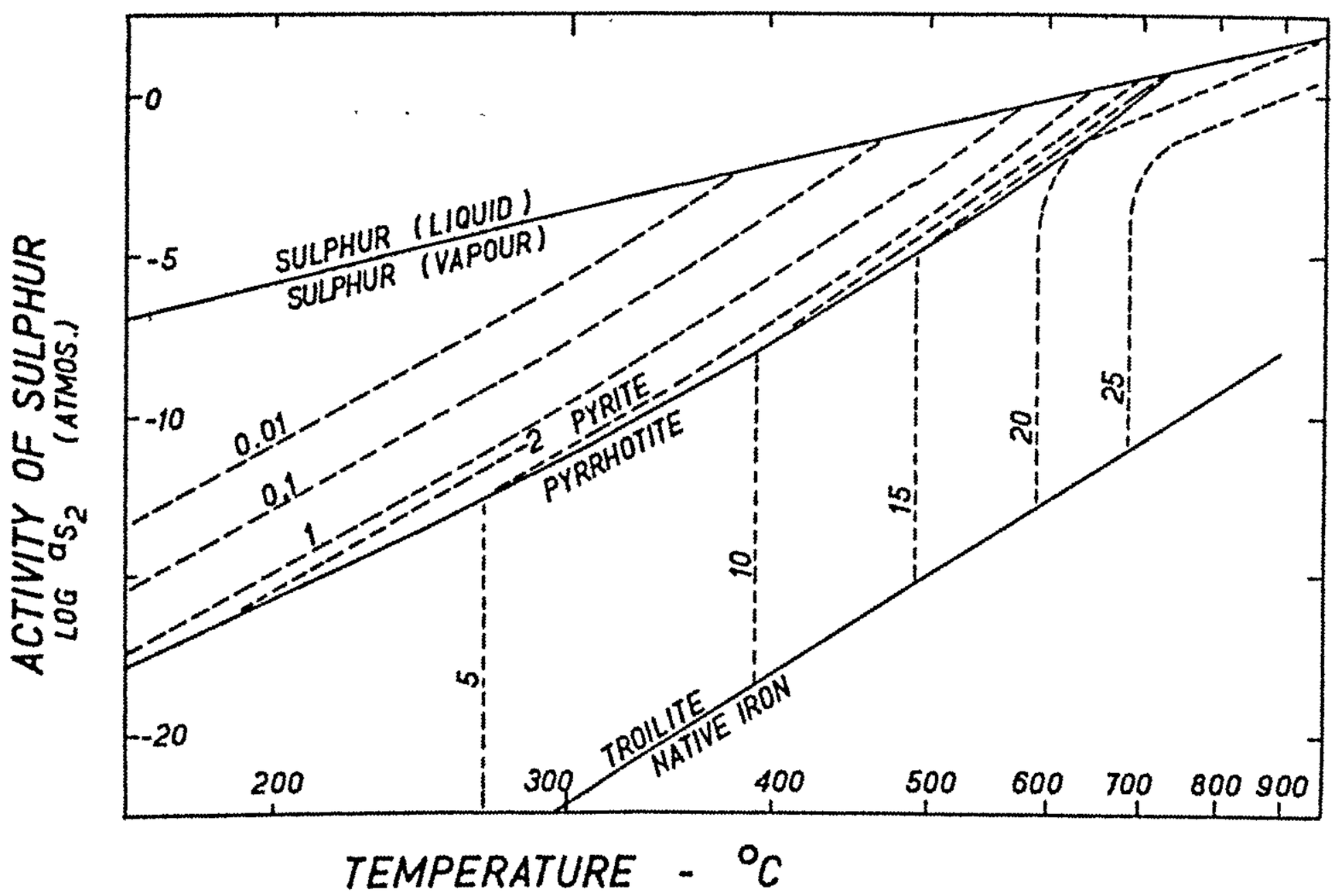
Table 7.9 shows the trace element content of 11 sphalerite samples, all of which, excepting sample K 7, are from the Main Vein. Section 6 shows the positions of the samples and their indium and germanium concentrations.

The majority of the Main Vein samples are from stringers in the wall rock or from the margins of the vein. The concentrations of cobalt, tin, bismuth, and manganese, in most of the samples varies from 3-15, 30-50, 15-30 and 3-30 p.p.m., repectively; there is no significant variation either vertically or laterally. One sample, J17, has a content

*This temperature determination is based partly on Kullerud's data, some of which has recently been found to be inaccurate and is being currently revised.

FIG. 7.2 STABILITY FIELDS OF THE Fe-Zn-S SYSTEM

(AFTER BARTON AND SIMS, 1961)



1 MOLE % FeS IN SPHALERITE

of 150 p.p.m. of both tin and manganese; it may be significant that the Main Vein at which point this sample was collected, cuts a quartz-pyrite vein, and it is conceivable that local remobilisation of the trace elements in the pyrite has taken place during the later lead-zinc mineralisation.

The cadmium content (not shown in Table 7.10) varies from 5000 to 10,000 p.p.m.; there is no significant trend either vertically or laterally. Most workers have found that the cadmium content of the sphalerite is apparently independent of the conditions of formation (Fleischer, 1955). The manganese content of sphalerite generally follows that of iron, but no such relationship is exhibited by the Greenside samples.

The concentration of antimony varies from 100 - 1500 p.p.m. Some of the high values are due to the presence of small amounts of galena and tetrahedrite, but other samples are apparently free from such impurities. The samples in which lead, due to the presence of galena, was detected are shown in Table 7.9 thus - (Pb). It is uncertain whether the tetrahedrite inclusions in the sphalerite are the result of exsolution or of simultaneous crystallisation. The antimony values of apparently uncontaminated samples are rather high compared with the concentration found in most sphalerite samples. There are too few values to delineate a trend either vertically or laterally.

The wealth of data on the trace element content of sphalerite (Fleischer, 1955) has shown that in most cases the gallium and germanium concentrations vary antipathetically with temperature while indium , on the other hand, is sympathetic with temperature. The indium and germanium values of the Greenside samples tend to vary inversely, but the

gallium values are erratic. Only germanium values show a significant trend throughout the orebody, the decrease with depth probably being related to an increase in the temperature of formation. The high germanium and low indium content of the late generation sphalerite (sample G 34) suggests that it was formed at a similar temperature to that of the Main Vein sphalerite from the upper levels.

4. Barite.

The strontium content of the 18 barite samples from the Main and other veins was determined by X-ray fluorescence analysis.

A. Sample Preparation and Analysis.

Most of the samples were coarse grained, well developed cock's - comb aggregates being fairly common. The samples were crushed to a fragment size of 1 mm. or less. Using a camel-hair brush, clean cleavage fragments were selected and transferred to a glass tube; about 2 gms. were required. The samples were then crushed in an agate pestle and mortar to about 200 mesh.

Although barite is often associated with several other minerals, these were easily separated as a result of the initial crushing. Examination under the binocular microscope showed the selected barite fraction to be generally free from impurities.

The analyses were carried out by Dr.J.R.Butler of the Pure Geochemistry Department of the Royal School of Mines. The standards were composed of $BaSO_4$ with additions of $SrCO_3$ in the range 0.1 - 2.5% Sr. Estimations were made by comparing the scanned K_a radiation intensities produced by the samples with those produced by the standards. The results have a standard deviation of $\pm$ 15%.

B. Results and Conclusions.

Table 7.10 shows the strontium content of 18 barite samples collected from the Main Vein, branches and 'fliers' associated with the latter, the Hicks Vein, and the 348 W Vein. Section 7 shows in addition to the strontium values, the positions of the samples.

The distribution and mode of occurrence of barite has been described in the preceding chapter. Barite from the Main Vein is found in three main environments :-

(a) In central infillings or vugs.

(b) In narrow veins containing no other minerals.

(c) Throughout the vein, but often partially or completely replaced by quartz.

The barite from environment (a) was assumed to have been formed at essentially the same time throughout the mine. Several phases of mineralisation are probably represented by the barite of environments (b) and (c).

The strontium content of the barite samples from the Main Vein varies from 0.24 to 1.82%. The samples from environment (a), the most common environment, show no significant variation either vertically or laterally. The range of strontium content, even over short distances on the same level is very great, for example samples S9 and S18 (contents 1.82 and 0.26% Sr respectively). The barite samples from environments (b) and (c) show erratic values and no conclusions can be drawn. The strontium content of the samples from other veins varies from 0.48 to 2.09%, and again the values are erratic.

Campbell (1959) has studied the strontium content of barite from the Torbrit Silver Mine B.C. Using data by Goldschmidt (1938) and Gordon

TABLE 7-10 Sr CONTENT OF BARITE SAMPLES FROM THE MAIN AND OTHER VEINS

SPEC. LAB. NO	SAMPLE NO	LEVEL	LATITUDE	Sr %	REMARKS
6580	20	(SURFACE)	520 S	.30	H.W. SIDE, MAIN VEIN
6581	21	(SURFACE)	240 N	.54	FROM VUG, MAIN VEIN
6582	22	(SURFACE)	760 N	1.63	FROM MAIN VEIN, BARREN ZONE
6583	23	(SURFACE)	2140 N	1.50	MAIN VEIN, ASSOCD. WITH QTZ.
6095	A 4	HIGH HORSE	1640 N	.89	FROM MAIN VEIN, BARREN ZONE
6093	B 6	LOW HORSE	1610 N	.42	BRANCH VEIN IN H.W., FROM VUG
6094	D 12	LUCY	400 S	.64	MAIN VEIN, CENTRAL VUG
6100	S 9	20 FM.	625 N	1.82	MAIN VEIN, VUG ON H.W. SIDE
6101	S 16	20 FM.	800 N	.67	H.W. SIDE, MAIN VEIN
6102	S 18	20 FM.	800 N	.26	MAIN VEIN, CENTRAL VUG
6098	E 42	40 FM.	1158 N	.24	CENTRE OF MAIN VEIN
6097	E 26	40 FM.	1344 N	1.57	CENTRE OF MAIN VEIN
6096	E 20	40 FM.	1425 N	2.09	'FLIER' IN QTZ. PORPHYRY
6103	F 34	90 FM.	445 N	.40	MAIN VEIN, CENTRAL VUG
6104	K 144	175 FM.	1700 S	.78	348 W VEIN
6099	S 1	20 FM.	580 N	.48	HICKS VEIN

et al (1954) he illustrated graphically the relation of the strontium content of the barite and that of solution precipitating it. It was concluded from this experimental data that the concentration of strontium in barite depended on the concentration of strontium in the solution and the temperature, the Sr/Ba ratio of the barite becoming greater as temperature increased.

The large and erratic variation of the strontium content of the barite samples from a single environment at Greenside probably reflects changes of the composition of the solution rather than changes of temperature, although both factors were probably operative. Campbell reached a similar conclusion for the barite at the Torbrit Silver Mine.

5. Physicochemical Conditions during Ore Deposition.

The structural environment of the Greenside Vein, the banded, crustified vein-structure and the negligible amount of replacement indicate that this ore deposit is best referred to the leptothermal category, as defined by Dunham (1950). However the wall rock alteration associated with ore deposits of the leptothermal category is stated to be feeble, while the wall rock alteration at Greenside is extensive in parts of the lower levels of the mine. The Greenside Vein cannot be genetically related to any known igneous intrusion. Lead isotope data on the Greenside galena (Moorbath, 1962) indicate a Hercynian age, but no Hercynian acid intrusions are known in the north of England.

There are various lines of evidence by which a rough estimate of the temperature of formation of the Greenside Vein may be obtained. The iron content of the sphalerite, as noted previously, indicates a minimum

temperature of approximately 100 - 320°C. This of course is not necessarily a minimum temperature for the vein as a whole, but only the minimum temperature for the early part of Stage 1 of the mineralisation. The presence of marcasite in vugs and as inclusions in galena indicates an upper temperature of 450°C, since above this temperature the mineral is rapidly converted to pyrite (Ingerson, 1955). The quartz of the Greenside Vein was originally precipitated as α-quartz, and is sometimes chalcedonic. High β-quartz inverts to α-quartz at approximately 573°C, but this temperature is influenced by any impurities present. The presence of chalcedony at Greenside is suggestive of low temperatures but no quantitive estimation can be made. The absence of exsolved chalcopyrite in sphalerite indicates that the latter was formed below 350 -400°C (Buerger, 1934). Hydrothermal synthesis of minerals has shown that sericite, which is found in the altered wall rocks at Greenside, formed between 100°C and 550°C (Stringham, 1952). This lata on geothermometry is summarised below:-

		Indicated Temperature -°C.
1.	Fe content of sphalerite	100-320
2.	marcasite-pyrite	< 450
3.	quartz	< 573
4.	sphalerite-chalcopyrite	350-400
5.	sericite	100-550

It is concluded that the range of the temperature of formation probably lies between 100°C and 400°C.

The genetic classification, paragenisis, and zoning of ore deposits are clearly inter-related, all depending on the physicochemical conditions

FIG. 6.20/ FIG. 7.3 PARAGENESIS OF THE VEIN MINERALS

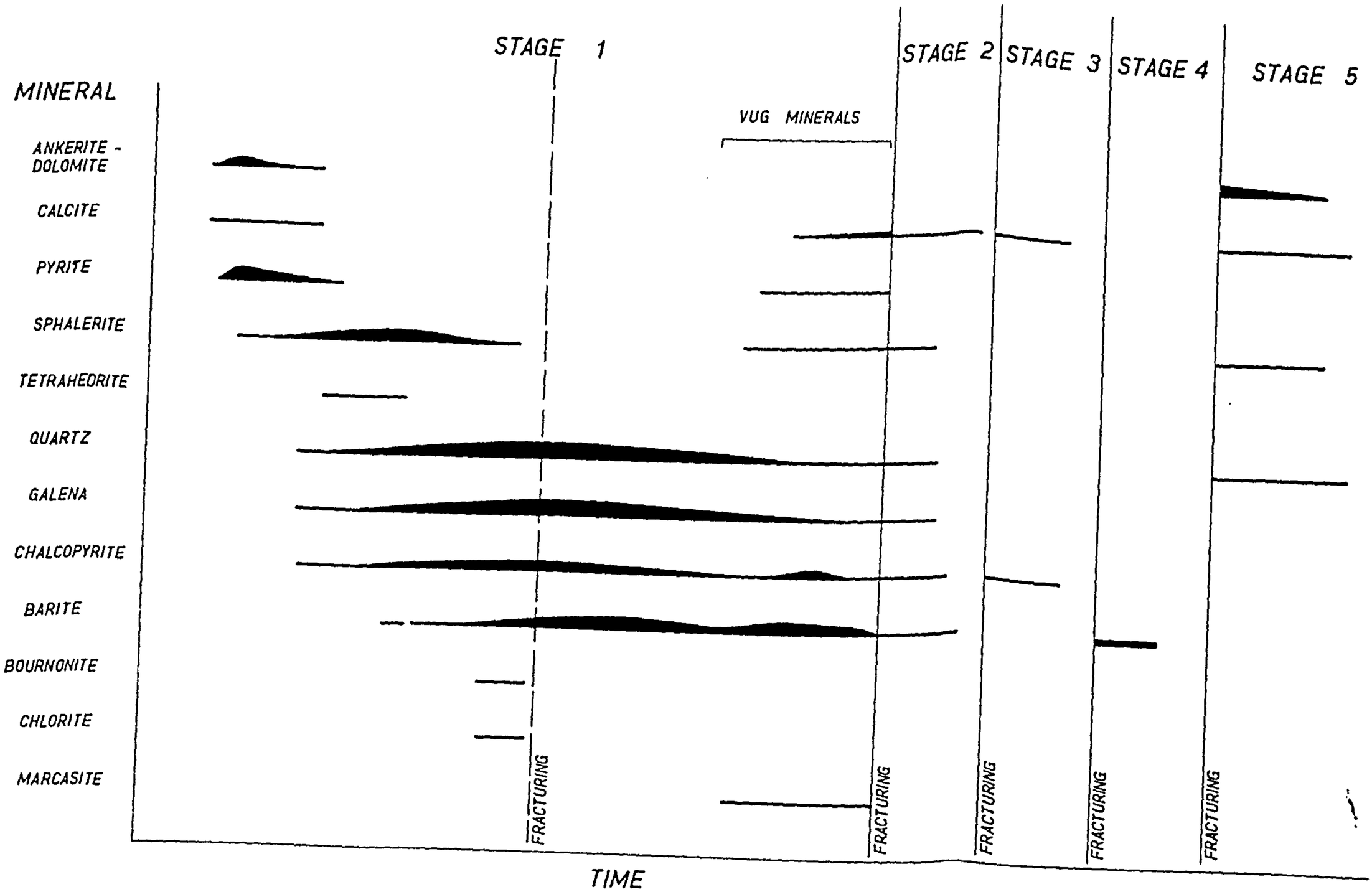
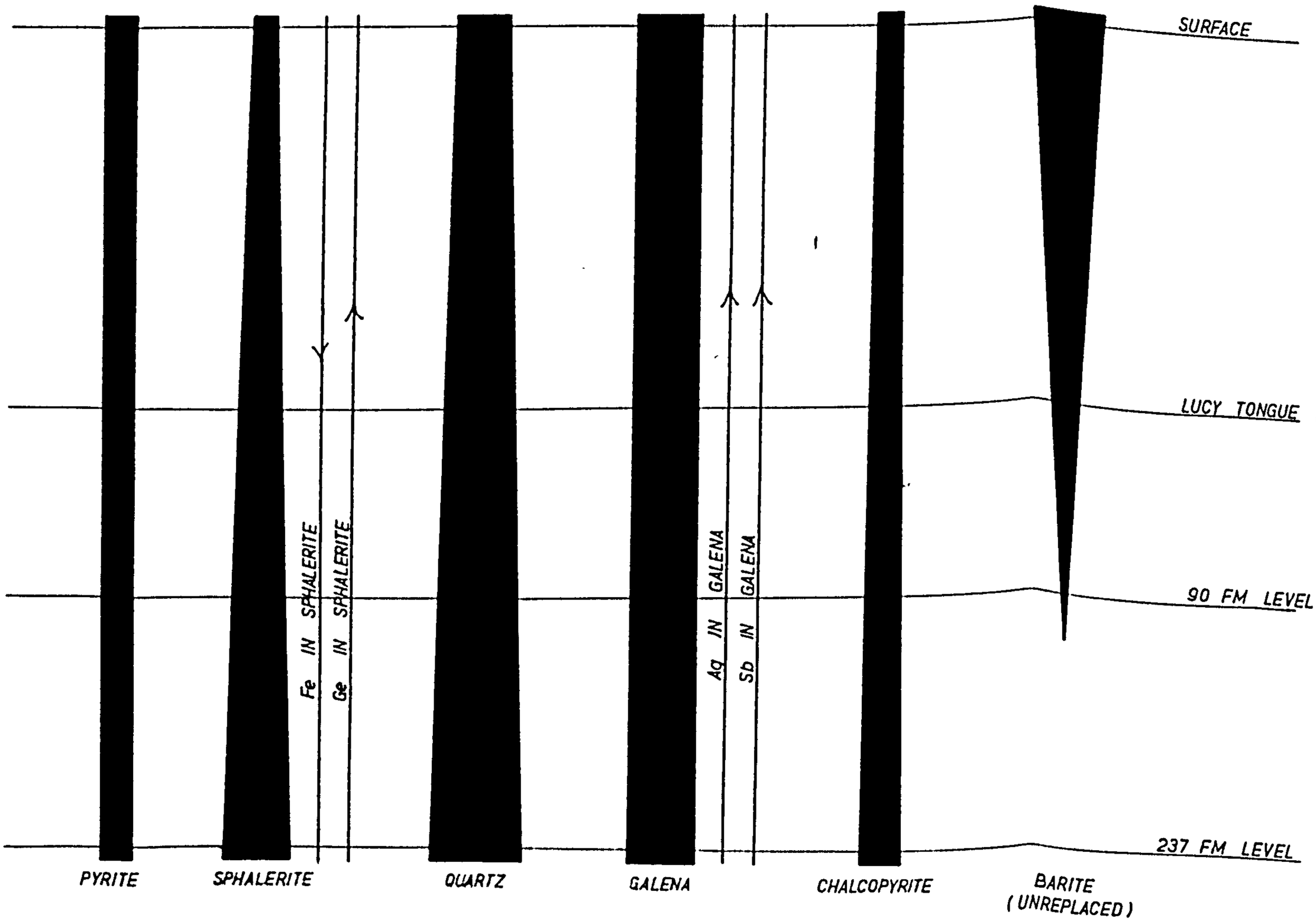


FIG. 7.4 DISTRIBUTION OF THE MAJOR VEIN MINERALS



D. G. 1962

during ore deposition. The term zoning is here used merely to describe the d stribution of the minerals and has no genetic implications. Fig. 7.3 shows the distribution of the minerals and the minor elements contained in them; Fig. 7.4 is a duplicate of the paragenesis table shown on p. 172 for comparison. As in most zoned deposits, the minerals are progressively of older formation as the depth increases. However the barite in the vein which is partially replaced by quartz (environment (c)) shows a secondary zonal distribution which reflects the extent of silicification. There is no apparent lateral zoning.

The wealth of data on zoned ore deposits (Park,(1955) gives an excellent bibliography) indicates that a definite sequence of minerals , and a similar world-wide zoning pattern is an established fact. The causes of zoning, however, lie in the realm of theory and are still unknown.

Basically, the zoning of any deposit may result from one or both of the following processes, as suggested by Bradbury (1961) :-

(a) Progressive change in the composition of the ore-forming fluid at its source, resulting in the first-formed minerals being precipitated in open spaces near the source, and minerals of later formation being precipitated in the remaining open spaces further away from the source.

(b) Successive precipitation of various minerals from a solution initially carrying several metals; the sequence of precipitation is controlled at the site of deposition.

The change in the composition of the ore-bearing solutions with time (process (a)) is poorly understood and must at present lie in the field of conjecture. Most workers have neglected this "time zoning" and have

tried to explain zoning by the variation of physical and chemical properties of the minerals precipitated (process (b)) . However, all the properties suggested, e.g. mineral solubility, melting point, specific gravity, hardness, mineral bonding, free energy of formation etc. do not match the observed pattern of zoning. A few of the properties approximate the pattern of zoning, but any theory of zoning must also explain the method of transport and precipitation of the metals. Barnes (1962), suggested that the zoning pattern matches the stability of covalent sulphide-containing complexes of the divalent metals, and this merits further investigation. The observed zoning of galena and spalerite at Greenside can perhaps be explained on this basis.

Any theory of zoning must also explain the zoning of trace elements in minerals. It has been shown previously that the silver and antimony contents of the Greenside galena increases with time. However most workers who have analysed galena samples have found that silver and antimony vary sympathetically with temperature. Tischendorf (1955) who studied the Freiberg lead deposit, E. Germany, concluded that the amounts of bismuth, silver copper and antimony in galena varied directly with temperature. Oftedal (1940) and El Shazly (1951) who studied, repectively, ores from Norway, and from the British Isles, Portugal, Spain and Nigeria also concluded that silver, antimony and bismuth tended to increase with the temperature of formation. However the antimony content of galena samples from the Eastern Alps, according to Schroll (1955), passes through a maximum at low temperatures while the silver and bismuth values are greatest at high temperatures. (These deposits are, however, perhaps formed as a result of metamorphic redistribution). Marshall

and Joensuu (1961) who studied some lead deposits in the U.S.A., reached a similar conclusion. The only example of silver content increasing with decreasing temperature is recorded by Twelvetrees and Ward (1910), who described the zoned deposits of the Zeehan Field, Tasmania.

This erratic and anomalous behaviour of silver and antimony is not readily explained. The variation in the availability of these elements in different metallogenetic provinces must, however, be an important factor. Thus the silver content of the low temperature Mississippi Valley type of ore deposits is low, but in other low temperature deposits, in which galena is associated with silver and antimony minerals, the silver content of galena may be high.

Since antimony and silver minerals in most ore deposits are later than galena, it is suggested that an increase in the concentration of antimony and silver in the mineralising solutions is to be expected. Gigoryan (1960) has in fact shown that the sulphur-containing complexes enable antimony to remain for a long time in solution. However at Greenside the silver and antimony concentrations of the mineralising solutions were never sufficient to form separate silver and antimony minerals. The origin of occasional inclusions of tetrahedrite in galena is uncertain: if the mineral was precipitated simultaneously with galena then the antimony values of the galena are saturation values , but if the tetrahedrite was formed by exsolution then the concentration of antimony in the galena is not necessarily the saturation value. Since tetrahedrite is rare and when present shows inconclusive time relations with galena, it is prudent to regard all the antimony concentrations as non-saturation values.

It follows that the silver and antimony c ntents of the galena are not

related directly to the temperature of formation, or other factors controlling the extent of solid solution. However the increasing availibility of these elements with time probably occurred on a decreasing temperature gradient so that the silver and antimony contents have an indirect relation with temperature of formation, i.e. the temperature does not control the specific concentration of silver and antimony in a single galena crystal but reflects the general trend of these elements in several galena samples, of successively later formation.

Turning now to sphalerite - if this mineral is precipitated from a solution which is saturated with respect to iron, then the iron content of the mineral is a function of the temperature of formation, as mentioned previously. Non-saturation with respect to iron was probably the case at Greenside and therefore the apparent decrease of iron in the sphalerite with temperature is an indirect relation. The trend shown by the germanium content of the sphalerite is again probably related indirectly with temperature.

The mechanisms of transport and precipitation of the ore material will now be considered. Each stage of mineralisation consisted of a series of pulses or phases each characterised by slightly differing physico-chemical conditions. Minor fluctuation within each pulse is indicated by the variation of composition in successive growth zones of sphalerite and galena crystals.

The divergence of the solubilities of the common sulphides and the observed pattern of zoning suggests that most ore material is not carried in the form of simple ions. Complex sulphur-containing ions are more probable meansof transport (Barnes, 1962, Hemley, 1953). Precipitation

probably resulted from a change of one or more of the following factors:-

(a) temperature

(b) pH

(c) activity of sulphur

Mixing with groundwater was perhaps an important factor.

The exact process by which barite was replaced by quartz with accompanying sulphide introduction, is uncertain. The large variation of the antimony and silver values of galena in successive bands of lamellar quartz suggests that the replacement was not a single event. It seems more likely that an alternating sequence of barite formation and silicification with sulphide introduction occurred.

Barnes and Kullerud (1961) have shown that if barite and sphalerite were formed simultaneously, then the solution from which they were precipitated is necessarily restricted in pH and the state of oxidation. At Greenside these minerals were locally precipitated simultaneously, and therefore the mineralising solutions from which they were derived were necessarily reduced, and neutral to alkaline.

CHAPTER 8

THE RELATION OF THE GREENSIDE VEIN TO THE LAKE DISTRICT MINING FIELD

1. Introduction

Although the mines at Coniston, in the Vale of Newlands, and in the Caldbeck Fells were operating in Elizabethan days and probably earlier, the heyday of Lake District mining was in the latter half of the last century. Except for Greenside, most of the mines had closed down by 1920, and today only Pottsghyll is operating, although Force Crag is currently being reopened. Accurate geological information on the majority of the mines, as might be expected, is scanty. At the outset, therefore, a correlation of the Greenside Vein with other veins of the Lake District is restricted.

The Lake District mining field has produced an estimated 300,000 tons of lead concentrates, 50,000 tons of zinc concentrates, 100,000 tons of copper concentrates and 150,000 tons of barite. Compared with other British mining fields, particularly the Northern Pennines ,which has produced 4,000,000 tons of lead concentrates (Dunham, 1959), the output of lead and zinc is relatively small. Nevertheless, Greenside ranks with seven other mines in the British Isles which have produced more than 200,000 tons of concentrates. The bulk of the total production of the Lake District has been obtained from just a few veins; thus the Greenside, Thornthwaite-Yewthwaite, Threlkeld and Roughtongill veins account for the bulk of lead and zinc production, while the Coniston , Goldscope, and Roughtongill veins account for the bulk of the copper production.

All the veins of the Lake District are simple fissure infillings, probably along normal faults. The lead and copper veins occur in both the Skiddaw Slates and the Borrowdale Volcanic Series, but there is no clear stratigraphical control; the iron veins also occur in the granitic intrusions in addition to the above strata. Apart from the centres of mineralisation west of Keswick, in the Caldbeck Fells, and at Coniston, the veins have a scattered distribution.

2. Classification, Age and Origin of the Lake District Ore Deposits

In this Thesis the veins of the Lake District are classified as shown in Table 8.1 (overleaf). For convenience the chalcopyrite-pyrite quartz- veins are termed 'cppper' veins, the wolframite-scheelite-quartz veins are termed 'tungsten' veins, the galena-sphalerite-chalcopyrite-barite-quartz veins - 'lead'veins , and the hematite-quartz-dolomite veins - 'iron'veins.

The lead veins of the Glenridding area are closely comparable, with regard to vein structure, mineralogy, paragenesis, and geochemistry, to the lead veins of the remainder of the Lake District. All of the veins have a crustified, vuggy vein structure, which is typical of leptothermal fissure infillings.. The main metallic vein minerals are galena, sphalerite and chalcopyrite, and the predominant gangue minerals are quartz and barite. Less important minerals include calcite, ankerite-dolomite, siderite, pyrite, marcasite and psilomelane. Fluorite is present in small quantities at Force Crag and Hartsop Hall, and bournonite and tetrahedrite have been observed in polished sections of the Greenside ore. A characteristic feature of the veins is the

Table 8.1. Classification of the Lake District Veins

1. Caledonian Veins

A. Chalcopyrite-pyrite-quartz veins

Minor minerals:- arsenopyrite, calcite, dolomite, magnetite Co-Ni minerals. Rare sphalerite and galena

Mesothermal fissure infillings

Examples:- Coniston, Seathwaite, Tilberthwaite, Greenburn, Goldscope, Dale Head, Castle Nook, Copper Plate, Saltwell.

B. Wolframite-scheelite-quartz veins

Minor minerals:- arsenopyrite, pyrite, pyrrhotite, molybdenite, bismuth, chalcopyrite, fluorite, tourmaline, apatite. Rare cassiterite.

Hypothermal fissure infillings, associated with Skiddaw Granite.

Trend :- N-S

Example :- Carrock Fell

2. Hercynian Veins

A. Galena-sphalerite-chalcopyrite-quartz-barite veins

Minor minerals:- calcite, ankerite-dolomite, siderite, pyrite, marcasite, psilomelane. Rare tetrahedrite, bournonite, chlorite, fluorite.

Leptothermal fissure infillings.

Trends :- N-S to NNW, E-W to ENE, and NE-SW.

Examples:- Greenside, Castle Nook (lead veins), Goldscope (lead veins) Force Crag, Brundholme, Threlkeld, Roughtongill., Driggith, Sandbeds (lead vein), Drygill, Hartsop Hall, Eagle Crag, Ruthwaite Lodge, Wythburn, Myers Head, Thornthwaite, Barrow, Yewthwaite, Brandlehow.

B. Barite veins

Minor minerals :- quartz, dolomite.

Leptothermal fissure infillings.

Trends :- E-W.

Examples:- Pottsghyll, Sandbeds (barite vein), Ruthwaite.

3. Post-Triassic Veins.

Hematite-quartz-calcite-dolomite veins

Supergene fissure infillings, some replacement.

Trends :- NW-SE.

Examples :- Kelton, Knockmurton, Nab Gill, Ore Gap, Tongue Gill.

presence of lamellar quartz, which represents earlier barite.

The relative proportions of galena, sphalerite, chalcopyrite and barite vary from one vein to another. Thus Greenside has yielded solely lead, Thornthwaite has yielded lead and zinc, and Roughtongill has yielded lead, zinc, copper and barite. However, there is no well defined regional variation, or lateral zoning, such as that exhibited in the Northern Pennines. Nevertheless , single veins, for example Greenside and Force Crag, show a well marked vertical zoning.

Moorbath (1962) has recently determined the lead isotope content of galena from several Lake District veins. The model ages of the galena samples is shown in Table 8. 2. (Overleaf).

The galena from the Buttermere Vein, an isolated vein in the Borrowdale Volcanic Series in the western part of the Lake District, has a rather anomalous model age, which is apparently pre-Caledonian. The model age of the galena associated with the Shap Granite, which is demonstrably Caledonian in age (p. 29), corresponds closely with the mean potassium/argon and strontium/rubidium age determinations of this rock - 385 $\pm$7 My (Kulp et al, 1960).

Excepting the galena from the Hensingham Borehole, and the galena described in the preceding paragraph, all the veins listed in Table 8.2 have been included by the author in the galena-sphalerite-chalcopyrite-quartz-barite category (See Table 8.1). The model ages of these veins vary from 170 to 340 My, the mean model age being 280 My. For comparison, the lead veins of south-west England, which are clearly genetically associated with granites of demonstrable Hercynian age, have a mean model age of 280 $\pm$30 My; the mean of the potassium/argon and

Table 8.2. Model Ages of Galena Samples from the Lake District.

(Reproduced from Moorbath, 1962)

Vein or locality	Model age (My)
Greenside	330 ±90
Eagle Crag	170 ±80
Hartsop Hall	210 ±70
Myers Head	310 ±80
Woodend Vein (Threlkeld)	340 ±70
Carrock (E-W lead vein)	210 ±70
Roughtongill	220 ±40
Driggith	260 ±90
Barrow	300 ±80
Goldscope (lead vein)	310 ±80
Hensingham Borehole (galena occurs as replacement in Carb. Lst. in W. Cumb.)	320 ±70
Shap Blue Rock Quarry no. 1	370 ±60
Shap Blue Rock Quarry no.2	360 ±80
Buttermere	470 ±50

strontium/rubudium age determinations of the granites is 274 ±5 My. (Kulp et al, 1960).

It can be seen from Table 8. 2 that the values tend to be grouped about 210 My. or 320 My. On account of this, Moorbath (1962) suggested that there were two periods of mineralisation - one possibly in the Upper Triassic, and the other in the Lower or Middle Carboniferous. However, the lead veins considered are very similar in all respects, and a common and essentially simultaneous origin is strongly advocated by the author. It is suggested that the variation of model ages is due to the contamination or regeneration of leads. The anomalous and irregular nature of the lead isotopes of fissure infilling deposits is well known (Stanton and Russell, 1959).

The veins composed almost entirely of barite, for example the Potteghyll and Sandbeds veins, very probably represent the later stages of the Hercynian mineralisation. At Sandbeds, the barite vein apparently cuts through the North and South Roughtongill veins (Shaw, 1959). The presence of barite, almost to the exclusion of other minerals, in the upper levels at Force Crag, which has yielded zinc and lead at depth indicates a connection with the lead mineralisation. Furthermore, the barite at Greenside, which occurs in vugs and central pockets in the Main Vein (Stage 4 of the mineralisation sequence), also occurs as cross-veins (e.g. the Hick's Vein) which cut through the Main Vein. At Ruthwaite the barite is post-Carboniferous, since one wall of the vein is composed of basal Carboniferous conglomerate (the other wall being composed of Borrowdale Volcanics).

The veins in the Lake District which have yielded solely copper,

have a very different mineralogy and vein structure from the lead veins. Firstly, the veins frequently form a plexus, for example at Coniston and at Castle Nook-Dale Head (west of Derwentwater); a crusty, vuggy vein-structure such as that found in the lead veins is absent. The chief vein minerals are chalcopyrite, pyrite and quartz; minor minerals include arsenopyrite, dolomite and calcite. Magnetite is important in the lower part of the Bonser Vein, while small quantities of Co-Ni minerals, sphalerite and galena have also been recorded at this mine. In contrast to the sugary and lamellar quartz of the lead veins the quartz of the copper veins is invariably vitreous. The mineralogy and vein-structure of the copper veins suggest a higher temperature of formation than the lead veins, and a probable reference to the mesothermal category.

At Goldscope, Dale Head and Castle Nook (Map 4) the copper veins are cut and displaced by the later lead veins. In the lower level at Hartsop Hall the author noted a chalcopyrite-quartz vein, containing traces of galena, which was cut and displaced by the lead vein. It may also be significant that the Clay Fault, which is earlier than the Greensido Fault, shows copper mineralisation to the west (the Thirlspot trial on Map 4). It is therefore suggested that the veins have a Caledonian age. On the other hand it has been pointed out by Dunham (1952) that the intersection of the copper veins by the lower temperature lead veins could possibly represent successive stages in a single period of mineralisation, as for example, in south-west England where lead-zinc veins cut the tin veins. However, the complete absence of transitional characteristics of the two veins, such as that observable in south-west England, strongly contends this hypothesis.

The absence of similar copper veins in the Pennines also substantiates a Caledonian age for these ore deposits. Nevertheless the veins cannot be genetically related to any exposed Caledonian intrusion.

In contrast the wolframite-scheelite-quartz veins at Carrock Fell are clearly genetically related to the Grainsgill (Skiddaw) Granite. The veins can probably be included in the hypothermal category. Compared with the proven Caledonian Shap Granite, the Skiddaw Granite is slightly younger, on the basis of rubidium/strontium determinations,* However the age of the emplacement and the mineralisation can justifiably be termed Caledonian. The time relations of the tungsten veins with the lead veins is clearly established at Carrock Fell where an E-W lead vein (model age 210 $\pm$70 My) cuts and displaces the former veins.

A trivial amount of mineralisation is associated with the Shap Granite. The minerals formed include galena, sphalerite, chalcopyrite, bismuthinite, pyrite as well as fluorite, quartz, calcite and barite. As noted on page 204 the model age of galena agrees with age determinations of the granite.

At Borrowdale, pipes and strings of graphite occur in a diorite intrusion. The mineral is probably genetically related to the diorite, which, on general grounds, is probably Caledonian in age.

Several iron veins have been worked in the Lake District. The most important of these occur in the western part of the region, and occur in the Eskdale Granite and Ennerdale Granophyre as well as the Skiddaw Slates and the Borrowdale Volcanic Series. The veins generally have a NW trend and are parallel to, or sometimes an extension of, veins and hematised faults which cut the Permo-Triassic and Carboniferous strata (Map 4).

(*Dodson and Moorbath, 1961)

A relation with the henatite deposits of West Cumberland is therefore clearly established. The latter are probably Tertiary in age, and were formed from descending iron-rich solutions which were derived from the weathering of ferriferous strata (Dunham,1952). It is suggested that similar rocks at one time extended to the east, and that the iron veins,and also the hematised faults, of the Lake District have a similar origin.

3. Structural Control of the Veins

Map 4 illustrates the veins of the Lake District and the major fold axes and faults. The veins have been plotted from the Geological Survey maps, and include practically all those veins which have been worked or noted. In addition to the latter source of information, the geological maps produced by several workers during the last forty years, have been employed in the delineation of folds and faults. It should be noted that the high density of faults in some areas is frequently an artifact and merely reflects the detail of the geological mapping.

The copper veins, which have a probable Caledonian age , occur in two main areas - in the Vale of Newlands (west of Derwentwater) and in the Coniston area. In the former area the veins trend ENE-WSW, and are parallel to, and lie along, the Caledonian Buttermere-Derwentwater anticline. All the veins here dip south between 50° and 70°; at Goldscope the vein was developed in the steeper sections of the fault,thus pointing to normal movement. The faults along which the veins were formed, are possibly release fractures associated with the Caledonian anticline. The northerly dipping fractures, which would represent the complementary

part of this postulated conjugate pattern, are apparently absent.

In the Coniston area the veins are again approximately parallel to the fold axis. However, at the northern section of Coniston Mine, the veins apparently make an angle with the fold axis direction. According to Mitchell (1940) the veins cut across several fold axes, but reference to the Geological Survey map shows only southerly dips. A similar relation to the folding as in the Vale of Newlands is advocated. Some of the cross-faults at Coniston are mineralised at their intersections with the veins, thus suggesting that they have a similar age; on this basis the cross-faults perhaps represent tear directions related to the Caledonian compression.

The N-S faults along which tungsten mineralisation has occurred intersect the Caledonian fold axes at about 70°. (For clarity the axes have been ommited from Map 4). It is therefore possible that the faults were initiated as tear fractures related to the Caledonian compression. However, the time relations of the emplacement of the Skiddaw Granite and the main period of folding are uncertain.

Of the three trends of the lead veins, viz. N-S to NNW, NE and E-W, the former trend is the most favourable to mineralisation. The faults of this trend which have been mineralised have a greater strike length than the faults of other trends, suggesting that they have suffered greater displacement. As noted in Chapter 4, the extent of openings formed along a fault will depend, up to a certain extent, on the amount of displacement.

The Vale of Newlands has also been a favourable area for lead

mineralisation. The veins trend mainly between N-S and NNW and form a plexus; the main veins worked at Thornthwaite, Barrow and Yewthwaite are probably one and the same vein. It is likely that the faults along which the lead veins were developed are also associated with the Buttermere-Derwentwater anticline, which was probably accentuated during the Hercynian orogeny. A similar relation of doming movements and fracturing, as that exhibited between the Glencoyne anticline and the Greenside Fault is advocated. The Buttermere-Derwentwater anticline probably extends eastwards along the Vale of Threlkeld. The N-S veins at Brundholme and Threlkeld are possibly associated with this anticline.

There is no clear evidence as to the relative ages of the lead veins with differing trends. As in the Glenridding area, the simultaneous formation of normal faults , if this is the case, is not fully understood. It is possible that the N-S to NNW faults were initiated as tear fractures, while the E-W fractures were formed later as release fractures (related to a N-S or NNW Hercynian compression), but this is rather conjectural. The presence of NE-SW trending veins, for example at Roughtongill, and NW trending veins (mainly in isolated areas - west of Crummock Water and west of Brotherswater), adds a further difficulty, As noted previously, The E-W barite veins are apparently later than the lead veins.

The Greenside Fault has been localised by the Skiddaw Slates/Borrowdale Volcanic Series junction and a quart-porphyry dyke. Pre-existing planes of weakness have also been followed by the Drygill Vein, the copper veins in St. John's Vale near Threlkeld, and possibly the Roughtongill veins. The relation of the Lake District veins to the major faults of

the region will now be considered.

As noted previously, the iron veins are clearly related to the post-Triassic NW trending faults of West Cumberland. It is suggested that many of the faults with similar trends in the Lake District, especially those that are hematised, have a similar age. The copper veins are considered to be Caledonian strike faults, but except for the Glenridding area, NW to NNE trendings faults are more dominant than the ENE faults. Many faults of the former trend are persistent, powerful fractures. The lead veins of the Lake District lie along faults with relatively small displacements which, except for the Thornthwaite-Yewthwaite Vein, are impersistant. Although the N-S to NNW lead veins are parallel to some of these powerful faults, there is no clear connection. The complete absence of mineralisation along the latter faults points to a different age of formation. The age of one of these powerful faults, the Dunney Beck-Fairfield-Grisedale-Rake Fault has been discussed on page 95 .

Unfortunately there is little data on the localisation of ore shoots at the mines of the Lake District. The most important single factor at Greenside is the variation in dip and strike of the fault plane. At Threlkeld and Goldscope the steeply dipping sections of the fault were favourable to mineralisation, thus suggesting normal displacement. The coarser tuffs, rather than the fine-grained hornstones and slates, were favourable to mineralisation at Coniston, while at Threlkeld, Yewthwaite, Brandlehow and possibly Thornthwaite, the intersections of the veins with dykes were said to be favourable; whether these relations are connected with a change in the course of the vein, is uncertain.

The localisation of ore shoots at intersections with pre-mineralisation

cross-faults or earlier veins is illustrated at several mines besides Greenside. The 'Great Lead Bunch' at the intersection with the copper vein at Goldscope, and vein/cross-fault intersections at Coniston may be cited. The enrichment of the vein at the junction with a branch fault is probably shown at Threlkeld, at the intersection of the Woodend and Gategill veins, however it is possible that these veins cross each other rather than unite.

A feature of the lead veins in the Skiddaw Slates is the apparent dying out of the vein in a zone of 'disordered ground'. Zones of this type were encountered at Threlkeld, Thornthwaite and Force Crag. It seems probable that the fault, along which the vein is developed, has died out and is overlapped by another parallel fault, the two faults being separated by a zone of ill-defined en echelon fractures.

4. Paragenesis, Zoning and Geochemistry of the Veins.

This section concerns the paragenesis, zoning and geochemistry of the lead veins. Ewart (1957) has described the paragenesis of the tungsten veins at Carrock Fell, while data on the paragenesis of the copper, iron and barite veins is scanty.

The general paragenetic sequence of the lead veins in the Glen-ridding-Patterdale-Helvellyn area, and the remainder of the Lake District is basically as follows :-

1. Pyrite, dolomite-ankerite.
2. Sphalerite and quartz.
3. Galena, chalcopyrite and quartz.
4. Barite, minor galena and chalcopyrite.
5. Calcite, ankerite-dolomite, psilomelane, minor pyrite.

Pyrite has been formed early in the paragenetic sequence at Greenside, but shows no relation with depth; however at Threlkeld and Thornthwaite this mineral is concentrated in the lower levels. Ankerite-dolomite was formed early in the paragenetic sequence at Greenside, but except for the dolomite associated with the pyrite at Thornthwaite, there is no record of its early formation elsewhere.

At Force Crag , Greenside, and possibly Eagle Crag, sphalerite was more important at depth; however at Threlkeld and Thornthwaite, which were the main zinc producers, there is apparently no such variation. Chalcopyrite at Greenside tends to be concentrated at depth, but in other veins there is apparently no variation.

A well marked increase in the quantity of barite in the vein, generally at the expense of quartz, is shown at Greenside and especially Force Crag, but data on other veins where barite is present, notably in the Caldbeck Fells, is lacking. Calcite, dolomite and ankerite were formed late in the paragenetic sequence at many mines, while psilomelane and pyrite, which are not represented at Greenside, were formed at Roughtongill and Force Crag. The closely comparable paragenetic sequence of the lead veins of the Lake District points to similar physico-chemical conditions during ore deposition.

Table 8. 3 shows the silver content of galena from several veins in the Lake District. The values which have been determined by spectrographic analysis (see Table 7. 7) are indicated thus - S, while those determined by assay (given in Eastwood, 1922) are indicated thus - A.

Table 8.3 Silver Content of the Galena from the Lake District Veins.

Vein	Ag Content - p.p.m.	
Greenside	100 - 500	SA
Eagle Crag	500	S
Hartsop Hall	500 - 600	SA
Myers Head	350 - 500	SA
Threlkeld	200 - 250	A
Thornthwaite	240 - 260	A
Brandlehow	280	A
Goldscope	170 - 190	A
Force Crag	700 - 900	A
Roughtongill	240	A
Driggith	600 - 700	A

It should be noted that a single spectrographic value, for example that of the Eagle Crag Vein probably does not have a great deal of significance, since at Greenside the variation of silver from one sample to another is very great. For this reason the results of El Shazly (1951), which are based on single samples, are not included in the table.

As concluded by Eastwood (1922) the veins with a large proportion of barite, e.g. Force Crag and Driggith, tend to have high silver values. This is consistent with the upward increase in silver at Greenside. However at Thornthwaite, the silver was said to increase slightly with depth (Eastwood, 1922) : prior to 1915 the ore assayed just over 10 oz.

of silver per ton of pig lead, while in 1918, when presumably mining had proceeded to a greater depth, the silver content was 10.97 oz. per ton. However, fluctuations of this magnitude, or even much greater, were common at Greenside from year to year, and therefore the validity of this apparent increase is dubious.

The antimony contents of the galena at Thornthwaite, Threlkeld, and Goldscope, which vary from 300 to 500 p.p.m. (El Shazly,1951), are significantly lower than the values at Greenside, Eagle Crag, Hartsop Hall and Myers Head (Table 8.3). No bismuth or manganese was recorded by El Shazly in the galena in the former veins, and at Greenside these values are generally low.

The values of Ge, Ga, In, Mn, Cd, and Co in the sphalerite from Thornthwaite, Threlkeld and Force Crag are of a similar order of magnitude as the values determined for the Greenside sphalerite. However the antimony content of the latter sphalerite is significantly higher.

5. The Relation of the Lake District and the Northern Pennines Mining Fields

The veins and replacement flats of the Northern Pennines can be referred to the Mississippi Valley type of ore deposit . Many geological problems are posed by the latter, the most important of which is probably the absence of igneous bodies from which the mineralising solutions could be derived. The basement of the ore-bearing strata - in this case the Carboniferous Limestone - is therefore of great interest. The basement of the Northern Pennines can perhaps be regarded as being essentially similar to the Lower Palaeozoic rocks and Caledonian

intrusions exposed in the Lake District. The inliers at Cross Fell and at Horton-in-Ribblesdale indicate an eastward extension of the Ordovician volcanics and sediments, while the magnetic anomaly of the Askrigg Block can perhaps be attributed to similar rocks.(Bott, 1961). Because of the similarity of the Northern Pennines basement and the Lake District, the stratigraphy, intrusions, tectonics and mineralisation of the latter are pertinent to the origin of the Northern Pennine ore deposits.

Table 8.4 shows a comparison of the galena-sphalerite-chalcopyrite-quartz-barite veins of the Lake District and the galena-sphalerite-fluorite-barite deposits of the Northern Pennines. As noted previously the chalcopyrite-pyrite-pyrite-quartz veins of the Lake District are very probably Caledonian in age.

It is felt that the weight of evidence favours an essentially common origin. However there are some striking mineralogical differences, particularly the presence of fluorite as a major mineral in the Northern Pennines, and its almost complete absence in the Lake District, where quartz is the major gangue mineral. It is conceivable that the Lake District veins represent the intermediate and outer zones of the Northern Pennine mineralisation, in which case the absence of fluorite would not be surprising (Dunham, 1952). However the absence of non-ferrous mineralisation in the Carboniferous Limestone which forms the periphery of the Lake District, tends to suggest that the veins were derived from a separate, though related, source. On this basis the divergence in the mineralogy of the veins in the two regions could be attributed to the nature of the wall rocks - the fluorine of the ore

Table 8.4 A Comparison of the lead-zinc-copper-barite-quartz Veins of the Lake District and the lead-zinc-fluorite-barite Veins of the Northern Pennines.

	Lake District	Northern Pennines
1. Type of Ore Deposit	Leptothermal fissure infillings	Telethermal fissure infillings and replacement flats.
2. Trends of veins	N-S toNNW, E-W,NE	ENE,WNW,NNW .
3. Origin of veins	Related to doming	Related to doming.
4. Wall rock	Skiddaw Slates and Borrowdale Volcanic Series	Carboniferous Limestone (also Millstone Grit and Coal Measures).
5. Major vein minerals	gal-sphal-cpy-qtz-bar	gal-sphal-fluor-bar
6. Major vein minerals	calc, ank-dol,sid,fluor, py,marc,tetra,bournon.	cpy,py,marc,calc,qtz,sid, ank,bornite,pyrrh,arag, with.
7. Zoning	Vertical zoning-zinc in depth,barite uppermost. No lateral zoning.	Vertical zoning-cpy-pyrrh-qtz-marc in depth, then fluorite followed by barite. Lateral zoning corresponds.
8. Ag content of galena	100 - 900 p.p.m.	30 - 1200 p.p.m.
9. Model age of galena	170 $\pm$80 to 340 $\pm$70 My	260 $\pm$60 to 310 $\pm$70 My

solutions in the Northern Pennines having reacted with the calcite of the limestone to form fluorite, while in the Lake District the fluorine must have been dissipated in some way.

Both the Lake District and the Northern Pennine ore deposits were probably derived from ascending hydrothermal solutions. The absence of Hercynian intrusions from which the solutions could be derived is unexplained. On account of a strong negative gravity anomaly which coincides with the inner (fluorite) zone of the Alston Block(Bott,1960), a Hercynian acid intrusion - the Weardale Granite - was postulated. However, contrary to expectations, a borehole in this fluorite zone proved a foliated granite, which, on the basis of strontium/rubidium and potassium/argon determinations, is Caledonian in age (Dunham et al,1961, Dodson and Moorbath, 1961). The sources of the mineralisation therefore remain obscure; nevertheless the granite may well have channelised the ore solutions. However the lead veins of the Lake District veins show no spacial relationship to the Caledonian intrusions .

CHAPTER 9

CONCLUSIONS

1. The Glenriddingarea is composed of two series of strata - the Skiddaw Slates and the Borrowdale Volcanic Series. Only the topmost beds of the former series are represented, and these are dark-coloured shales. The graptolite fauna indicate that the strata can be referred to the lower part of the bifidus zone. The Skiddaw Slates are succeeded conformably by the Borrowdale Volcanic Series; near the junction of the two series there is frequently analternation of shale and andesite bands, in addition to bands of breccia composed of both rocks. The Borrowdale Volcanic Series varies from 4600 feet to 8300 feet in thickness. The succession elucidated by the author differs markedly from that proposed by Hartley (1942). On account of the erroneous succession of the latter, the correlation with adjoining areas, proposed herein, differs from that proposed by earlier workers. However, the succession in the Glenridding and adjoining areas is now seen to have a greater similarity than was previously envisaged.

The strata of the Borrowdale Volcanic Series have been divided into three groups. The lowermost or Ullswater Group, the lower half of which forms the wall rocks of the Greenside Fault, is composed of andesites and basalts , subsidiary rhyolites,and intercalations of breccia and tuff. The andesites at the base of the group, which are interbedded with graptolitic Skiddaw Slates, probably have a submarine origin, while the reddened flow-breccias of the andesites higher in the group testify to their subaerial formation. The succeeding Glenridding Group is composed of rhyolites, water-lain tuffs and ignimbrites, while the topmost

Red Tarn Group includes rhyolites, tuffs which were formed from normal ash showers, and possibly ignimbrites. A general south-westerly source is suggested for these groups but a major conduit of lava could not be determined.

2. The intrusions of the Glenridding area occur in the form of small dykes and plugs. A wide variety of rock types have been recognised, including dolerites, 'porphryites', 'granite-porphyries', and quartz-porphyries; composite intrusions are common. Except for narrow basic dykes which can be referred to the Ordovician vulcanicity, the intrusions constitute a suite which is probably associated with the intrusive phase of the Caledonian orogeny. The intrusive sequence agrees in general with that elucidated in the Scafell area (Oliver, 1961). The intrusions have a negligible metamorphic effect, in general show no clear relation to the structure of the area, and, except for some of the 'porphyrites', post-date the cleavage. The main quartz-porphyry dyke at Greenside is probably associated with the Threlkeld Microgranite. Various lines of evidence suggest that the latter has a Caledonian age. One new line of evidence - the presence of tourmaline which was probably derived from the microgranite, in the Devonian Mell Fell conglomerate - substantiates a Caledonian data of emplacement.

3. No pre-Bala folding was observed in the Glenridding area. There are two main folds - the Helvellyn Syncline and the Glencoyne Anticline. Both folds are broad, open structures, and have a ENE-WSW trend, which is typical of the Lake District; they are therefore assumed to be

Caledonian in age. In contradiction to Hartley's (1942) postulated structure, no minor, tight or isoclinal folds were recognised. The Helvellyn Syncline is developed in the west of the area; eastwards the fold becomes monoclinal and eventually dies out. Oliver (1961) has recognised the continuation of the fold in the Scafell area, while to the east of the Glenridding area the structure is developed again on the other side of Ullswater (Moseley, 1960). The Glencoyne Anticline plunges to the west and appears to die out in this direction. Both folds show a marked assymmetry, the pattern of which is similar to that of the folds south-east of Ullswater.

4. Cleavage is best developed in the fine-grained tuffs; andesites and basalts generally show only incipient cleavage. Throughout the Glenridding area, the strike and dip of the cleavage is fairly constant. The close similarity of the trends of the folds and the cleavage suggest an essentially common origin. However, in contrast to the dip of the latter, the axial planes of the folds dip to the south; this perhaps suggests that the cleavage was formed towards the end of the folding period, under a slightly changed direction of Caledonian compression.

5. On account of the complexity of the tectonic sequence of the area, the analysis of joint directions must necessarily be rather hypothetical. However, the general pattern agrees with that found south-east of Ullswater (Moseley, 1960). Two of the joint maxima possibly represent conjugate tear directions related to the Caledonian compression, and one of these maxima perhaps includes tensional joints, which were formed

parallel to the compression direction. Tensional release joints may also be represented.

6. In the Glenridding area three groups of faults, each with a characteristic type of mineralisation, have been recognised. The groups are as follows :-

(1) E-W toENE-WSW normal faults. Probable Caledonian age. Quartz-pyrite-dolomite-ankerite-calcite mineralisation.

(2) N-S, E-W and NE-SW normal faults. Probable Hercynian age. Galena-sphalerite-quartz-barite mineralisation.

(3) NNE-SSW and NW-SE faults. Post-Triassic age. Dolomite-barite-quartz-calcite-hematite mineralisation.

There is direct evidence of the age of Group 2 and 3 faults. The model age of the galena from Greenside and Eagle Crag veins suggests that the Group 2 faults, along which they were formed, have a Hercynian age. The Group 3 faults, some of which are hematised, can be related to the similar hematised faults in West Cumberland which have a post-Triassic age.

The Group 1 faults are parallel to the Caledonian folds, and probably represent conjugate release fractures. During the Hercynian orogeny the Caledonian folds were accentuated as a result of doming movements; the Group 2 faults were probably formed on the release of the compression. Similar but later doming probably gave rise to the Group 3 faults. During the Hercynian and post-Triassic orogenic activity, renewed movement took place along pre-existing faults.

It is probable, judging from the complexity of the fault sequence in the Glenridding area that the interpretations of the fault patterns

in other areas of the Lake District, with regard to a single orogeny, are oversimplified. Although several workers have realised that the faulting has more than one age, it is believed that this is the first time that the tectonic sequence has been clearly demonstrated. The relation of the faults to the mineralisation, another little understood topic, has also been substantially clarified.

7. Some aspects of the controversial relationship between the Skiddaw Slates and the Borrowdale Volcanic Series in the Lake District have been elucidated by the study of the junction at Greenside, but several new questions have been raised. The interpretation of a thrusted contact of the two series in the Glenridding - Ullswater area, as proposed by Moseley (1960), has been criticised, since it is felt that the lithological variations must be also taken into account. In contrast to the postulated, gently-dipping junction proposed by Moseley, the junction at Greenside has an irregular and often steep dip. The Skiddaw Slates in the lower levels of the mine form a dome-like structure, the easterly limb of which is followed by the Greenside Fault. The relation of this dome to the Skiddaw Slates encountered at the north end of the 120 fm. level is not fully understood, but testifies to the highly irregular disposition of the junction.

The dome is not reflected in the overlying volcanics and dies out upwards. The origin of the dome is uncertain, especially since the N-S axis of the dome contrasts with the ENE fold axes. It is conceivable that the N-S axis can be attributed to pre-Bala folding and the E-W axis

to the Caledonian folding. However, a more plausible explanation is that the Borrowdale Volcanic Series were formed on an irregular sea floor composed of Skiddaw Slates. This irregularity could be attributed to the disruption of the sea floor by the upward-moving penetrations of lava, or alternately by the uneven loading of the sea floor resulting from lens-like volcanic accumulations.

8. The Greenside Fault was probably formed on the release of the compression at the close of the Hercynian doming movements, which accentuated the Glencoyne Anticline. The fracture was localised by pre-existing planes of weakness afforded by the Skiddaw Slates/Borrowdale Volcanic Series junction, and the margins of a quartz-porphyry dyke. The Greenside Vein, which was formed along the Greenside Fault , is a simple fissure infilling.

9. The Greenside Vein on reaching the junction of the Skiddaw Slates and the Borrowdale Volcanic Series abruptly pinches out. The effect of the Skiddaw Slates, apart from its important role in the localisation of the Greenside Fault, is two-fold: firstly, the dip of the Greenside Fault rapidly decreases when the foot-wall is composed of these rocks (low dips are unfavourable to the formation of openings), and secondly, potential openings would tend to collapse because of the incompetent nature of the shales. The enrichment of the vein above the tight junction of the Skiddaw Slates and the Borrowdale Volcanic Series testifies to a sudden decrease in the pressure of the mineralising solutions.

10. The main quartz-porphyry dyke at Greenside can conveniently be divided into two sections. The N-S section controls the course of the Main Fault and the disposition of several branch faults; the E-W section controls the North Fault - a pre-mineralisation cross-fault. Although the Main Fault does not invariably closely follow the foot-wall contact of the dyke, the dip and strike of the latter certaily influence that of the Main Fault. The dip and strike of the branch faults are controlled in a similar fashion. The quartz-porphyry also has a lithological effect on the mineralisation: the North ore shoot, which is controlled by the dyke, tends to have a higher lead and especially zinc values than the other ore shoots. The cutting through of the quartz-porphyry dyke by the Main Fault in the northern upper section of the mine, has an important effect on the localisation of ore shoots. The line joining all points where the Main Fault cuts into the quartz-porphyry, approximately marks the limit of stoping. The geological reasons for this are obscure.

11. The three pre-mineralisation faults at Greenside have an important effect on the localisation of ore shoots. The Greenside Fault swings westwards and dies out in a horsetail structure before reaching the Clay Fault; the southern limit of the South ore shoot and the position of the dying out of the Greenside Fault are clearly related to the Clay Fault .

It is probable that during the Hercynian orogeny, the stress in the vicinity if the pre-existing Clay Fault was relieved by renewed movement along the latter, rather than by the southerly continuation of the Greenside Fault. The North Fault has three main effects on the

Greenside Fault: firstly on approaching the North Fault from the south, the Greenside Fault tends to swing to the NE, and concomitantly the dip increases; secondly, the Greenside Fault dies out in places and is succeeded by an overlapping fault; and thirdly, the fault splits locally. The first-mentioned effect is favourable to the formation of openings, and below 120 fm. level the southern limit of the North ore shoot is marked approximately by the North Fault. The relation of the strike slip of the Greenside Fault and the disposition of the overlapping fault agrees with the conclusions of Lovering and Goddard (1950). The Wynn Fault partially controls the localisation of the 2300 N ore shoot.

12. The relatively small-scale mineralisation along the branches of the Greenside Fault has been attributed to their smaller displacement compared with that of the Main Fault. However, at or near the intersection of the Main and branch faults, both faults are generally mineralised, but in contrast to veins of other regions, the enrichment is not due to the mineralisation of a wedge-shaped breccia zone between the faults. A mutual control, by the strike and dip of the Main and branch faults on the formation of openings along each, is advocated.

13. The variation in the dip and strike of the Greenside Fault is the most important single factor controlling the localisation of ore shoots. However, this variation can be largely attributed to factors considered previously, viz. the dip and strike of the Skiddaw Slates/Borrowdale Volcanic Series contact and the quartz-porphyry margins, and the presence of pre-mineralisation cross-faults. The lithology

of the wall rocks composed of the Borrowdale Volcanic Series apparently has little or no influence on the localisation of ore shoots; The cleavage plays a minor role, but the effect of joints is probably more important.

The contoured dip diagram developed by the author, provides a a quantitive approach to the localisation of the ore shoots. The basis of the method lies in a graphical representation of a series of profiles of the fault plane, each profile being orientated with respect to the net slip direction of the fault. Because of the variation in the dip of the bearing surfaces from one section of the fault to another, a single contour does not accurately outline all of the ore shoots: However, in general the correlation of actual and theoretical ore shoots is excellent. Except for the patchy Central ore shoot, the limits of each ore shoot are marked by a steep dip gradient. This is clearly a most significant factor.

14. The hydrothermal alteration of the wall rocks of the Greenside Fault has been superimposed on a widespread regional alteration. The extent and intensity of the alteration vary according to depth, rock-type, degree of brecciation, distance from the vein, and the width of the vein. The processes involved in the alteration are silicification, sericitisation, carbonatisation, chloritisation and sulphide introduction. Silicia, carbon dioxide , potassium, lead and zinc were apparently introduced, sodium and titanium were removed, while iron, calcium, and magnesium were redistributed. The minerals developed as a result of the alteration, vary according to the distance from the vein. Three zones have been recognised; basically silicification, sericitisation, carbonatisation and sulphide

introduction are greatest adjacent to the vein, while chlorite is developed further from the vein, and has a patchy distribution. The close association of the ore and the altered wall rock suggests that mineralisation and wall rock alteration occurred approximately contemporaneously. The bleaching and induration of the wall rocks, as a result of the alteration, have undoubtedly been a guide to ore.

15. The Greenside Vein is a simple fissure infilling and shows only minor replacement. The vein structure is crustified and vuggy. Five stages of mineralisation have been recognised, each stage being separated by a period of fracturing. The sequence is as follows;-

1. Ankerite-dolomite, calcite, pyrite, sphalerite, quartz, galena, chalcopyrite, barite, calcite,
2. Galena, sphalerite, chalcopyrite, quartz, barite, calcite.
3. Calcite, chalcopyrite.
4. Barite.
5. Ankerite , sphalerite, calcite, quartz.

In addition to the minerals mentioned, tetrahedrite, bournonite and chlorite were also observed. The general paragenetic sequence is similar to that of many lead-zinc veins. An anomalous feature, however, is the relatively early formation of barite, followed by its replacement by quartz and the concomitant introduction of sulphides. The paragenetic sequence and the pattern of vertical zoning are closely comparable. The causes of zoning were discussed and it was concluded that the relative stability of the sulphur-containing complexes of the divalent metals, as suggested by Barnes (1962), is a possible mechanism, which may have operated at Greenside.

16. The silver and antimony contents of the galena at Greenside vary from 100 to 500 p.p.m. and from 500 to 5000 p.p.m., respectively. The values of both these elements decrease with depth, suggesting that the silver and antimony content of the mineralising solutions increased with time. Since the galena was not formed in equilibrium with antimony and silver minerals, the concentrations of antimony and silver in the galena is not directly related to the temperature of formation or other factors controlling the extent of solid solution. However, the increasing availability of these elements with time probably occurred on a decreasing temperature gradient, so that silver and antimony values have an indirect relation with temperature. This conclusion differs from those of other workers, especially in the case of silver. However, since the silver and antimony minerals are generally later in the paragenetic sequence than galena, an increase in the concentration of silver and antimony is to be expected. Theoretical physico-chemical considerations support this conclusion in the case of antimony. On the other hand, a complication arises since it is conceivable that the galena lattice is able to contain a greater quantity of these elements at higher temperatures. No relation between the trace element content and the crystal habit, or grain-size was observed at Greenside; sheared galena, as far as could be determined, has a similar trace element content as undeformed galena.

17. The sphalerite at Greenside was not formed in equilibrium with pyrite or pyrrhotite and therefore the Fe-Zn-S system of geothermometry has a limited application. The minimum temperatures indicated range

between 100 and 320°C, at a pressure of 1 atmosphere. The increase of the iron content, and the decrease of the germanium content with depth can probably be related to the temperature offormation. The trends shown by these elememts are in agreement with conclusions of previous workers. The values of other trace elments in the sphalerite show no significant variations.

18. The barite at Greenside shows erratic strontium values. These can probably be attributed to changes in the composition of the mineralising solutions rather than to changes in the physico-chemical conditions.

19. On account of the large variation in the silver and antimony contents of successive bands of galena, it is probable that each stage of mineralisation was not a continuous process but occurred in a series of pulses. It is probable that the metals were carried in the form of complex sulphur-containing ions. Precipitation probably resulted from a change of temperature, pH, or the activity of sulphur, or a combination of these. Mixing with groundwater was perhaps an important factor. The co-precipitation of sphalerite and barite indicates that the solutions from which they were derived were reduced, and neutral to alkaline.

20. The structural environment of the Greenside Vein, the banded, crustified, vuggy vein-structure, and the minor amount of replacement indicate that this ore deposit can be included in the leptothermal category. It is suggested that the vein was formed from ascending

hydrothermal solutions, derived from a granitic source; the lead isotope content of the galena suggests a basically Hercynian age, but no exposed granites of this age are found in the North of England.

21. The veins of the Lake District have been classified as follows:-

1. Caledonian	A.	Chalcopyrite-pyrite-quartz veins.
	B.	Wolframite-scheelite-quartz veins.
2. Hercynian	A.	Galena-sphalerite-chalcopyrite-barite-quartz veins.
	B.	Barite veins.
3. Post-Triassic		Hematite-quartz-dolomite veins.

The classification differs in one main respect from that proposed by previous workers; the chalcopyrite-pyrite-quartz veins exhibit many features which separate them from the galena-sphalerite-chalcopyrite-barite-quartz veins, and are considered for these and other reasons to be Caledonian in age. The galena-sphalerite-chalcopyrite-barite-quartz veins of the Lake District are similar in all respects, and an essentially simultaneous origin is advocated, in spite of the divergent lead isotope values. The veins which have yeilded solely barite are believed to represent the last stages of the above mineralisation. The hematite-quartz-dolomite veins can be related to the post-Triassic hematite deposits of West Cumberland.

22. The chalcopyrite-pyrite-quartz veins are approximately parallel to the fold axes, suggesting that the faults along which they were formed represent conjugate release fractures. The veins in the Vale of Newlands are proabably related to the Buttermere-Derwentwater Anticline.

The galena-sphalerite-chalcopyrite-barite-quartz veins are believed to have been formed on the release of the compression following the Hercynian doming movements, which accentuated the Caledonian anticlines. The relation of the Greenside Vein to the Glencoyne Anticline, and the veins in the Vale of Newlands to the Buttermere-Derwentwater Anticline is significant.

23. The veins of the Lake District are fissure infillings, probably along normal faults. Little data on the localisation of ore shoots is available, but the steeper sections of the faults, and the intersections of the veins with cross-faults and branch faults, are apparently the most important controls.

24. The galena-sphalerite-chalcopyrite-barite-quartz veins of the Lake District were compared with the galena-sphalerite-fluorite-barite veins of the Northern Pennines. It was concluded that the balance of evidence favoured a basically similar age and origin. Nevertheless, the almost complete absence of fluorite in the Lake District is not easily explained. The source of the mineralising solutions in both mining fields is obscure.

25. Future Research. Several areas of the Lake District have now been remapped; the intervening stretches between these areas need to be completed so that the great amount of knowledge amassed can be synthesised. On account of the close association of the tectonic and mineralisation sequence in the Glenridding area, it is strongly

advocated that the mineralisation along the faults should not be neglected but studied in detail.

Unfortunately there is little opportunity for underground geological examination in the Lake District. However there is much scope for a study of the mineralogy, paragenesis and geochemistry of the veins; the chalcopyrite-pyrite-quartz veins, in particular, have not been examined in detail. The replacement of barite by quartz, with concomitant introduction of sulphides, was not studied comprehensively by the author, and merits further investigation.

From a broader point of view, it is believed that the contoured dip diagram may be of use in the search for ore shoots. It is hoped that this method will be tested in other mining fields. The factors controlling the deviations in the strike and dip of faults, and also the variations in the strike and dip of the bearing surfaces, are not clearly understood, and would certainly repay further investigation.

Although many workers have determined the trace element content of various minerals, little experimental work has been carried out in this field; such a study would surely elucidate many problems.

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